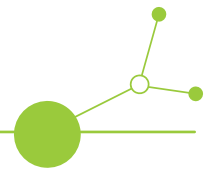


DATA COLLECTION AND ANALYSES

D2.1.2



03 2026

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1. Introduction

Deliverable D2.1.2 gathers the results of an extensive monitoring effort carried out across the HUMANITA pilot sites, offering an integrated view of how protected natural areas respond to different forms of tourist activity. The document reflects the diversity of contexts encountered during fieldwork, ranging from steep mountain paths to forested slopes and coastal environments, and illustrates how specific indicators can be measured to assess the anthropic impact in the protected area.

The monitoring is organised around five main thematic domains. The first one concerns **visitor dynamics**, examining how people move across trails and recreational sites, how these movements fluctuate seasonally, and how they generate different levels of pressure on the environment. The second domain focuses on **vegetation**, documenting changes in plant communities, shifts in species composition, and signs of stress or disturbance that may emerge where trampling or repeated passage occurs. A third area addresses **erosion and landscape change**, considering how soil surfaces and trail morphology evolve over time under the combined influence of natural factors and human use. The deliverable also includes a dedicated section on **wildlife**, capturing how selected animal groups respond to the presence of visitors in sensitive habitats. Finally, the theme of **pollution** is explored by assessing conditions in water bodies and soils, with the aim of detecting traces of anthropogenic impact and understanding how they relate to tourism intensity and local land use. Monitoring activities that do not directly fall in one of these categories, but still provide valuable support and additional insights for specific tasks, are also included in this report.

Bringing all these elements together, the document offers a broad and coherent perspective on the state of the monitored environments. The results reveal patterns that often become evident only when different types of observations are viewed side by side and, at the same time, acknowledge the influence of external drivers such as climate variability, topography, and background ecological dynamics, all of which contribute to the changes observed in the field.

Rather than producing a single conclusion, this document provides a **shared reference framework for interpreting environmental conditions** across the pilot areas. It also defines the baseline from which partners can continue monitoring activities and identify where management action may be needed to safeguard ecological integrity, while at the same time promoting responsible visitor use.



2. Visitors monitoring

2.1. Visitors distribution and frequency with infrared technology

Protected Area: Malá Fatra National Park

Project Partner: UNIZA

We use five ECO-Counter PYRO NANO automatic tourist counters, installed next to the hiking trails (Figure 1). The PYRO Nano is a small outdoor sensor that automatically counts people passing by a specific point on a trail or path. It uses passive infrared technology to detect the heat emitted by human bodies. The counter is designed for discreet installation in natural environments.

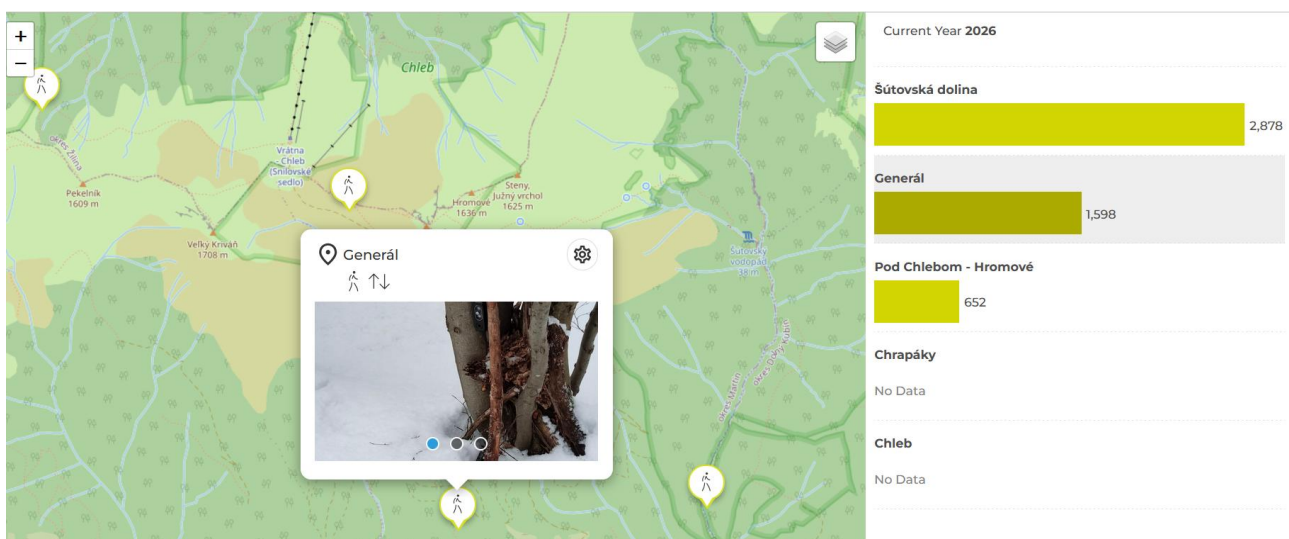


Figure 1. Location of sensors and data collected for period 1-3/2026

The device stores the timestamp and direction of movement. The counter can detect visitors up to about 4 meters from the device, making it suitable for narrow trails or entrances to natural areas. The counters are designed for outdoor use and are waterproof, with an operating temperature range from $-25\text{ }^{\circ}\text{C}$ to $+70\text{ }^{\circ}\text{C}$. The expected battery life of the devices is approximately two years. Sensors can also determine movement direction. This works by analyzing the sequence of signals detected across the sensor's detection zones. This allows managers to estimate the number of visitors entering an area, the number of visitors leaving, and approximate visitor flows along trails.

We installed the counters at locations with the highest visitor movement (hiking trails), and access points to protected habitats. The devices were mounted on trees, branches, or trail signs depending on the site conditions and visibility of the trail corridor. The counters store the collected data internally. During field visits, the data were downloaded via Bluetooth using the Eco-Link Evo mobile application. After downloading, the datasets were uploaded to the Eco-Visio analysis platform, where we analyzed visitor patterns, including daily visitor numbers, peak visiting hours, seasonal trends.

2.1.1. Results, assessment, and interpretation

Figure 2 presents daily visitor traffic recorded between September 9, 2024 and December 19, 2025 at a monitoring point located on the trail between Chleb Peak and Snilovské sedlo, near upper cable car station. This area is one of the most visited place the park. The two lines in the graph represent opposite movement directions recorded by the same counter. The data show significant temporal variability in visitor numbers, with clear seasonal patterns and short-term peaks.



The visitor numbers are highest during the summer season, particularly between July and September. During this period, daily counts occasionally exceeded 1,500 visitors per day in one of the movement directions. This suggests that the area experiences the highest tourist pressure during the main hiking season, when weather conditions are favorable and mountain trails are fully accessible.

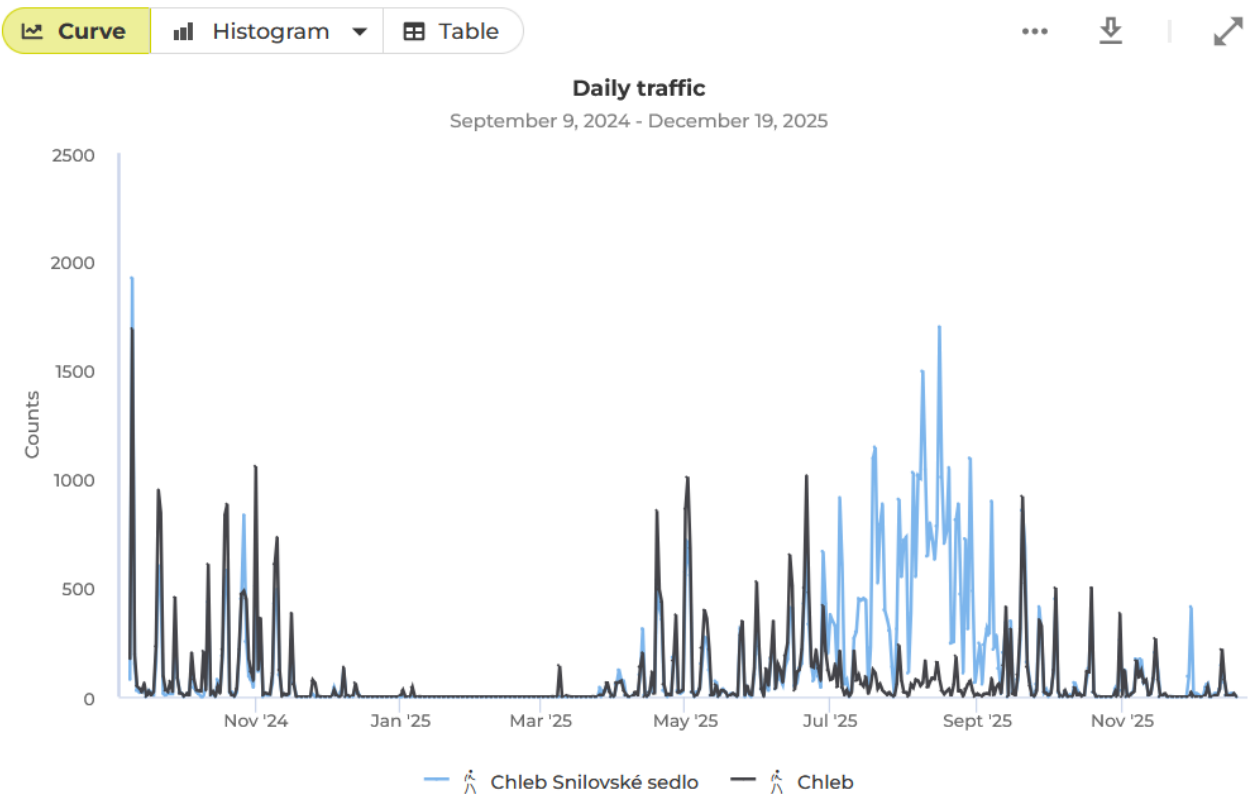


Figure 2. Daily traffic on the most visited trail in the period September, 2024 – December, 2025 – both directions

In contrast, winter and early spring months (December-March) show very low visitation levels, often close to zero or only a small number of visitors per day. This pattern can reflect bad weather conditions or snow cover with reduced accessibility of hiking trails. In general, both directions follow similar temporal patterns, which indicates a natural flow of hikers moving along the same trail segment. However, occasional occur due to different hiking routes used for ascent and descent. Several sharp daily peaks are visible corresponding to weekends, public holidays, and periods of favorable weather conditions. Such spikes demonstrate that visitor pressure can increase rapidly within short time periods, which may lead to temporary overcrowding and increased pressure on trails and surrounding ecosystems. From May onwards, visitor numbers gradually increase, reaching their maximum during mid-summer. This trend corresponds with the typical hiking season in mountain protected areas, when tourism activity intensifies.

The other two counters (Chrapáky, Pod Chlebom Hromové) were located at high-traffic locations. The counters were used to obtain an overview of the total number of visitors and to better understand the movement patterns of tourists within the study area. One counter (General) was placed in a location where visitors frequently leave the marked trail and enter sensitive habitats. This area is known to host several rare species. Monitoring visitor numbers at this site allows us to assess the intensity of unauthorized movement outside the marked trail network and to evaluate its potential influence on the abundance and distribution of rare species. A site where Western capercaillie were historically present, but were disturbed by tourists who did not comply with the established visitor regulations. During a three-month period in the winter season 2026, more than 1,500 tourists passed through the area, many of whom were ski touring enthusiast.



HUMANITA

Another counter was installed on the trail connecting the Šútovská Valley and Chata pod Chlebom. This counter records the number of visitors moving in both directions along this route. The data provide information on the number of tourists approaching the hut from the valley as well as those descending in the opposite direction. Together with the third counter placed along the trail section between Chata pod Chlebom and Hromové sedlo, these measurements help to more accurately estimate the distribution of tourists moving through this important mountain corridor on several trails.

In addition to automatic counters installed along the monitored trails, several complementary data sources were used to improve the accuracy of visitor monitoring. Camera traps were deployed to record movement patterns and verify the number of visitors passing through selected locations. However data have not been evaluated yet. Furthermore, aggregated mobility data from the Strava application, provided through the Strava Metro platform, were used to capture spatial and temporal patterns of recreational activity in the area (Figure 3). This combination of monitoring tools made it possible to obtain a more comprehensive understanding of visitor flows and activity types within the study area.

The aggregated mobility data indicate a significant and growing level of recreational use within the monitored area. During the latest full year, a total of 249,900 trips were recorded, representing an increase of approximately 19.5% compared to the previous year. Weekend activity constitutes a substantial share of this use, with 90,100 trips (+18.7%), confirming the strong recreational character of the location. The dataset also shows that 31,900 individual users generated these trips, which represents a 21.3% increase, suggesting both a growing popularity of the area and an expanding user base.

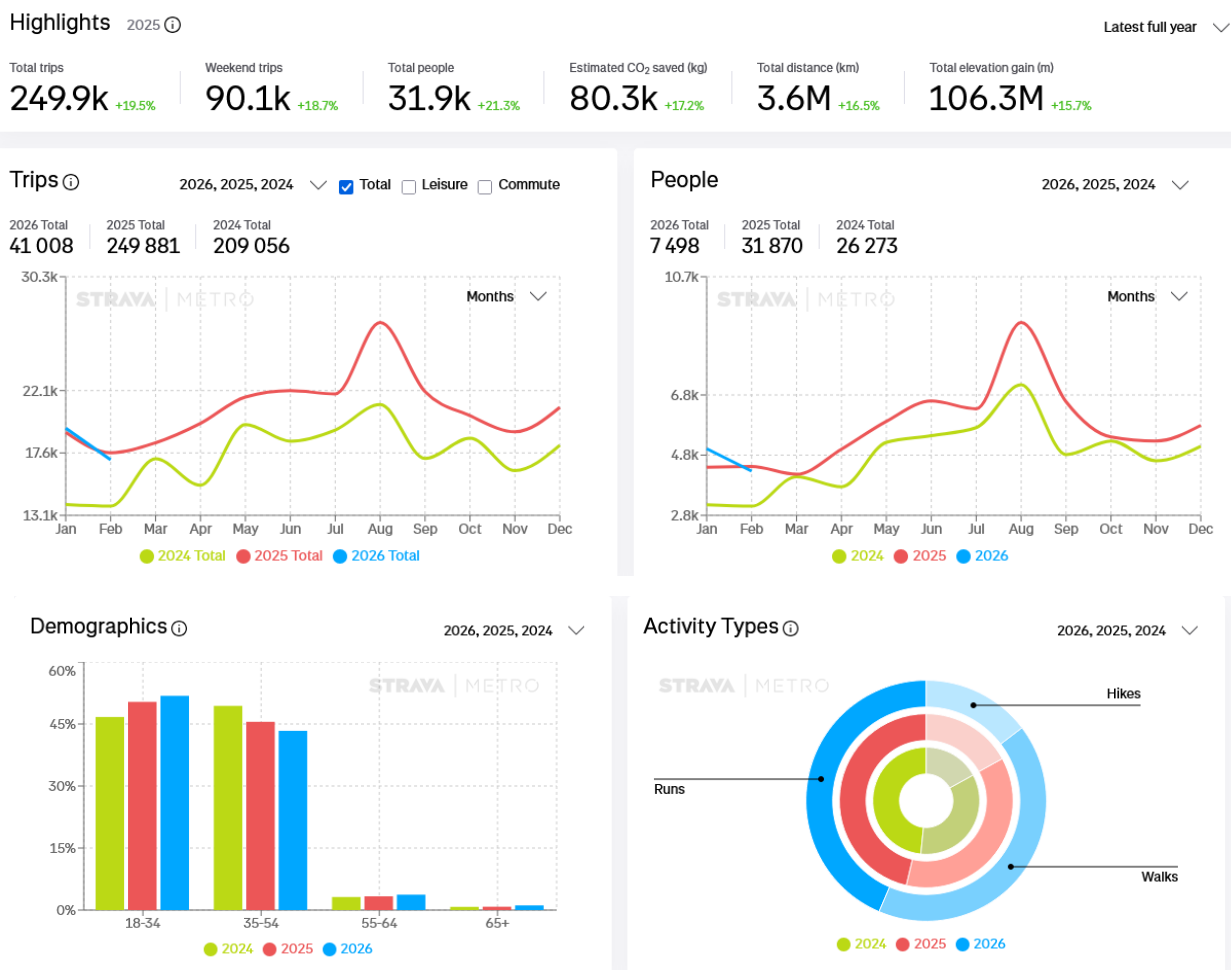


Figure 3. Statistics from Strava for entire area of the park



Taken together, the demographic and activity data suggest that the area is mainly used by younger, physically active visitors engaged in hiking, walking, and running. This user profile is consistent with typical patterns observed in mountain and nature-based recreational environments. At the same time, it is important to note that data derived from Strava-based monitoring may be biased toward technologically engaged users, meaning that certain groups (such as older visitors or casual tourists who do not use activity-tracking applications) may be underrepresented.

2.1.2. Conclusions and Recommendations

Counters provide objective data on how many people visit a site. They identify peak use periods and show busiest days, peak hours, and seasonal visitation patterns. In this way we can see when and if visitation exceeds ecological limits. On the basis of this information, park managers can redirect visitors, close some trails temporarily or improve trail conditions. Key advantages of systems like PYRO Nano include non-intrusive monitoring, anonymous data collection, low maintenance, long battery life, high accuracy, easy installation, and relocation.

Several limitations may affect data collection. One of the main issues occurs during the winter season, when the devices may become partially or completely covered by snow. This effect can also be seen in Figure 2, when during the winter months the counter did not correctly count all tourists due to snow cover and weather conditions. To minimize this problem, counters should be installed at an appropriate height above the ground or mounted on elevated structures. Another limitation relates to the accuracy of detection when visitors move in groups. When several people pass the sensor very close together, the device may register them as a single event, which can lead to underestimation of the actual number of visitors. In addition, incorrect installation of the sensor, such as improper orientation toward the trail or an excessively wide detection angle, can negatively affect the quality of the data. Environmental factors may also influence the counting accuracy. For example, movement of nearby vegetation, such as tree branches or tall grasses affected by wind, can occasionally trigger the sensor and create false counts. To reduce such errors, it is important to carefully select installation sites and to regularly check the surroundings of the device.

Visitor monitoring combined several complementary methods, including automatic counters, camera traps, and aggregated mobility data from the Strava application. While the camera trap data have not yet been evaluated, the Strava Metro dataset indicates a significant and increasing level of recreational use in the monitored area. A substantial proportion of these trips occurred during weekends (90,100 trips) correlates very well with findings from counters.

2.2. RadioBeam technology for visitors counting

Protected Area: EGTC Geopark Karawanken-Karavanke

Project Partner: EGTC GEOPARK

We established 11 locations with 11 visitor counters based on RadioBeam technology from Chambers Electronics. To enhance the visitor experience, we have implemented a network of three types of "visitor counters" in key locations across two pilot sites: a **simple visitor counter** - counting only hikers or only bikers; **visitor counters A-B** - counting only hikers while establishing the direction of approach; and **complex triple visitor counters** - counting and differentiating between vehicles, bikers, and hikers with establishing the direction of approach where needed.

The counters were placed at the locations with the **highest visitor traffic**, including hiking and biking trails, as well as **at access points to protected areas** and starting positions for these activities on key locations across two pilot sites, Petzen/Peca (Figure 4) and Hochobir/Ojstrc (Figure 5). The triple visitor counter Petzen Straße - dirt road (Petzen/Peca) will be moved to the NEW location in summer 2026 near the mountain cottage "Dom na Peci" to cover the opposite direction of visitor approach to the mountain peak.



The triple visitor counter from Trögerner Klamm - gorge (Hochobir/Ojstrc) will be moved to the more appropriate location (still needs to be determined in summer 2026).

The dual-sided sensors (receiver and transmitter) capture everyone who passes through - on foot, by bike or otherwise (depending on the counter and position of the monitoring) - without the need for a complex setup. The meters are battery-powered, weather-resistant, easy to install and suitable for trails, parks and remote locations. RadioBeam counters provide a simple and effective way to measure visitor numbers and traffic flow.

The counter can detect passing up to approximately 4 meters between the units (hikers and bikers), and up to 6 meters distance for triple counters; however, it is recommended to narrow the space between the units for hikers and bikers to approximately 2,5 meters and vehicles to approximately 4 meters for better results.

Our selected counters operate as part of a wireless monitoring network, with data collected automatically transferred via NB-IoT or satellite to the Dashboard, where we can instantly analyse visitor patterns, including daily visitor numbers, peak visiting hours, and seasonal trends.

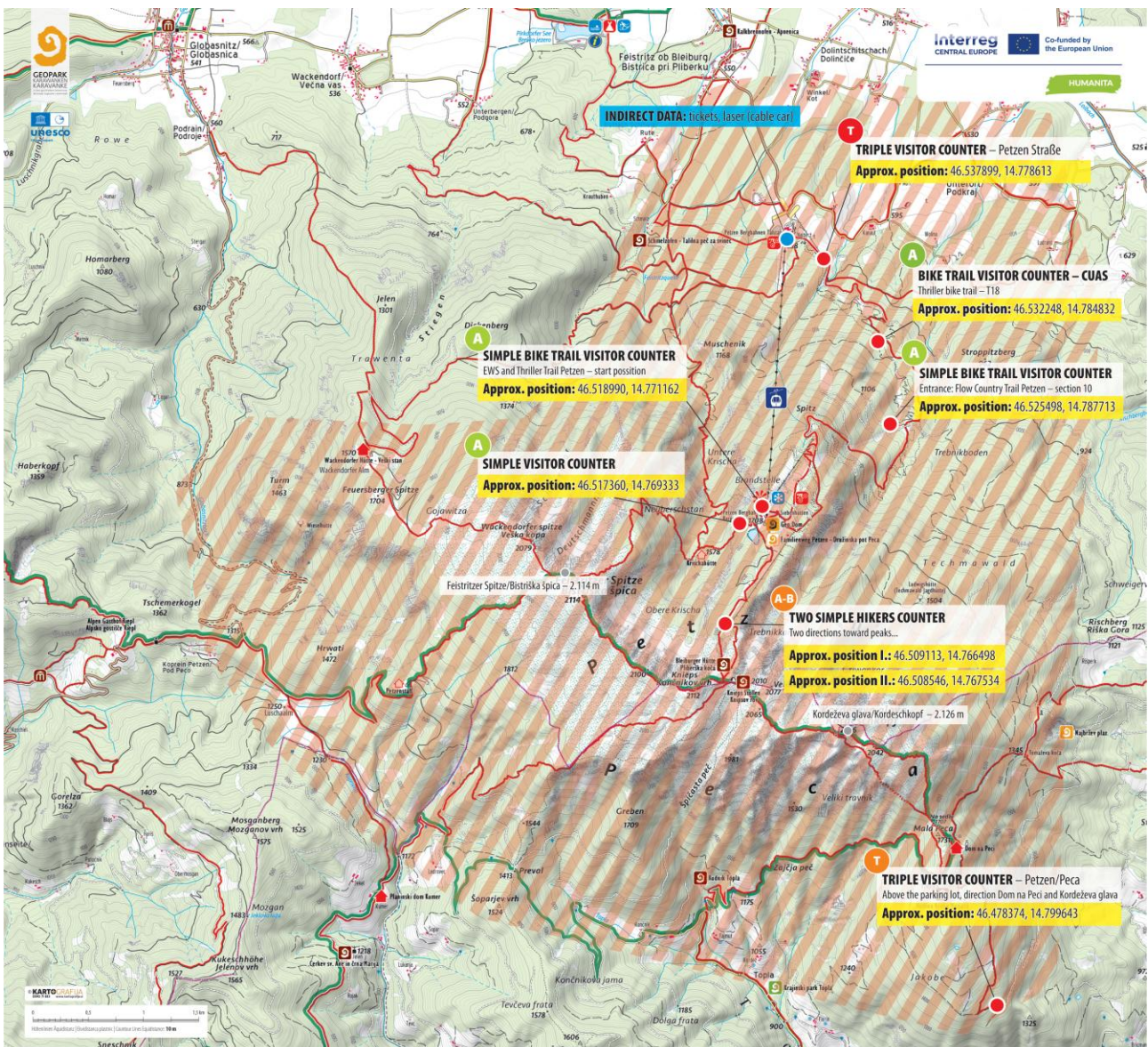


Figure 4. Location of visitor counters on the pilot site Petzen/Peca

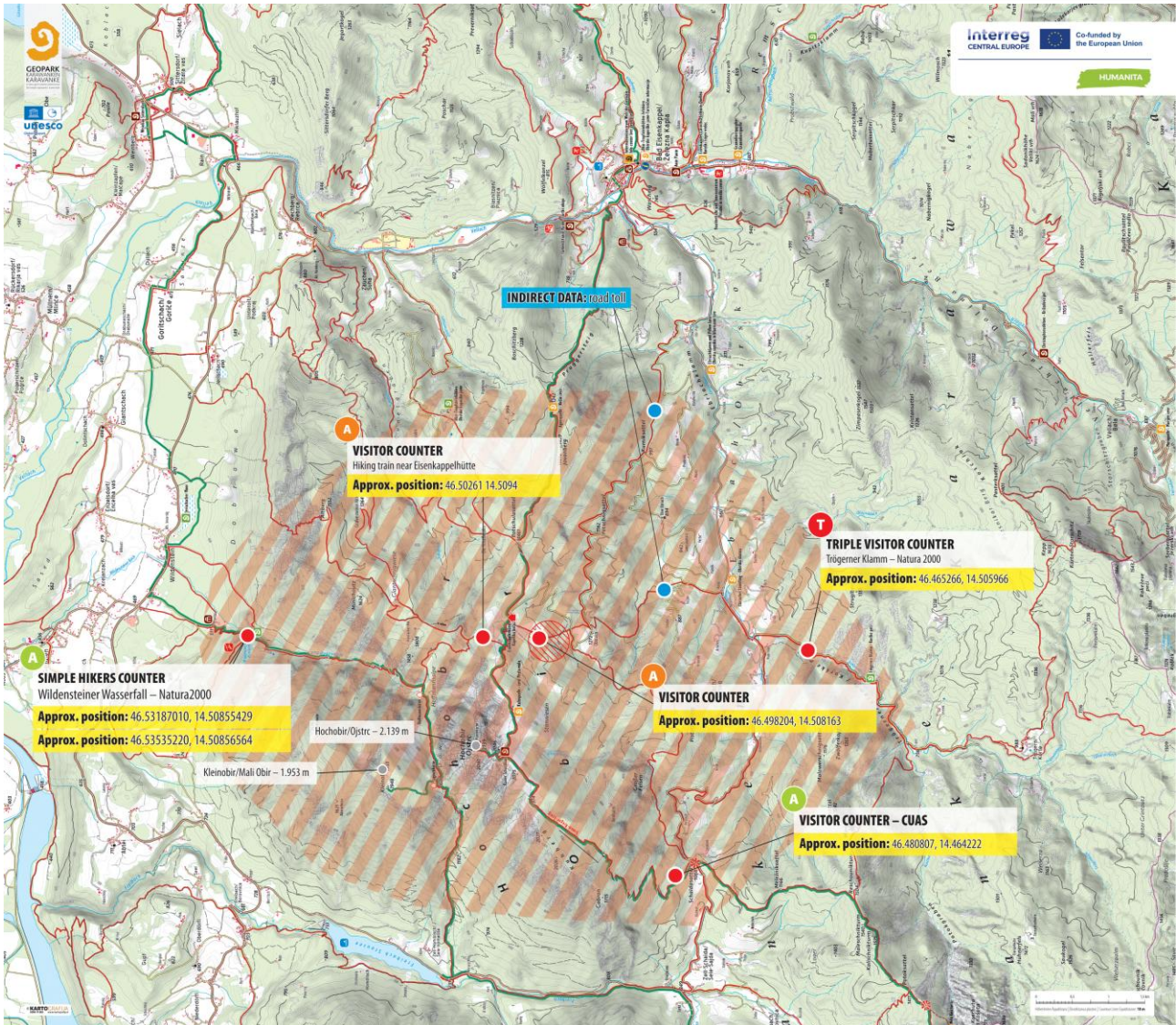


Figure 5. Location of visitor counters on pilot site Hochobir/Ojstrc

All devices log the date, time, number of passes, and basic weather conditions, including temperature, humidity, wind speed, and pressure, as well as the time of sunrise and sunset at the installation location. All devices also send basic information about the counters, including battery status, location, error messages, and the timing of the last data transmission (information for the smooth operation of the devices to define the gaps).

Some selected devices (A-B) also record and distinguish the directions of movement of the passages.

Complex triple visitor counters, along with all the aforementioned data, monitor, record and distinguish between the number of vehicles, bikers and pedestrians.

2.2.1. Results, Assessment, and Interpretation

Figure 6 The following graph displays daily data collected from June 23 to October 31, 2025, at a specific location along the circular hiking trail on Mt. Petzen/Peca between Slovenia and Austria. This location is situated above the mountain station of the cable car (1.705 meters above sea level) at an altitude of 1.905 meters above sea level. Name of the counter: 005 Petzen H1. The data captures one of the access points to two peaks on the mountain, as well as the opportunity for hikers to cross between the two countries. This area is one of the most frequently visited sites within the Geopark, as its proximity to the operation



time of the cable car and open road connections on the Slovenian side significantly facilitates access, especially during the summer season.

The graph shows the recording of two directions (visitor access and descent) at the visitor counter location. The data show a logical temporal variability in the number of visitors with a clear behavioural pattern, which is defined by peaks in the summer season, especially in July and August, and highlights of visits during favourable weather conditions.

Recording the direction of movement and the clear differences between ascent and descent along a given route also highlights the route's popularity and difficulty level. Hikers generally prefer ascending in one direction rather than descending on this trail. To better understand the number of visitors at the trail, we need to apply a **correction factor of 1.24**, as the counter is approximately **81% accurate** based on our testing period at the location. A more comprehensive analysis and calculation of the data from all visitor counters in the surrounding area (3), with the connections to the access routes, and visitor movements on the pilot site, is necessary to conclude the approximate number of visitors on the spots. The given number covers the impact on one trail, but not the area itself.

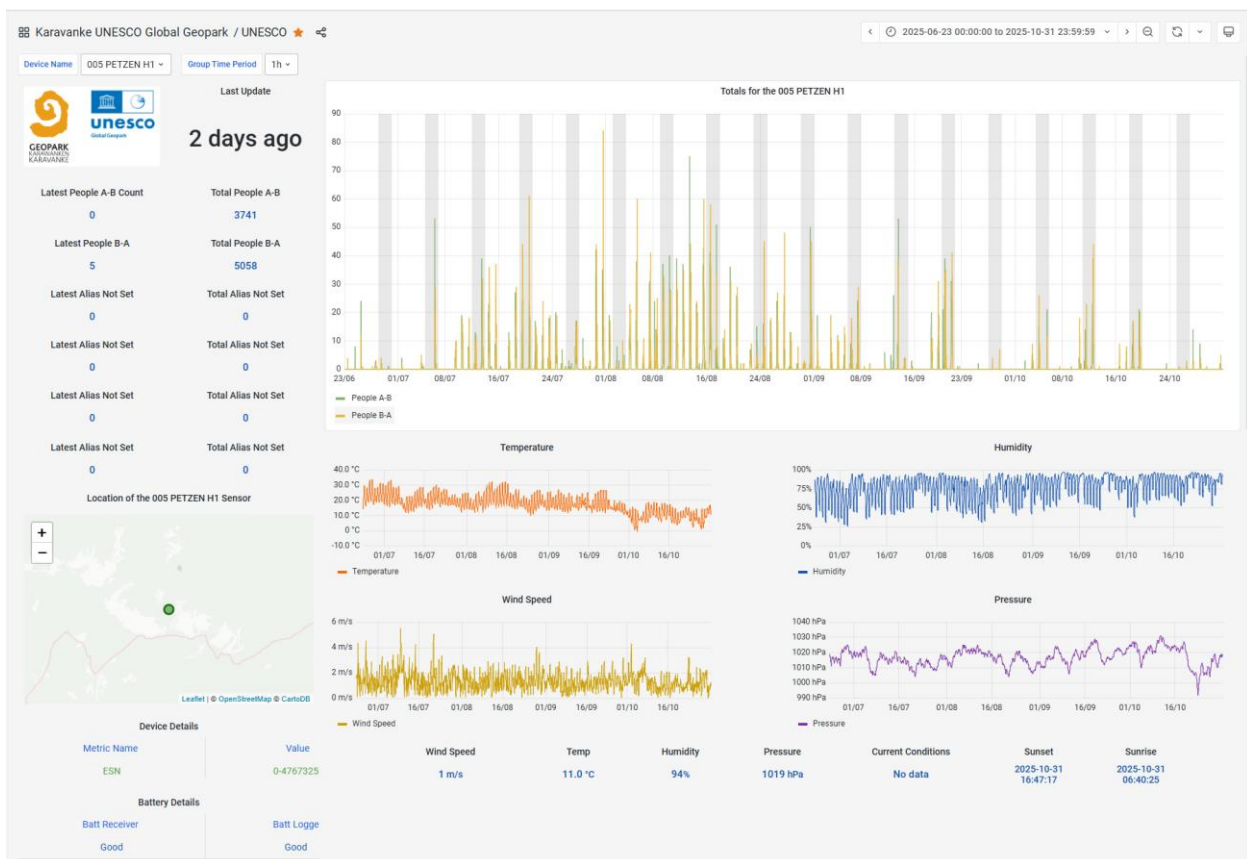


Figure 6. Daily data collection of visitor flow on hiking trail on Mt. Petzen/Peca from June 23 to October 31, 2025 – both directions.

Two additional visitor counters have been installed to monitor the routes leading to the peaks of Mt. Petzen/Peca in the nearby area. One counter, named **006 Petzen H1**, is positioned along the bypass trails that connect the summit trails of 005 Petzen H1 counter, providing access to both the Austrian and Slovenian sides of the mountain, which stands at an altitude of 1'905 meters above sea level. This new counter is the same type as the parallel counter and gathers the same data for its designated directions.

The third counter, named **004 Petzen H1**, is situated closer to the mountain station of the cable car, beneath the artificial lake, at an altitude of 1'677 meters above sea level. This route is directed towards the Austrian peak of the mountain and passes over Krischa/Križe. The counter doesn't distinguish between directions and detects all passings on the hiking trail.



A flat rate analysis comparing and combining data from all three measuring devices shows the frequency of use of different trails in the same direction (Figure 7).



Pilot site: Petzen/Peca

Flat rate analysis

Comparison period: August 2025

Visitor counter	Type of counter	A– B	B– A	no direction	All	CF	Final	Recap	%	%
004 PETZEN H1	Single – hike	/	/	1.660	1.660	1,25	2.075	1.400	23,43%	23,43%
005 PETZEN H1	Simple A-B	1.750	2.370	/	4.120	1,24	5.110	2.555	42,76%	76,57%
006 PETZEN H1*	Simple A-B	1.463	1.257	/	2.720	1,35 / 1,1	4.040	2.020	33,81%	
								5.975	100%	100%

*Gaps: 2.8. – 4.8.2025 / 21.8. – 25.8.2025

Figure 7. A flat-rate analysis comparing and combining data from three visitor counters for comparative analyses of trail use in the same directions. Monthly visit comparison from August 2025 (peak of the summer season).

*Peaks of hiking tourism are mainly tied to the seasonal summer operating hours of the cable car, which take place between mid-May and the end of October. In winter, the location itself is a popular ski resort. Measurements in winter are difficult due to the snow cover that obscures the hiking trails and also the measuring devices (the snow cover can be up to 1.5 meters high), and hiking is not feasible during this time, or it is spread out of the classical summer trails (ski touring and occasional snowshoeing). The monitoring with existing visitor counters in the wintertime will not give a satisfactory result. There are no visible hiking trails for hikers to remain on the path, and the visitor can easily bypass the monitoring sites due to the wide winter panorama.

The combined data provides insight into the number of visitors during the visiting periods who are heading to the mountain peaks. There is still a gap in the coverage of the monitoring locations, and we are currently only estimating the number of visitors who use directions and can avoid detection by the visitor counters. A comparison of the routes clearly shows that both parallel routes are **3x more congested** than the hiking trail that leads directly to the Austrian Peak, and is also a more demanding and longer route.

Existing data shows that in **August 2025** alone, an average of **around 6'000 visitors** set off in three directions from the Austrian side towards both peaks.

Yet to come: In the following, we will also compare this number with the number of cable car tickets sold. To analyse the comparison of how many cable car users continue their journey to the summit and how many remain near the viewpoint of the upper cable car station and the Panorama Restaurant - culinary experience.

We will continue and expand the network of visitor counter monitoring with a focus on strategic guidelines for understanding visitor behaviour patterns on Mt. Petzen/Peca, to determine the use of different mountain trails to the mountain peak directions.

STRAVA Metro remains the basis for detecting illegal outdoor recreational activities, especially mountain biking outside legal bike trails and illegal biking access to mountain peaks. **The goal is also to reduce errors and fill the gaps in missing data collections.**

2.2.2. Conclusions and Recommendations

Counters provide objective data on the usage of hiking, biking, and other trails. By utilising a set of data from various locations and positions of measuring devices along a common route, we can estimate the number of visitors over specific time frames. These measurements help identify peak visitation periods and reveal patterns regarding the busiest days and seasons.

The data serves as an important indicator that helps to calculate the **carrying capacity of the trail** and determine when ecological limits are exceeded. Additionally, it provides insights into the popularity and usability of the trails and directions.



Armed with this information, **park managers** and **trail supervisors** can effectively **redirect visitors**, **limit access**, or **temporarily close certain trails** to improve their condition. In cases where trails are consistently underused or have become unusable, **permanent closures** may be considered.

Preliminary tests conducted at the beginning of the Humanita project examined various technologies and different suppliers of visitor counters (such as magnetometers, infrared sensors, RadioBeam, and AI). These tests revealed that no technology or visitor counter can guarantee 100% measurement accuracy. Therefore, it is essential not only to focus on the technology itself but also to adapt it to the specific monitoring location.

Nevertheless, **the advantages** of systems such as RadioBeam technology include **affordability** (user-friendly price), **no maintenance costs**, **low annual data transfer costs** (approximately 139,00 €/year), **long battery life** (3 years), **easy installation** (no settings needed), **easy relocation** if needed, **automatic data transfer** (Dashboard), **weather resistance**, a certain degree of **robustness** and **shock resistance**, **satisfactory measurement accuracy** with **non-invasive anonymous data collection** (numbers).

During the testing phase (as mentioned above), we identified various factors that can influence the data collection of the measuring devices and sought solutions to address them.

Here are some general observations that can reduce the accuracy of measuring positions, along with potential solutions:

- **Detection:** Most suppliers guarantee the performance of their counter devices at distances of up to 4 meters, regardless of the technology used. At this distance, hikers may walk in parallel or form groups without maintaining any space between them. This often confuses the sensors, leading to situations where the device records only one person or fails to detect anyone at all because the object appears too big. **A straightforward solution** is to establish a designated path where hikers cannot group or walk in parallel and must walk in a single file. We recommend a **width of the monitoring position of around 2 meters** to minimise this issue.
- **Automatic data transfer:** Avoid enclosed areas such as dense forests, closed, narrow valleys and gorges, which can limit or interfere with the signal for automatic data transmission. Open sky above the devices and open, unobstructed space in the immediate vicinity provide a good signal. If you find that the device does not have a strong enough signal or that it occasionally loses the signal required for automatic data transmission, we suggest **moving the device until you have a strong enough signal** for smooth operation.
- **External natural factors:** Avoid the installation area where there are moving elements near the device, such as branches, tall grass, wind carrying leaves, ... The rule of thumb for free space is 2x the diameter of the sensor's tracking length to avoid impact from surroundings.
- **Weather effects:** even though there are no potential visitors in nature in bad weather, heavy rain or snowfall can affect the triggering of the sensor by overlapping the measurement direction (some technologies are more affected, others less - in case of bad weather conditions, check the data captured by the measuring device). **Sun:** It is advisable to avoid placing measuring devices directly facing the sun in all cases.
- **Other possible external factors:** avoid proximity to large metal, electrical or electromagnetic structures, as well as devices that emit micro vibrations into the surrounding area.
- **Instruction:** Follow the manufacturer's instructions, such as the height at which the device should be mounted, where it should be oriented, how batteries should be installed, how to test the device, and other technical characteristics when starting the devices.
- **To assess the accuracy of the device's data collection at the measuring point**, it's important to note that no technology or device is 100% accurate. Numerous factors can influence the results. To



better understand and correct the results, we suggest conducting an accuracy test. In our case, we performed this test directly at the visitor counter location by manually counting the number of passages through the measuring devices. This counting was repeated 4 to 5 times throughout a whole day, lasting up to 6 hours during peak visitation times. We then compared the manually counted data with the automatically recorded data. If the results were unsatisfactory (with an acceptable accuracy threshold of 80% comparative accuracy in our scenario), we adjusted the device's position, measurement angle, unit level, and reduced the distance visitors had to pass between the units. By repeatedly comparing the manual counts with the automatic counts, we were able to achieve a satisfactory accuracy level suitable for us (above 80%). Finally, we calculated a flat-rate correction factor for each visitor counter, which helps us estimate the true number of visitors at that specific location more accurately.

- **Animals:** Avoid pastures. Cows and sheep often rub against objects such as visitor counters. Their activity near monitoring positions will trigger sensors and add invalid crossings.

2.3. Synergic approach for visitor flow assessment

Protected Area: Bükk National Park Directorate

Project Partner: BNPD

Visitor flows were evaluated using a tripartite approach combining telecommunication data, Strava Metro statistics, and physical ForestVisit infrared counters. The telecommunication data provided daily traffic figures, weekend versus weekday splits, and estimated domestic and international visitor origins for specific polygons including Sár-hegy, Totovics, Nagy-Lápatető, Kékes Észak, Parádi legelő, and Suba-lyuk. Strava Metro data complemented this by mapping broader, monthly and yearly cycling and hiking trends across the park, while the physical counters provided precise, hourly passage rates in the Hór-valley and Tar-kő pilot sites (Figure 8).

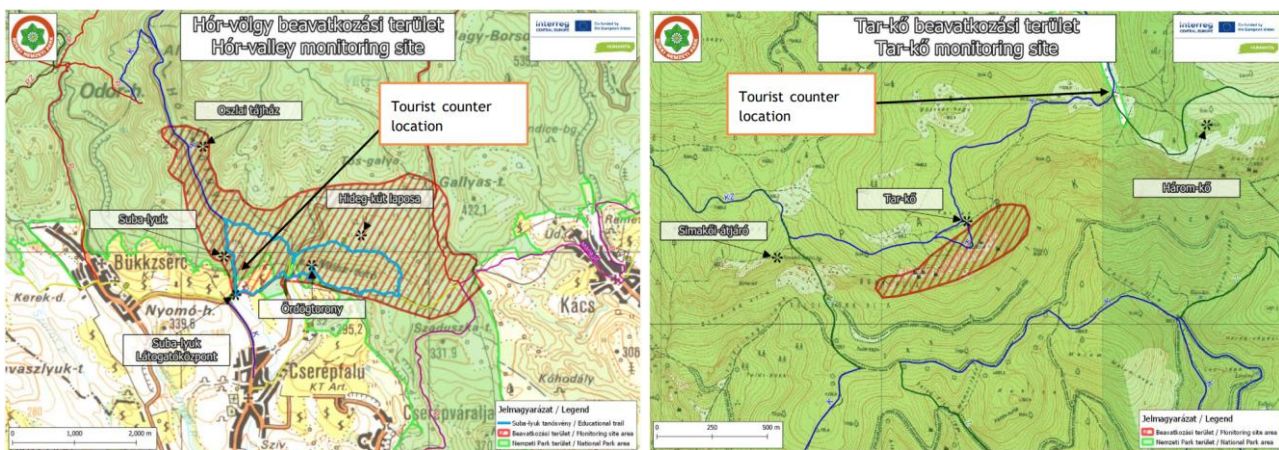


Figure 8. Location of visitor counters installed in the Hór-valley and Tar-kő pilot sites

In the case of the telecommunication data, "stays" in specific areas are defined as a sequence of events recorded within a single polygon where the time elapsed between events exceeds a pre-defined maximum (2 hours). The duration of a stay is the time between the first and last event of the sequence. A "visitor" is a user whose total duration of events within a single day exceeds a pre-defined minimum (1 hour). A "visit" is counted when an individual appears in a target area on a given day (per the description above). Multiple appearances in the same area on the same day count as a single visit. Consequently, visitors meeting the criteria every day of the month will increase the count for both weekday and weekend visits. The residence of visitors was categorized at the level of **Hungarian macro-regions** (with special focus on Budapest and areas surrounding the target polygons), at the **country level** for Europe, and by **world regions** for the rest of the world. Domestic residences are estimated from nocturnal locations in the 6 weeks preceding the visit,



while roaming visitors are categorized by **MCC (Mobile Country Code)**. To identify local residents, specific polygons were designated around the target areas.

Located at each of the vegetation monitoring sites, automatic counters using an infrared beam from the company ForestVisit Ltd. are present at the split towards the Suba-lyuk cave in the Hór valley and the “blue line” designated trail in the Keskeny valley east of the Tar-kő peak. Moreover, a mobile service analysis will be carried out by Telekom along designated trails at the pilot sites Kékes-North and Csörgő-valley in the Mátra Mountains. Spatially it coincides with the areas of the genetical survey, the educational trail and the participatory monitoring of littering. Tourist flows are further monitored using STRAVA Metro Data along designated trails in all pilot areas.

The raw data with hourly visitor numbers from the automatic counters was be uploaded to the project’s shared database, from where stand-alone or correlation analyses will be possible to conduct, in order to determine peak seasons and hours as well as potential correlation to trampling damages.

STRAVA METRO data (monthly and yearly, bikes and hikes) is collected from the relevant protected areas (Bükk National Park, Mátra Landscape Protection Area) and sent to project partner Carinthia University of Applied Sciences (CUAS) for analysis. STRAVA METRO data for the project duration was analysed by CUAS.

2.3.1. Results and integrated findings

Integrating the disparate datasets reveals complex, overlapping pressures that a single methodology could not expose.

Merging the telecommunication traffic data (Figure 9) with the amphibian swabbing results (Section 5.2) highlighted a direct correlation: Kékes North exhibited both high mobile device traffic and the highest Bd fungal infection rates, whereas Nagy-lápfő demonstrated low visitor traffic and a correspondingly low presence of the disease. Visitation data was used as supplementary information for the amphibian infection studies, providing valuable insights. The high visitation of the **Kékes-Észak** polygon correlates with the high chytrid infection rates at Haluskási út and Hidasi út. Similarly, the low visitation of the **Nagy-lápfő** polygon corresponds with the low infection values at Bagolykői út. The relatively high visitation of the **Parádi legelő** polygon is likely due to its proximity to roads; it is possible that the higher infection rate at Glóbusz út (compared to Bagolykői út) is linked to this.

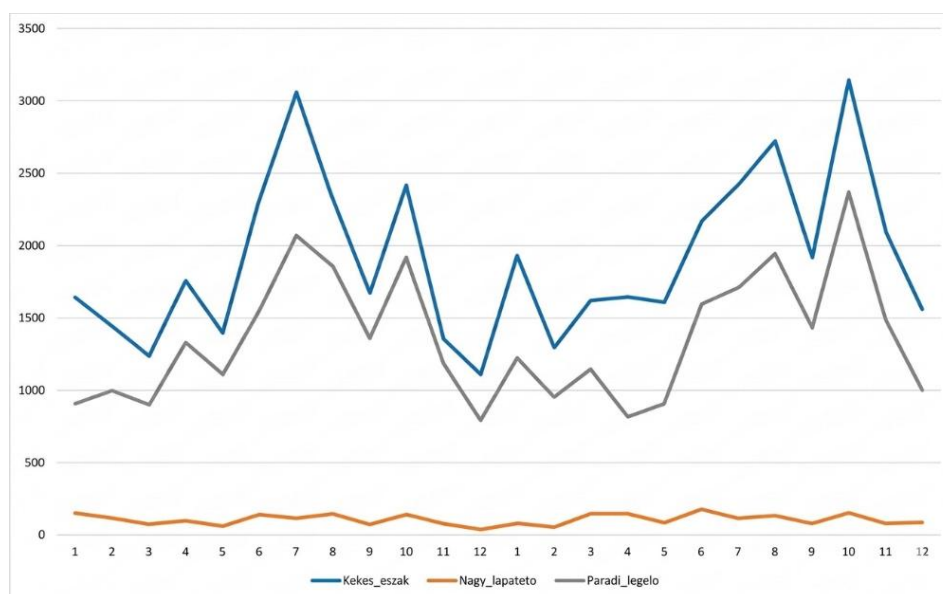


Figure 9. Monthly tourist traffic of Kékes-Észak, Nagy-lápfő, and Parádi legelő (2023–2024)

Examining visitor "origins" at Kékes-Észak, the highest number of European visitors come from **Germany (15%)**, but the number of visitors from **North America (14%)** is similarly high. **Romania (10%)**, **Slovakia**



(9%), and the **Czech Republic (8%)** are also highly represented. Guests arrived from nearly all parts of Europe, with other continents represented by the Middle East, Far East, Africa, Oceania, and South America. This distribution provides ample opportunity for the introduction of infectious diseases.

The high proportion of North American visitors is particularly noteworthy, as we must account for the potential introduction of **new genetic lineages** of both chytrid fungus and ranaviruses from that region. Among domestic visitors, local traffic from the Mátra region dominates, though the proportion of visitors from **Budapest** is nearly as high. In summary, tourism to Kékes-Észak presents a high probability for the domestic spread of amphibian pathogens. (Since Kékes-Észak is currently the only known site in Hungary where amphibian mortality caused by chytridiomycosis has been recorded, the risk of dispersal from here is of grave significance.). Similar visitation patterns were observed for Nagy-lápafő and Parádi legelő, though with a notably lower proportion of guests from North America.

This integration of human demographic data with wildlife pathology suggests a hypothetical but serious risk of new, virulent pathogen lineages being introduced from abroad.

Similarly, combining visitor heatmaps with vegetation transects (Section 3.2) confirms that while tourists rarely venture off the designated paths, their concentrated movement along these arteries is sufficient to alter the micro-climate and soil compaction enough to facilitate the rapid spread of invasive weeds like *Anthriscus cerefolium* into vulnerable habitats.

2.3.2. Refinement of monitoring strategy

A significant limitation arose from the telecommunications side, as the phase-out of the 2G network in September 2025 and the installation of new 4G cells altered the spatial distribution of geolocation signals. To counter this limitation, time-series modeling incorporating annual, monthly, and weekly seasonality had to be applied to forecast and complete the dataset for the final quarter of the year. Furthermore, aggregates with fewer than ten visitors were masked for GDPR compliance, slightly obscuring data for the least-visited trails. The combined analysis proves that while each dataset has blind spots, such as Strava's bias towards athletic users, integrating all three methods successfully captures both the volume and the spatial diffusion of tourists.

Moreover, installing a greater number of physical on-site visitor counters is crucial to establish reliable baselines. These physical counts are necessary to calibrate and validate the broader, aggregated mobile service data and STRAVA Metro datasets.

2.4. Cameras for vehicle counting in parking areas

Protected Area: Lower Kamenjak

Project Partner: PIK

Visitor monitoring was conducted through installed counter cameras at ten parking zones. Also, 10 LED panels were set up at each parking zone and a big LED panel was rented before the main entrance to the area to inform the visitors of the availability of space at each parking zone/beach. The data was collected through the three peak months of summer (July, August, September). To evaluate visitor activity, a model was developed that integrates data from Strava Metro with other available datasets.

The initial phase was to set up 10 camera counters for parking zone monitoring, 13 solar power plants to enable camera counters at the parking zones. The installation of LED panels is meant to inform the visitors about the availability of parking zones and thus prevent traffic jams and overcrowding. Also, the visitor movement is monitored by comparing data collected through the LPR cameras at the two main entrances, which show us the peak times, and times of less tourist pressure. The cameras also classify vehicles by type (motorcycle, car, bus, camper).

According to recorded data, seasonal tourism impact can be seen, as the highest numbers are in July and August, and before and after there is a very high drop in the total number of vehicles. That suggests a very



high ecological pressure on the area in a very short timeline. Overall, 227'647 vehicles have visited the area of Lower Kamenjak during the year 2025 (Figure 10). This kind of monitoring will enable PIK to introduce seasonal limitations and regulate movement, and actively reroute visitors to less crowded zones.

Long-term data collection is needed to better understand visitor trends and behaviour, to finally implement a meaningful visitor management strategy and make tourism in the area sustainable. Improvements can be and will be made to the monitoring by installing more cameras and establishing more parking zones. Overall, the counting system has enabled a better understanding of seasonal flows and identified critical spots of overcrowding and illegal parking. Also, regular updates are needed to fully utilize the camera counter monitoring network. Visitors can also be more thoroughly monitored if pedestrian and bicycle counters are installed, so visitor dynamics can be better understood. The monitoring system provides a foundation for the potential introduction of a planned carrying capacity of the area and predicting congestion hotspots in future management and planning.

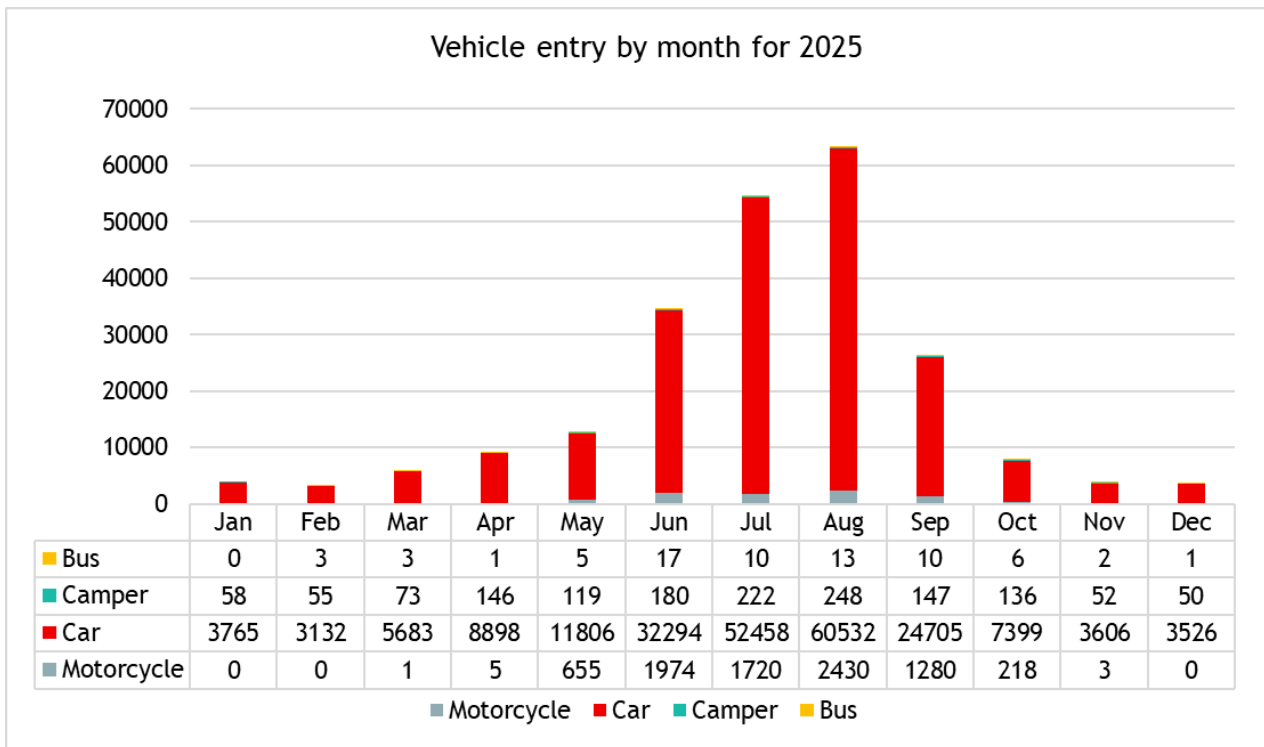


Figure 10. Vehicle entry by month in the area of Lower Kamenjak

2.4.1. Conclusions and recommendations

Continuous data collection from camera counters, LPR systems, and integrated datasets (such as Strava Metro) provides a clear picture of visitor flows, peak periods, and spatial distribution. This allows managers to identify when and where environmental pressure is highest. By understanding that the majority of visits are concentrated in July and August, authorities can introduce seasonal limits or restrictions during critical periods, reducing stress on ecosystems when they are most vulnerable.

Second, the use of LED panels to inform visitors about parking availability helps prevent traffic congestion, illegal parking, and unnecessary driving. This reduces vehicle emissions, soil degradation, and damage to vegetation caused by off-road parking.

Vehicle classification data enables more precise regulation strategies. For example, limits can be set on larger or more environmentally impactful vehicles, or incentives can be introduced for more sustainable transport options. This supports the promotion of low-impact mobility options and further reduces reliance on motor vehicles.



Long-term complex monitoring supports the development of a scientifically grounded carrying capacity for the area. Improvements, such as adding pedestrian and bicycle counters, will provide a more comprehensive understanding of visitor behavior.

Overall, the system transforms raw visitor data into actionable insights, enabling adaptive management, reducing environmental degradation, and ensuring that tourism development remains sustainable while preserving the natural integrity of the area.

2.5. GPS loggers carried by visitors to analyze tourism patterns

Protected Area: EGTC Geopark Karawanken-Karavanke

Project Partner: CUAS

GPS data were collected in the Karawanken-Karavanke UNESCO Global Geopark to analyze tourism patterns. This dataset was used to produce density and intensity maps, identifying areas with high visitor concentration and longer stays.

GPS loggers are compact devices equipped with positioning technology that capture detailed spatio-temporal information on individual movements. In this study, 40 Renkforce GT-730FL-S units were made available at the ticket office of the cable car valley station (Talstation Petzen Bergbahnen). Visitors were informed about the data collection through staff communication and informational posters placed throughout the area. Before being handed out, the devices were activated in advance to ensure proper signal acquisition and calibration. To increase participation, visitors were offered the chance to win a free ski pass through a random draw. Overall, 69 devices were distributed to pedestrians and hikers at the cable car station. Due to some devices being turned on and off during use, a total of 75 movement tracks were ultimately recorded and downloaded: 15 on 19 July 2024, 28 on 26 August 2025, and 32 on 19 September 2025. The loggers were configured to record location data every five seconds, allowing not only the reconstruction of movement paths but also the identification of areas where visitors remained longer, reflected by higher point densities.

The raw GPS data were processed in Python using a sequence of four filters, applied iteratively three times. First, a minimum distance threshold of 2 meters was introduced to reduce noise caused by the high recording frequency (every 5 seconds), which can generate inaccuracies when visitors remain stationary for short periods. Second, a maximum distance of 50 meters between consecutive points was imposed, as it is unlikely for pedestrians to exceed this range within 5 seconds. Third, a maximum speed limit of 6 km/h was applied to exclude unrealistic movements. Finally, a spatial filter was used to remove isolated points: clusters containing fewer than five points within a 50-meter radius were discarded.

All tracks were subsequently checked visually in QGIS, and those showing implausible movements were either corrected or removed. Three tracks were manually adjusted using the Move Feature tool, as they were slightly offset from the most probable trail. Additionally, seven tracks were excluded due to irregular GPS signals that could not be corrected through automated processing. These inconsistencies were likely caused by signal disturbances from the cable car, particularly affecting nearby trails.

A descriptive analysis was conducted in R, including summary statistics for travel distance and duration for each track. To investigate the spatial patterns of visitor activity, both the density of GPS points and the duration of stays were analyzed in QGIS. The density map was created using the Heatmap tool with a Kernel Density Estimation (KDE) approach, applying a search radius of 10 meters and a raster resolution of 0.10 meters. The intensity map was produced by calculating the average stay time in Python, resulting in a raster heatmap with a spatial resolution of 30 meters. Each track was processed individually, assigning points to grid cells; within each cell, the stay time was calculated as the difference between the earliest and latest timestamps of the points belonging to that track.



2.5.1. Results, Assessment, and Interpretation

The analysis was based on 68 GPS tracks collected within the Karawanken Geopark. On average, visitors covered a distance of 6.5 km, with values ranging from 0.11 km to 15 km (SD = 4.32 km). The mean duration of the tracks was 197 minutes, with a minimum of 3 minutes and a maximum of 421 minutes (SD = 112 minutes). Shorter distances and durations were mainly recorded near restaurant areas, where participants likely turned off the devices during breaks. These records were retained, as they were not considered to introduce significant bias into the analysis.

The Density Map (Figure 11) illustrates the spatial distribution of GPS points using a heatmap with a standardized scale from 0 (low spot) to 100 (high spot). For better interpretation, additional elements such as viewpoints, points of interest (POIs), the cable car route, and hiking trails are included.

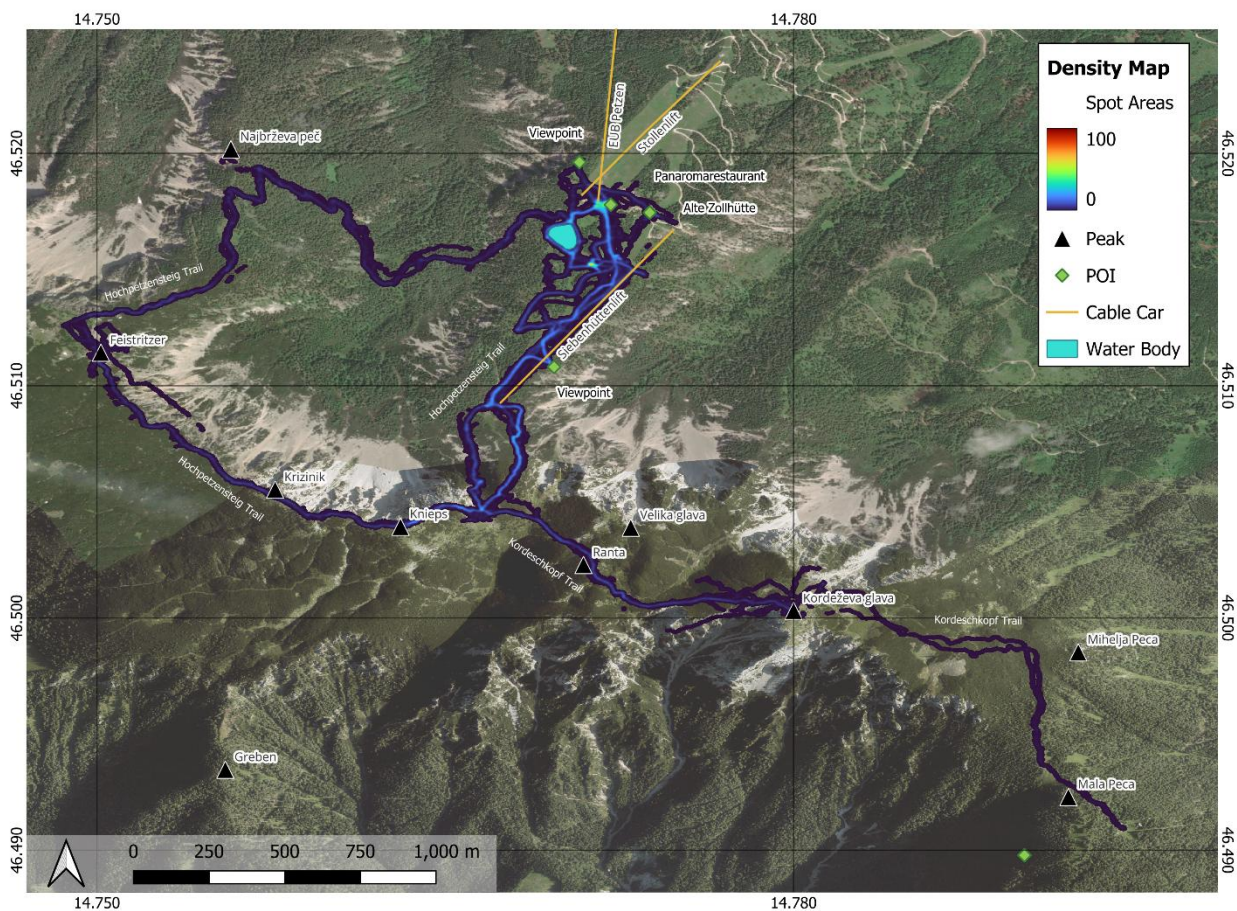


Figure 11. Density Map in the Mount Petzen area

The most prominent hotspot appears around the cable car valley station (Talstation Petzen Bergbahnen), which becomes highly congested during peak hours due to its role as the main departure point and the presence of services such as bike rental and dining facilities. A high concentration of visitors is also observed at the cable car mountain station (Bergstation Petzen-Kabinenbahn); however, this congestion tends to dissipate more quickly as visitors spread across multiple routes. Data from the valley station itself were excluded from the map because they were considered unreliable, as some devices were activated before the real start of the trips and, in some cases, remained on long after. At the mountain station, an artificial lake used for snowmaking in winter is surrounded by recreational areas, attracting visitors during the summer season. The Hochpetzensteig circular trail is frequently used in two alternative routes, either along the ski slope or via a forest road leading to a rest area near the top of the Siebenhütten lift. Many visitors turn back at the Knieps saddle, which serves as an accessible turnaround point without reaching the peaks. Others continue toward the Petzen summit (Feistritzer) and complete the loop, or head toward



Kordeschkopf, a popular destination also accessible from the Slovenian side. Overall, visitor density is higher in areas close to infrastructure, while it decreases in more remote, upper sections of the mountain. Some minor deviations of GPS points from the trail network were observed, likely due to signal inaccuracies.

The Intensity Map (Figure 12) represents the duration of visitor stays within 30-meter grid cells, ranging from less than 2 minutes up to 50-120 minutes. It uses the same visual framework as the density map to allow comparison.

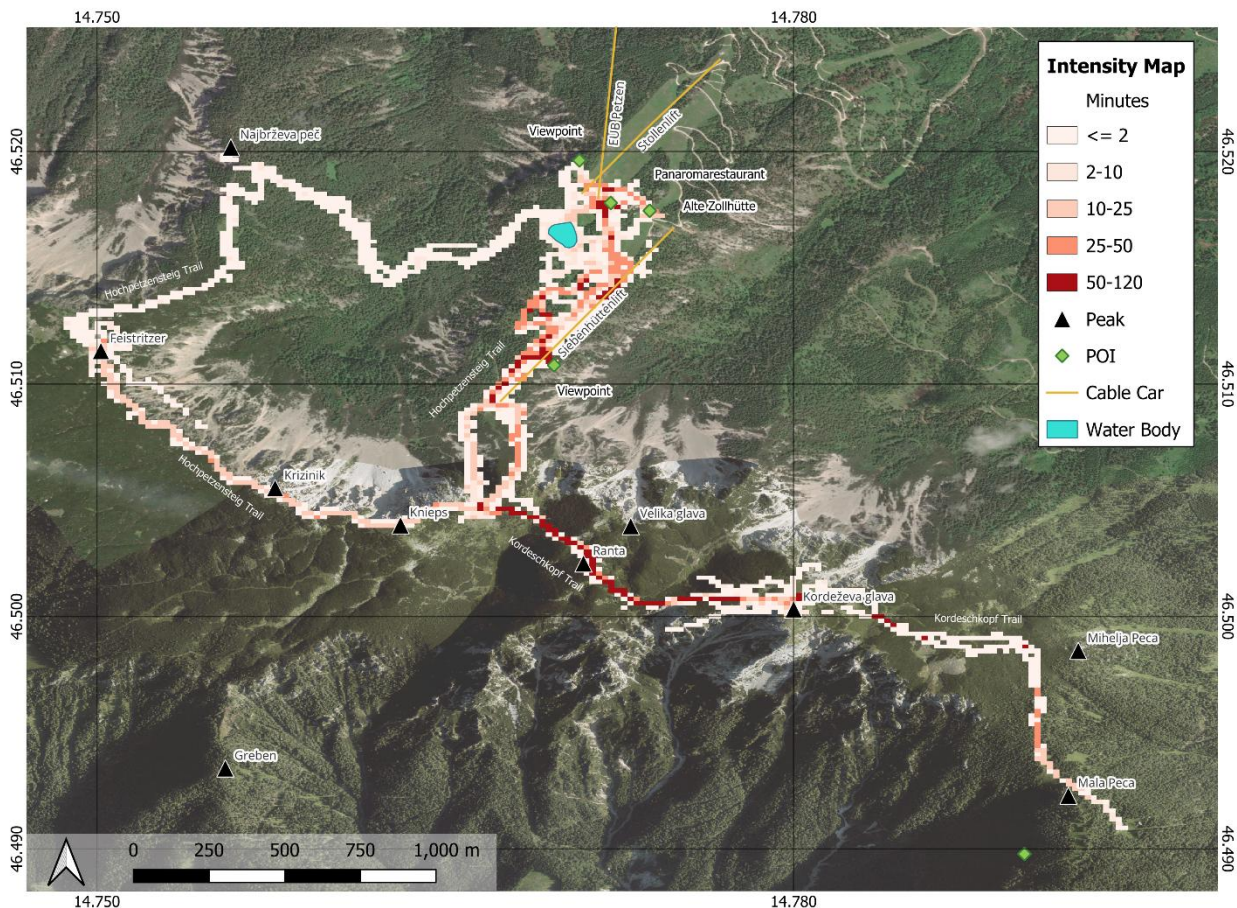


Figure 12. Intensity map in the Mount Petzen area.

At the cable car valley station, visitors tend to remain for 60 to 170 minutes, likely due to the availability of services such as restaurants, ticket offices, and bike facilities, although some of this may also reflect GPS-related inconsistencies. At the mountain station, visitors typically spend time near the lake, with durations varying between short stops (2-10 minutes) and longer stays (25-50 minutes). Longer stop durations are particularly evident on the eastern side of the mountain station, where facilities such as restaurants, mountain huts (e.g., Panoramarestaurant and Alte Zollhütte), and the Geopark visitor center (Geo.Dom) are located. Signal loss was occasionally observed in this area, likely when visitors entered buildings. On the western side, a viewpoint is associated with average stays of approximately 10-25 minutes. Along the trail network, especially at the junction leading from the Siebenhütten area to the Knieps saddle, visitors tend to spend more time on the left-hand path, likely due to its easier terrain and more scenic views. Routes leading toward the summit also show increased stop durations, as visitors pause to rest or enjoy viewpoints. At the summit of Mt. Petzen/Peca (Feistritz), average stay times of 25-50 minutes were recorded within a 30-meter grid cell. Finally, the Kordeschkopf trail network shows consistently high stay durations, which may partly reflect inaccuracies in some of the recorded GPS tracks in that area.



2.5.2. Conclusions and Recommendations

The findings highlight the strong potential of GPS logger technology to generate highly detailed data, enabling a wide range of applications. In particular, density and intensity maps offer valuable insights into visitor behavior, preferred routes, and temporal patterns of use. These outputs make it possible to identify the most frequently used trails and key tourist hotspots. Density patterns are especially useful for locating areas where interactions between visitors and the natural environment are most concentrated, helping managers prioritize monitoring and mitigation efforts. Intensity patterns, in addition, provide information on how long visitors remain in specific locations, contributing to a better understanding of the type of tourism taking place. Together, these insights support more informed decision-making, improving the balance between tourism activities and nature conservation.

During the data collection phase, the number of recorded tracks was relatively limited compared to the overall visitor capacity and flow of the area. Increasing the active involvement of park staff in distributing GPS devices and ensuring they understand both the innovation and its practical value is essential. This would also help guarantee that visitors receive clear and consistent instructions, ultimately improving participation and data quality.

The main technical difficulties were related to signal inaccuracies, which required manual correction. While the automated cleaning procedure in Python effectively addresses point-level errors, it does not account for the broader spatial context of movement paths. As a result, inconsistencies such as points deviating from plausible trails cannot be fully corrected automatically and must be handled manually. Although one of the objectives was to streamline and automate data processing to make the method more accessible, this remains challenging, particularly in natural environments or in areas with cable car infrastructure, where signal disturbances are more common.

Ensuring reliable results also depends on the technical characteristics of the GPS devices, especially the recording interval. In this case, positions were recorded every 5 seconds, producing highly detailed datasets and allowing for the estimation of stay durations. However, such high frequency may also lead to an overestimation of time spent in certain locations. For this reason, careful preprocessing and data cleaning are necessary to reduce bias and improve data accuracy. Nonetheless, as observed in the Kordeschkopf area, some inaccuracies may still persist even after filtering procedures.

In the Mt. Petzen area, the highest levels of crowding are concentrated in zones with dense infrastructure and services, such as cable car stations, equipment rental points, maintenance facilities, and restaurants. These locations also correspond to areas where visitors tend to spend most of their time, particularly those offering recreational opportunities. Many tourists remain close to the mountain station and do not venture far along the trail network, suggesting a predominantly family-oriented form of tourism facilitated by easy accessibility. As a result, picnic areas, lakeside zones, and mountain huts often experience high visitor pressure. In contrast, higher-altitude areas near the summit are mainly used for short passages, such as resting or enjoying viewpoints, and generally experience lower levels of congestion.

Presenting results through both spatial maps and numerical indicators provides a clearer picture of visitor dynamics. These tools enable a data-driven approach to managing protected areas at a fine spatial resolution. However, integrating multiple monitoring methods offers a more comprehensive understanding of tourism patterns. While GPS loggers are effective for identifying movement paths, stopping points, and hotspots, they do not provide information on the total number of visitors, which can instead be obtained through automated counters. Likewise, they do not capture visitors' perceptions or environmental attitudes, which require survey-based approaches. Combining these different tools therefore allows for a more complete assessment of visitor behavior.



2.6. Infrared sensors and camera traps for visitors counting

Protected Areas: Tuscan-Emilian Apennine National Park

Project Partner: PNATE

The monitoring activities carried out within the **Appennino Tosco-Emiliano National Park (PNATE)** aim to quantify the number of visitors who access four designated **pilot sites (Pietra di Bismantova, Monte Cusna, Fonti di Poiano and Val Parma Forest, represented in Figure 13)** and, in some cases, to evaluate their impacts on the local ecosystems, particularly on vegetation and disturbance to wildlife.



Figure 13. Location of visitor counting sensor

Another objective is to understand how visitors use certain areas (whether on foot, by bicycle, on horseback, or with motorized vehicles such as motorcycles and cars), in order to detect **unauthorized access with non-permitted means**. Examples include bicycles on the summit of **Pietra di Bismantova**, motorized vehicles in the **Monte Cusna** area, or to quantify the damage caused by hikers who leave the designated trails.

The **number of visitors** was quantified using two types of devices to count people: **visitor counters** and **camera traps**, installed in all four pilot sites: Pietra di Bismantova, Monte Cusna (Lama Lite), Fonti di Poiano and Gessi Triassici, and Val Parma Forest.

In all four pilot sites, both types of devices were installed. The selection of their exact placement was guided by both logistical and research requirements. In particular, people counters must be mounted on fixed poles, preferably with a highly stable base such as concrete, and require precise positioning in terms of distance and alignment to ensure proper functioning. At the same time, their placement had to take into account the most effective locations for accurately recording visitor flows.

As for the camera traps, the choice of installation sites resulted from consultation with experts from the University of Parma, who were conducting studies on root damage to trees along the trails. Given their easier and more flexible installation, their placement primarily followed the indications provided by these investigations.

Data collection and routine maintenance were carried out periodically by a designated operator, who was responsible for downloading the data and checking the devices (including battery status, potential vandalism, and overall functionality). These operations were conducted more frequently during periods of high tourist attendance and less frequently during the winter months.



2.6.1. Data Handling and Analytical Methods

Given the different nature of the two approaches, the data processing workflow differs slightly between people counters and camera traps.

For camera traps and people counters, data were processed and displayed through graphs and time series, representing visitor flows on daily, weekly, and seasonal scales. These visualizations allow the identification of visitation patterns, peak periods, and differences among monitoring sites, facilitating the interpretation of tourism dynamics.

For infrared people counters, raw data are accessed through the dedicated web platform *CheckinWeb* developed by Microlog Srl. A standardized protocol was adopted for data extraction, consisting of downloading both hourly and daily data for complete monthly periods (from the first to the last day of each month) in CSV format. These datasets are subsequently uploaded to the HUMANITA dashboard, where they are processed and visualized through time-series graphs. Although the *CheckinWeb* platform itself provides graphical visualization, the integration of these data into the shared HUMANITA dashboard ensures a consistent graphical format across datasets, facilitating direct comparison with outputs derived from other monitoring systems.

Camera trap data follow a different workflow. Video files collected in the field are directly uploaded to the HUMANITA dashboard, where they are processed using an artificial intelligence-based system capable of detecting and classifying visitors. The outputs are automatically converted into structured data and visualized through graphs. This dual workflow enables the integration of heterogeneous data sources within a unified visualization environment, improving the comparability and interpretability of visitor monitoring results.

2.6.2. Results, Assessment, and Interpretation

As already mentioned, the dashboard processes and provides a large amount of data in various formats. With regard to the results of visitor monitoring, only a selected period from the most recent tourist season is presented here for illustrative purposes, consistent across all pilot sites, spanning from 20 July 2025 to 10 August 2025, selected as representative of the peak summer season, although the full dataset is not yet available. Within this time window, both camera traps and infrared people counters indicate an overall increase in visitor presence from late July to early August, with recurrent peaks that are consistent with weekends and holiday-related tourism.

The two monitoring systems, however, provide different types of information. Camera traps offer a more detailed reading of visitor use, as they make it possible to distinguish among different user categories and show that the monitored trail is used mainly by pedestrians, with only occasional detections of other means of access. Infrared people counters, by contrast, provide aggregated visitor counts and are not able to distinguish between walkers and other users. Their function is therefore mainly to capture the overall intensity and temporal variability of visitor flows.

As for the **Monte Cusna** site (Figure 14 and Figure 15), these datasets should not be interpreted as directly comparable in absolute terms, since the two devices were installed on different trails, located several hundred meters apart. Rather than measuring exactly the same flow of visitors, they provide complementary information on different portions of the site. Read in parallel, they suggest that visitor pressure is not uniformly distributed, but varies according to trail characteristics, accessibility, and patterns of use.

Overall, the observed patterns confirm that tourist pressure intensifies during the central summer period and becomes more concentrated along specific routes. This is particularly relevant for site management, as even predominantly pedestrian use may produce localized pressure on trails and surrounding habitats.

The interpretation of these results remains subject to some limitations. In addition to the different spatial positioning of the devices, camera traps may underestimate total passages because of their limited detection field, while infrared counters may include counting inaccuracies linked to bidirectional



movements or repeated crossings. Moreover, the present assessment is based on a restricted portion of the monitoring period and should therefore be regarded as indicative rather than exhaustive.

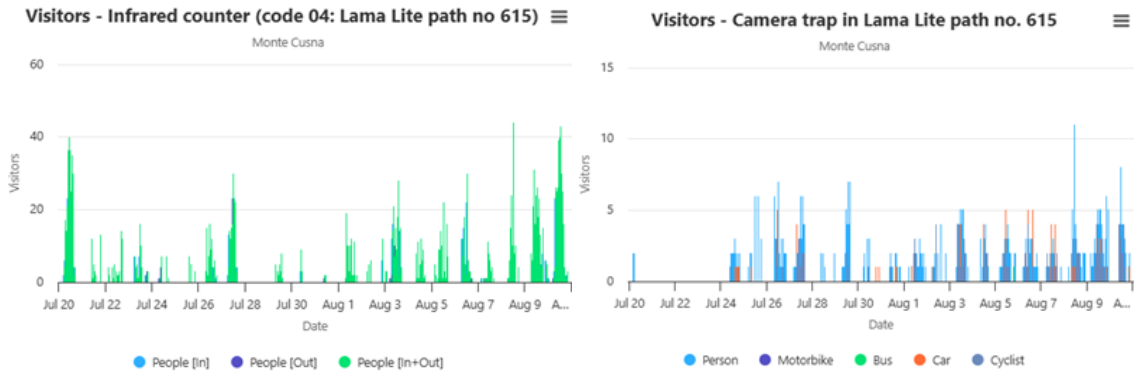


Figure 14. Graphical visualization of data from the HUMANITA dashboard for infrared people counters (on the left) and camera traps (on the right) at the Monte Cusna pilot site

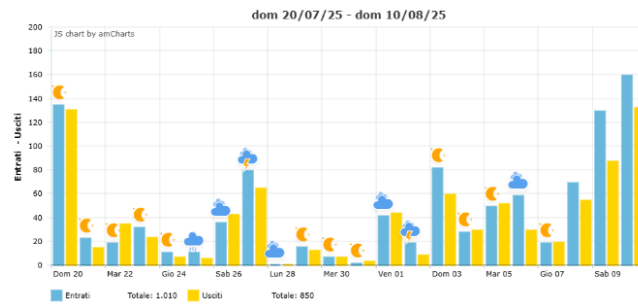


Figure 15. Graphical visualization from the Checkinweb platform for the people counters at the Monte Cusna pilot site

Visitor monitoring at the **Pietra di Bismantova** site highlight a consistently high level of visitor presence throughout the period, with marked daily variability and frequent peaks (Figure 16 and Figure 17).

Infrared people counters show intense and recurrent peaks of visitation, indicating a high concentration of visitors along the monitored access route. These peaks occur regularly across the entire time window and become particularly pronounced in late July and early August, reflecting sustained tourist pressure during the summer season.

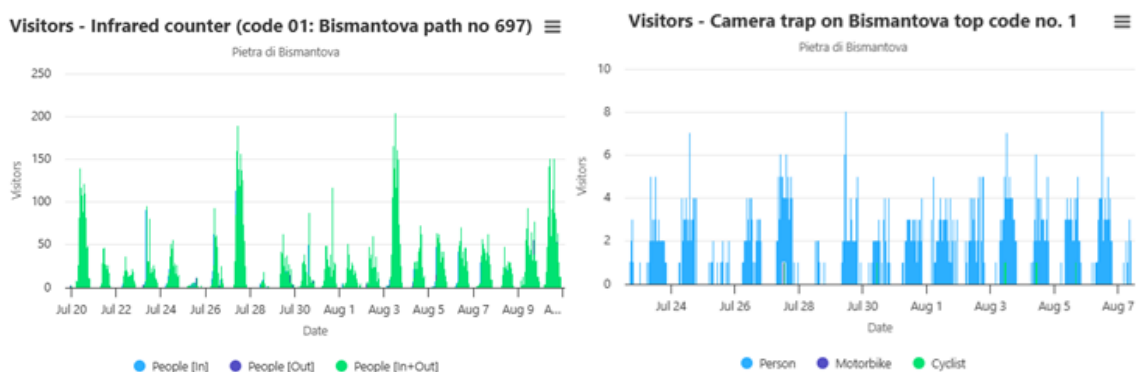


Figure 16. Graphical visualization of data from the Humanita dashboard for infrared people counters on the left and camera traps on the right at Pietra di Bismantova pilot site

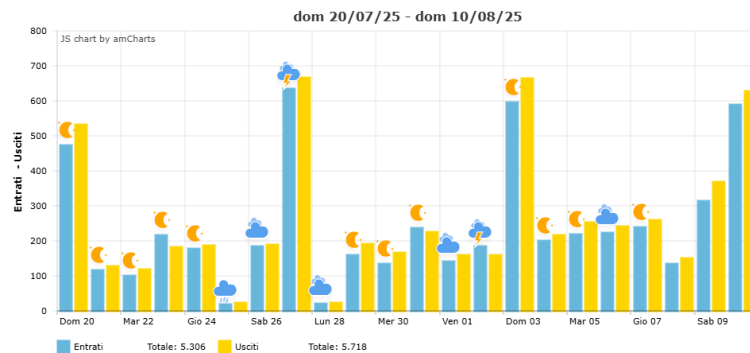


Figure 17. Graphical visualization from the Checkinweb platform for the people counters at the Monte Cusna pilot site.

Camera trap data, collected along a different trail on the summit area, show lower absolute values but confirm a continuous presence of visitors over time. As in the previous site, detections are dominated by pedestrians, with only occasional records of other user types. This supports the interpretation of the area as primarily used for hiking and recreational access on foot.

The two monitoring systems were installed in different locations within the site and therefore capture visitor dynamics along distinct trail segments. For this reason, the datasets are not directly comparable in quantitative terms, but rather provide complementary information on spatial patterns of use.

Taken together, the results suggest that Pietra di Bismantova experiences a higher and more continuous visitor pressure compared to other sites, with flows that are both temporally structured (daily and weekly peaks) and spatially concentrated along specific access routes. The intensity and frequency of peaks indicate that this site functions as a major tourist hotspot within the study area.

These patterns have important implications for site management, as sustained and concentrated pedestrian use is likely to increase pressure on trails, vegetation, and sensitive habitats, particularly in summit areas.

The interpretation of the results is subject to some limitations. As in other sites, differences in device location influence the comparability of the datasets, while each monitoring method presents intrinsic constraints (e.g., detection limits for camera traps and potential counting inaccuracies for infrared sensors). In addition, the analysis is based on a limited portion of the monitoring period and should therefore be considered indicative rather than exhaustive.

2.6.2.1. Comparative insights

When compared with the Lama Lite site, Pietra di Bismantova shows a markedly higher and more continuous level of visitor pressure. This is evident from the greater intensity and frequency of peaks recorded by the infrared counters, as well as from the relative continuity of visitor presence throughout the monitoring period.

This difference can likely be explained by the contrasting accessibility of the two sites. Pietra di Bismantova is easily reachable by car and requires only a short approach on foot, making it highly accessible to a broad range of visitors. In contrast, Lama Lite is located in a high-altitude environment and can only be reached on foot, except for limited authorized motorized access. This reduced accessibility likely limits the overall number of visitors and results in a more intermittent pattern of use.

At the same time, the lower visitation pressure observed at Lama Lite does not necessarily imply a lower level of vulnerability. On the contrary, high-altitude environments may host more fragile habitats, where even relatively limited but repeated disturbance can produce significant ecological impacts.

2.6.3. Conclusions and Recommendations

The monitoring of visitor flows confirmed that tourist pressure is highly uneven across sites and strongly influenced by accessibility and site attractiveness. Easily reachable locations, such as Pietra di Bismantova,



experience consistently high and concentrated visitation, while more remote areas show lower but still ecologically relevant levels of use.

The combined use of infrared people counters and camera traps proved effective in capturing both quantitative and qualitative aspects of visitor dynamics. While people counters provide robust data on flow intensity and temporal variability, camera traps allow for the identification of user typologies, confirming the predominance of pedestrian use with occasional unauthorized access by other means.

However, the results also highlight methodological limitations, including differences in device placement, potential counting inaccuracies, and the partial temporal coverage of the dataset.

According to these outcomes, future monitoring should prioritize:

- Extending the temporal coverage to include full seasonal and interannual variability
- Improving the spatial design of device placement to ensure better comparability between datasets
- Integrating visitor flow data with spatial analysis to identify hotspots of use and areas of concentrated pressure
- Strengthening the detection of unauthorized access through targeted placement of camera traps

Management strategies should focus not only on total visitor numbers but also on spatial distribution of use, in order to reduce localized impacts on sensitive areas.

2.7. Outdoor and Fitness Apps to describe visitors behavior

Protected Areas: EGTC Geopark Karawanken-Karavanke, Malá Fatra National Park, Bükk National Park Directorate, Tuscan-Emilian Apennine National Park, Lower Kamenjak

Project Partner: CUAS

The activity focused on analysing data from outdoor and fitness applications to better understand visitor behaviour in protected natural areas. With the increasing use of digital platforms such as Bergfex, Komoot, Outdooractive, and Strava, visitors are not only navigating and planning their activities digitally but also actively contributing content, including routes and points of interest. This has led to the proliferation of both official and unofficial trails, which can become particularly problematic in ecologically sensitive mountain regions, raising concerns about environmental impacts and regulatory compliance.

The primary objective of the analysis was to identify spatial patterns of visitor activity (hotspots and low-use areas), assess the popularity of routes, and detect potential conflicts between recreational use and conservation goals across several pilot areas, including touristic hotspots in the Karawanken-Karavanke UNESCO Global Geopark, Bükk National Park, Mala Fatra National Park, Significant Landscape Lower Kamenjak, and the Tuscan-Emilian Apennine National Park.

Data were collected from multiple platforms using different approaches depending on data availability and platform structure:

- **Strava Metro** provided aggregated and anonymized user activity data mapped onto an OpenStreetMap-based network. Monthly and yearly datasets covering 2019-2024 were downloaded, with a focus on aggregated temporal scales to ensure data reliability.
- **Outdooractive, Komoot, and Bergfex** data were collected through manual download of GPX tracks and associated metadata (e.g., user interactions, ratings, usage indicators).

Data collection was conducted as a one-time structured extraction (summer 2025), with retrospective coverage of multiple years where available.



2.7.1. Data Processing and Analytical Methods

A combination of GIS tools and Python scripts was used to process and harmonize the datasets:

- **Data cleaning** included removal of empty or duplicate records and clipping datasets to defined areas of interest.
- **Integration of datasets** was achieved by converting GPX tracks into shapefiles and linking them with metadata via unique tour IDs.
- **Handling missing values:** Missing metadata (e.g., in Komoot datasets) were set to zero in scoring calculations.
- **Normalization:** Min-max scaling was applied to ensure comparability across different metrics.
- **Data aggregation:** Temporal aggregation (monthly/yearly) and spatial aggregation (network-based segmentation) were performed, depending on dataset. Some data (e.g. STRAVA metro) was received monthly/yearly for all OpenStreetMap (OSM) network segments and then aggregated for the provided period (2019-2024) to an average visitor/year/segment value. Other datasets (Outdoor apps like komoot, OutdoorActive, bergfex) have no timely dimension and consist of complete tours provided and their corresponding metadata.
- **Network analysis:** Tour densities were calculated through spatial interpolation. Basis for the interpolation was an modified OSM-based network (without highway/motorway, additional segments if content was “offroad”). The promoted tours of each outdoor content provider where layed upon and counted for each segment based on a spatial distance of 20m. If needed, miscounts due to narrow infrastructure network parts (e.g. high density settlements with narrow roads) were manually removed.

The analysis combined several approaches:

- **Descriptive statistics:** quantifying number of tours, user counts, and interaction metrics.
- **Scoring models:** development of “Tour Scores” (for Komoot and Outdooractive) based on weighted, normalized engagement indicators.
- **Spatial analysis:** identification of hotspots using GIS-based heatmaps and density mapping.
- **Exploratory analysis:** identifying patterns in user behaviour across regions and activity types (e.g., cycling vs. hiking).

2.7.2. Results, Assessment, and Interpretation

A total of 2615 pedestrian tours and 2356 cycling tours were downloaded across Outdooractive, Komoot, Bergfex and trailforks within the project area of Humanita. Results are summarized in the following figures (from Figure 18 to Figure 22).

Tour Score analyses identified routes with high estimated usage based on user engagement metrics (e.g., downloads, ratings, interactions). Trailforks has its own popularity score, which contains hidden engagement metrics. As the engagement metrics are not accessible, the trailforks popularity score was used.



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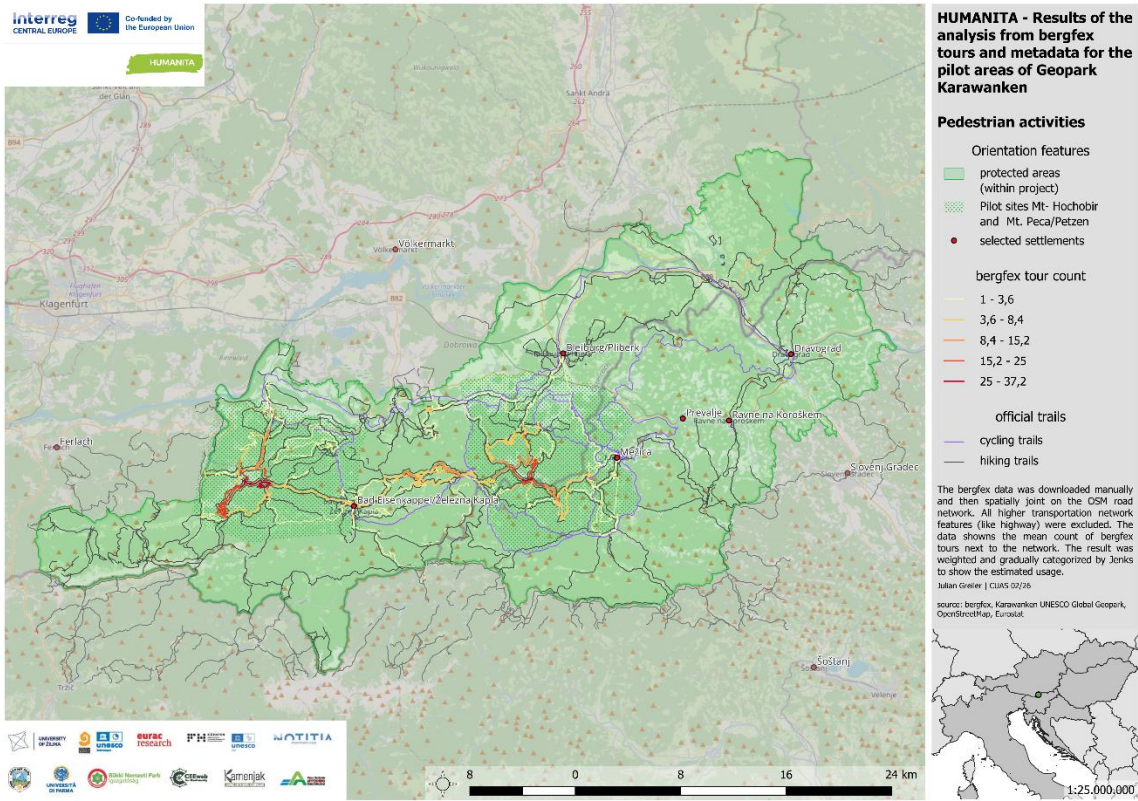


Figure 18. Bergfex pedestrian data at Hochobir and Petzen in the Karawanken-Karavanke UNESCO Global Geopark, Austria

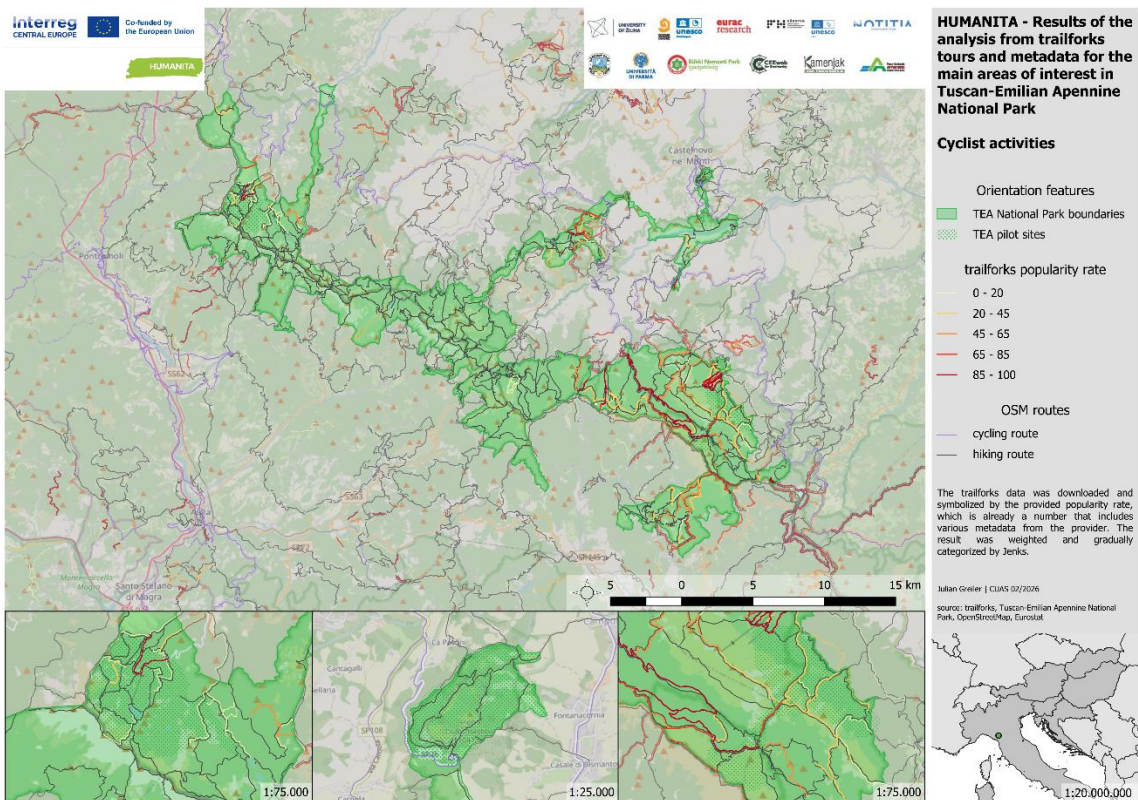


Figure 19. Trailforks cycling data in pilot areas of Tuscan-Emilian Apennine National Park



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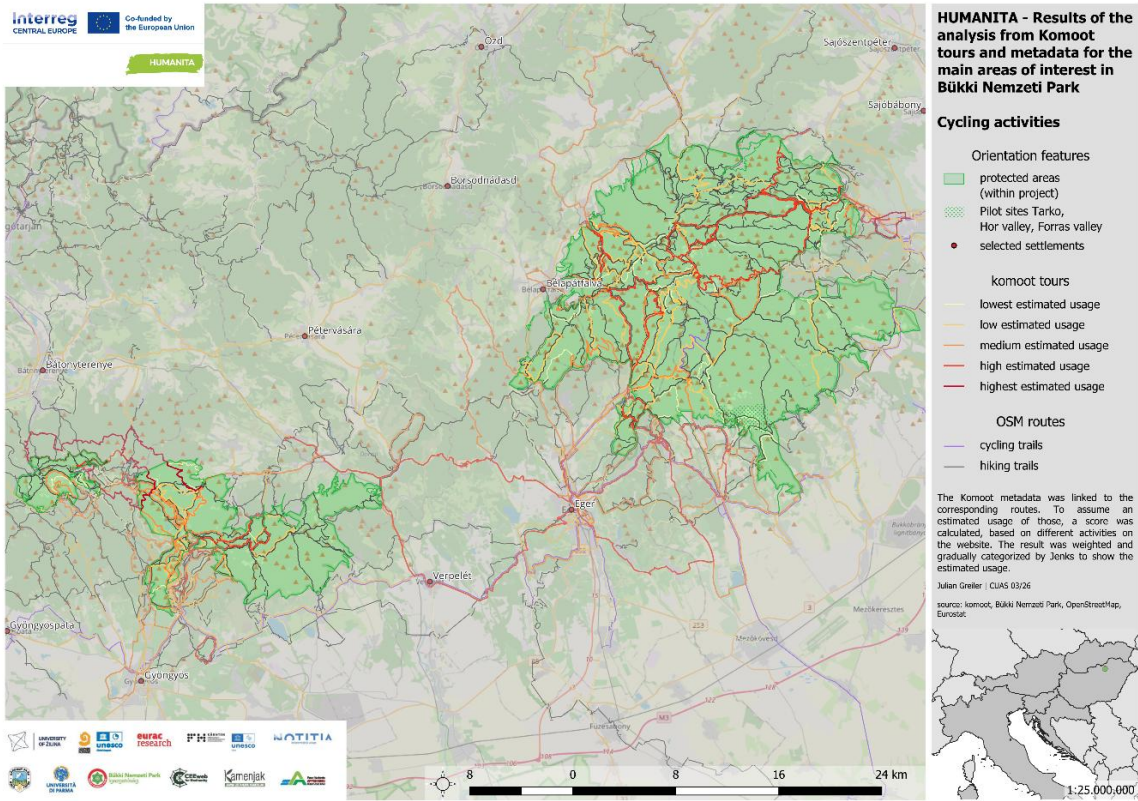


Figure 20. Komoot data in pilot areas of Bükk Nemzeti Park

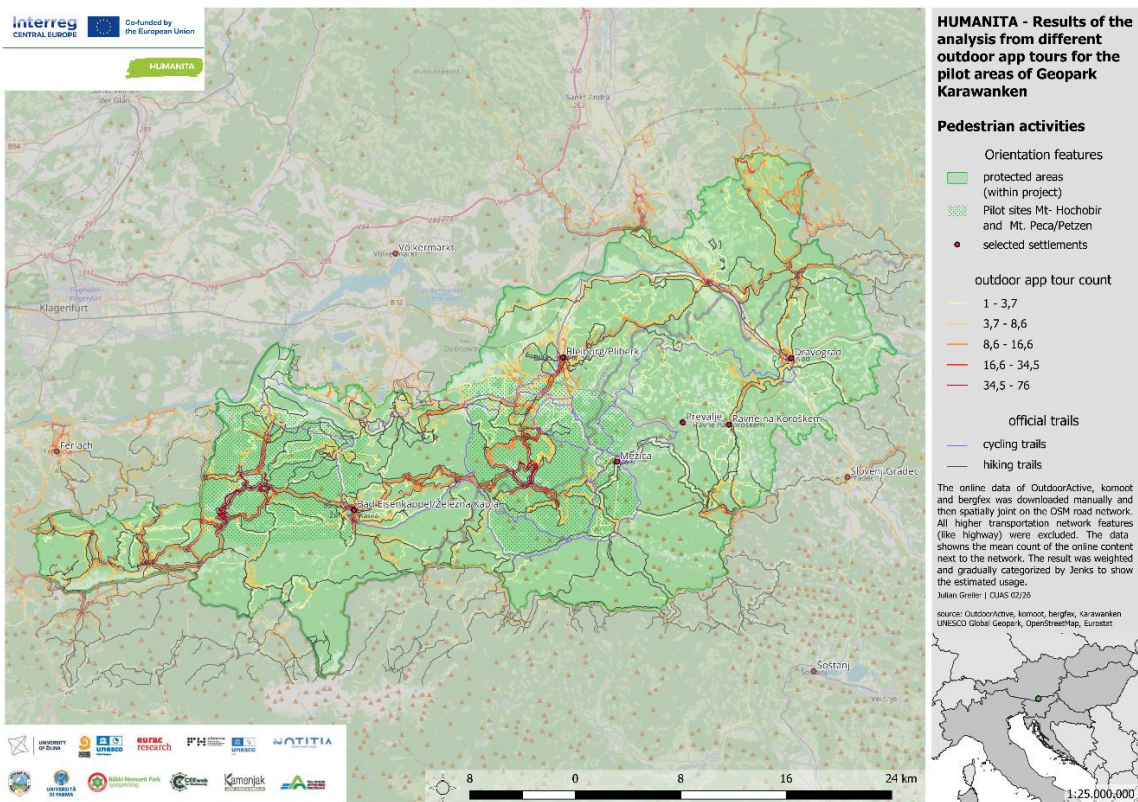


Figure 21. Total pedestrian online content downloaded across selected outdoor app platforms in Geopark Karawanken



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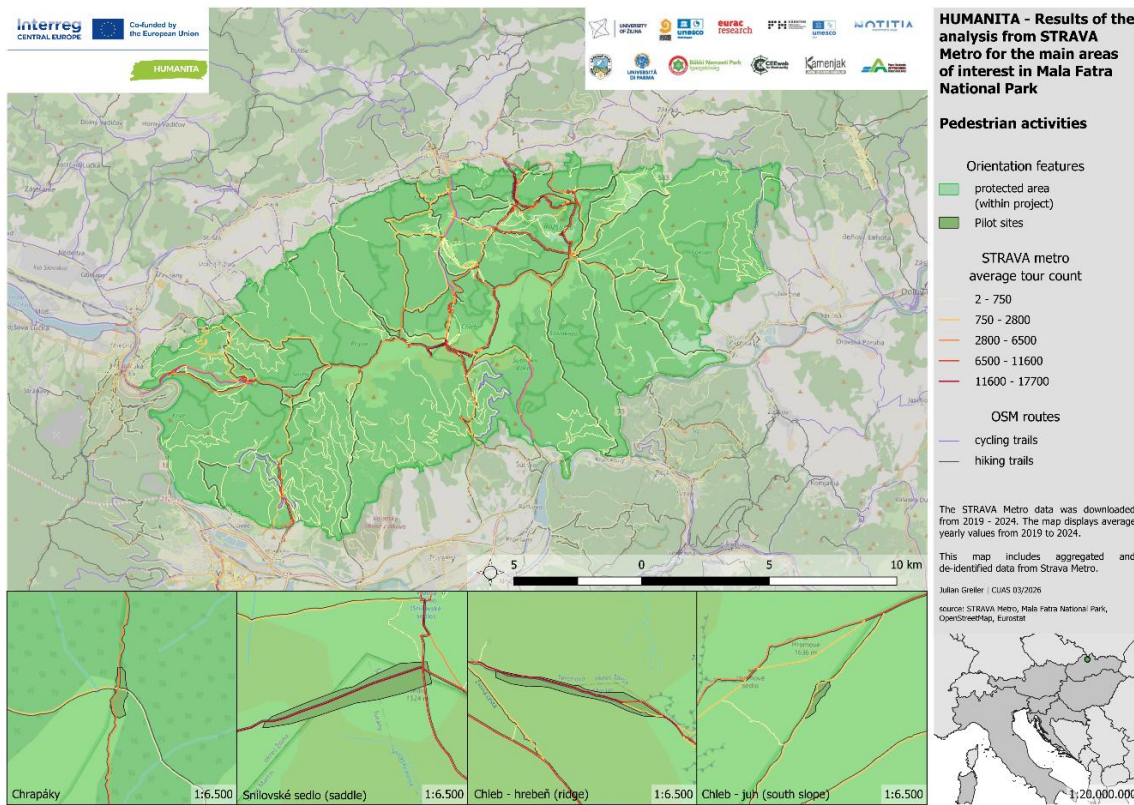


Figure 22. STRAVA Metro pedestrian data in Mala Fatra National Park

2.7.2.1. Qualitative Findings

A significant number of routes promoted on platforms are unofficial or non-compliant with local regulations. Especially mountain biking activities frequently occur on undesigned or restricted trails. Community-generated content on outdoor apps plays an increasing role in shaping visitor behaviour and route selection of app users. Regularly monitoring information on those platforms becomes important for conservation areas to make sure that digital trail information is in line with conservation goals.

A QGIS project was created for our conservation area partners integrating the collected data from outdoor and fitness apps and corresponding metadata. This project can become the starting point for PAs to manage the contents on the analysed platforms.

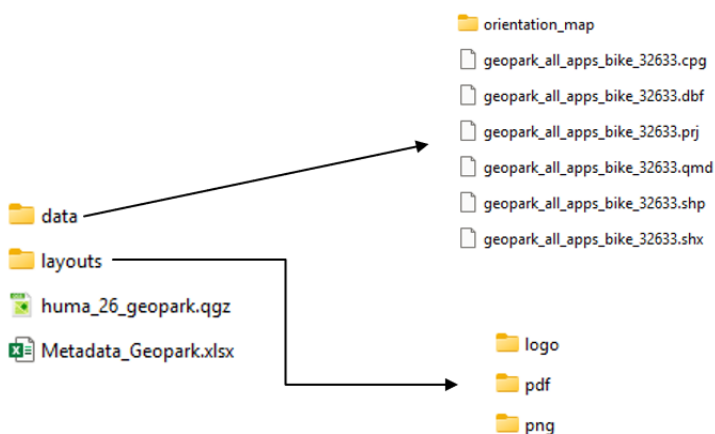


Figure 23. Structured QGIS project, including metadata and layouts

Based on the data they can easily identify problematic routes or future potentials, interact with users and content creators and platform managers or directly adapt metainformation of trails on Open Street Map. The OSM provides the base data source of most outdoor apps, so editing this data will improve the quality of information shown on outdoor apps. For each conservation area a delivery package was created, containing all analyzed datasets, including layouts (maps) and descriptive metadata as .xlsx (Figure 23).



The geodata is contained within Esri shapefiles including a QGIS project with symbolization suggestions. The QGIS project itself is well sorted and only contains the important data, including attribute tables with specific information for each content (e.g., Figure 24). The metadata collected from Outdooractive, Komoot and Trailforks is well suited for digital rangers to manage currently available unwanted online content.

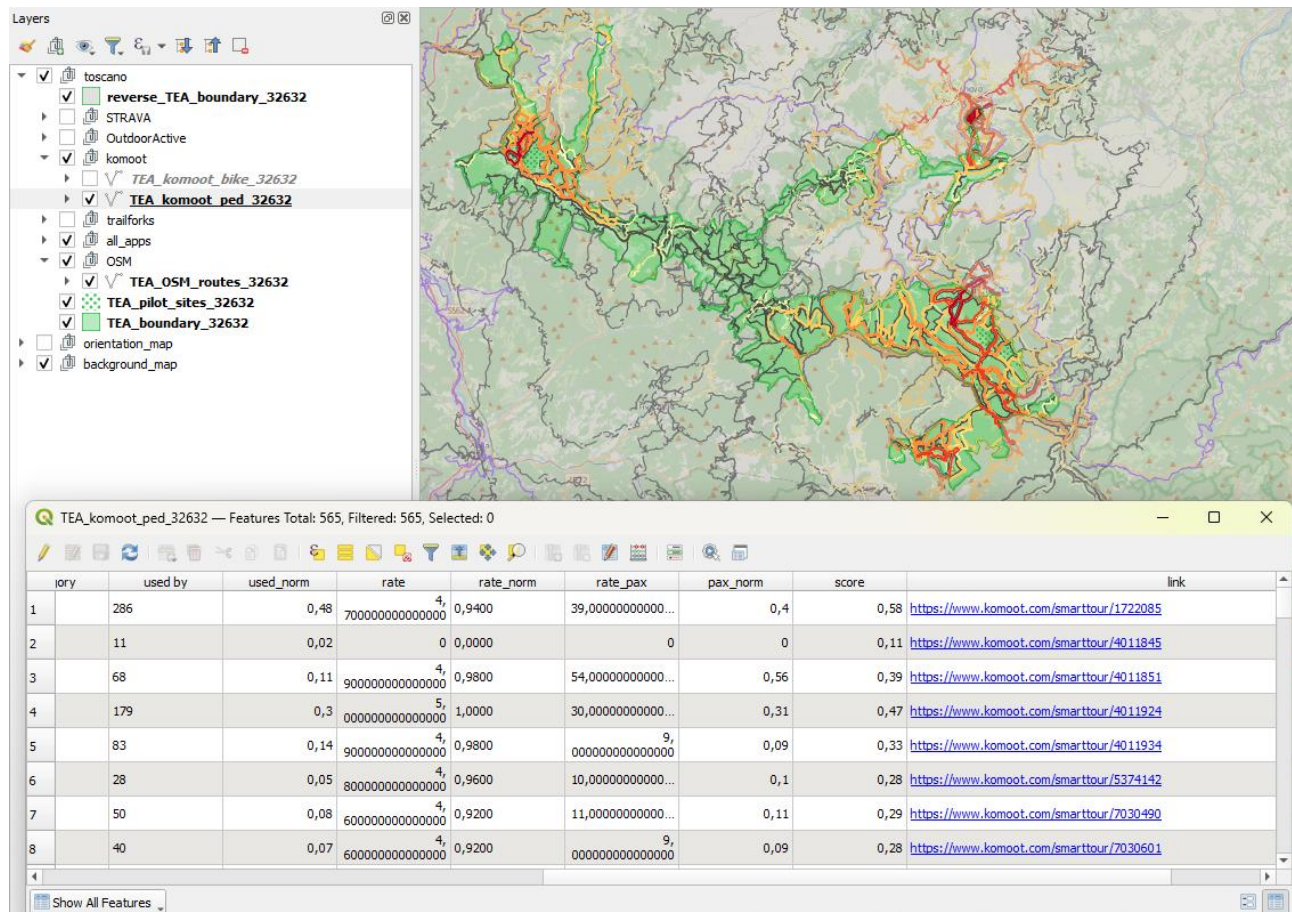


Figure 24. QGIS deliverable for TEA National Park, including attribute table of Komoot content

The findings suggest that digital platforms significantly influence visitor distribution and behaviour in protected areas. The widespread availability of user-generated routes increases the risk of unregulated exploration, particularly in mountain biking.

The mismatch between existing trail infrastructure and user demand - especially among cyclists - indicates a need for better-aligned recreational planning. Furthermore, inconsistencies in regulations and their communication contribute to unintended non-compliance.

2.7.2.2. Limitations and Uncertainties

The analysis reveals several important limitations related to the use of app-based data. Most notably, such data is not representative of the entire visitor population, as it only captures individuals who actively use specific platforms. This introduces a clear bias that must be acknowledged when drawing conclusions. Methodological constraints further affect the robustness of the results, particularly where data extraction relies on manual downloads or dynamic web content, both of which limit reproducibility. Moreover, the aggregation methods applied in datasets such as Strava, including the use of minimum thresholds, can reduce accuracy at finer temporal resolutions and obscure short-term variations in visitor behaviour.

Despite these limitations, the application of advanced analytical techniques provides clear added value. The use of normalized scoring models allows for meaningful comparisons across heterogeneous datasets, helping to harmonize data originating from different platforms. Furthermore, GIS-based network analysis



enables the precise spatial identification of visitor hotspots, offering detailed insights into patterns of use. The integration of multiple data sources significantly enhances the overall robustness of the findings, as it allows for cross-validation of observed patterns and reduces the reliance on any single dataset. Together, these approaches strengthen the analytical framework and demonstrate the potential of combining diverse digital data sources for environmental monitoring.

2.7.3. Conclusions and Recommendations

The analysis demonstrates that data derived from outdoor and fitness applications provides valuable complementary insights into visitor behaviour, particularly by revealing spatial patterns and identifying frequently used routes. At the same time, the findings underline that such data is only partially representative and subject to methodological limitations, which must be carefully considered when interpreting results.

In terms of methodological effectiveness, the continued use of multi-source data integration is recommended, as it enables a more comprehensive understanding of both promoted routes and actual usage patterns. To enhance the reliability of results, app-based data should be systematically combined with ground-truth sources, such as visitor counters, allowing for validation and calibration of digital observations.

With regard to data collection, there is a clear need to establish standardized protocols across different platforms in order to ensure consistency and comparability. Increasing the level of automation in data extraction processes would further improve reproducibility and efficiency. Additionally, datasets should be updated on a regular basis to account for the dynamic and frequently changing nature of platform content.

Monitoring strategies should also be refined to address the evolving role of digital data. Continuous monitoring approaches are particularly relevant in this context and could be supported by dedicated roles, such as “digital rangers,” who oversee and manage online content. Strengthening collaboration with application providers would facilitate better content validation and management. Furthermore, improvements in the mapping and tagging of protected areas and associated restrictions in OpenStreetMap would contribute to more accurate spatial analyses and better-informed users.

From an analytical perspective, further development of integrated GIS systems is essential, especially those that combine multiple datasets along with their associated metadata. Expanding comparative analyses between digital data sources and real-world visitor counts would deepen understanding and help identify discrepancies. In addition, scoring models should be refined and extended by incorporating additional variables, such as seasonal patterns, to better capture temporal dynamics.

Overall, the analysis highlights the growing importance of digital data sources in environmental monitoring. It also emphasizes the necessity of proactive and adaptive management strategies to mitigate potential unintended impacts of digital platforms on protected areas while leveraging their significant analytical potential.



3. Vegetation monitoring

3.1. Combined expert and citizen science approach

Protected Area: Malá Fatra National Park

Project Partner: UNIZA

We combined expert botanical monitoring with a citizen science approach using the iNaturalist app to improve the documentation and monitoring of rare plant species in the national park. Our goal was to connect regular scientific surveys with the observations from visitors and volunteers, and thus increase spatial coverage and the probability of detecting rare taxa. At the beginning of the project, we defined a monitoring framework based on expert botanical surveys in the past. We also identified a set of target rare plant species and priority habitats and established standardized field protocols including methods for recording population size, phenological stage, habitat characteristics, and precise locality data. Species were recorded at 5 pilot sites.

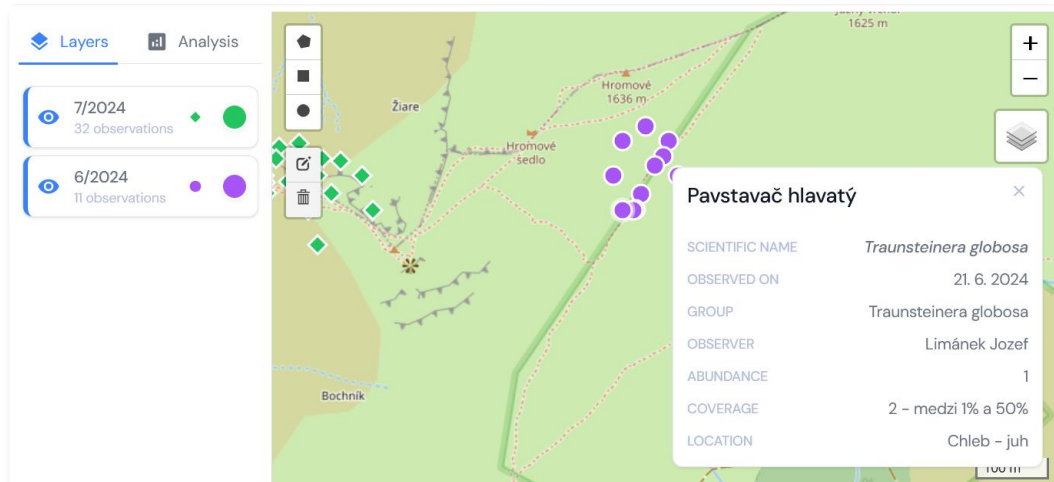
The botanical survey started at the beginning of June 2024, when the alpine vegetation was optimally developed. The participatory monitoring for the HUMANITA project via iNaturalist started in July 2024, when we posted a propagation video on the website and social media about the use of the app. Survey was repeated in the summer 2025. The start of the vegetation monitoring took place approximately at the same time as in year 2024 - half of the June. However, it was obvious that the vegetation was developing slower, maybe 7-10 days later. Many of the species recorded year before (e.g. orchids) were only beginning to form inflorescence, compared to full bloom in 2024.

This monitoring aims to record the presence of habitats of European and Slovak importance, as well as protected and endangered species of plants. We observed pilot sites step by step, wrote down all species, and assigned them a level of coverage according to the Braun - Blanquet scale. We took a lot of photos, and some plants were collected and later identified in the office. We determined the occurring habitats according to the recorded species.

To complement the expert surveys, we created a dedicated project on iNaturalist focused on the rare flora of the park. The project included a list of target species, identification tips, and clear instructions for documenting observations in the field. We also included guidelines emphasizing responsible behaviour to avoid disturbance of sensitive plant populations. Members of NP team reviewed incoming observations. This process ensured that the citizen science data reached a sufficient level of reliability.

3.1.1. Results, Assessment, and Interpretation

We conducted stepwise surveys at the pilot sites to assess plant community composition. Within each plot, we recorded all rare plant species present and estimated their cover-abundance using the Braun-Blanquet scale. For each species, we assigned a score reflecting its relative dominance, from very sparse to highly abundant. The Braun-Blanquet scale classifies species cover using a semi-quantitative approach, with categories ranging from r (very rare, solitary individuals) to 5 (species covering nearly the entire plot). Intermediate categories capture increasing abundance and density, providing a consistent method to compare species dominance across sites (Figure 25).



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Figure 25. Visualisation of survey results in HUMANITA dashboard

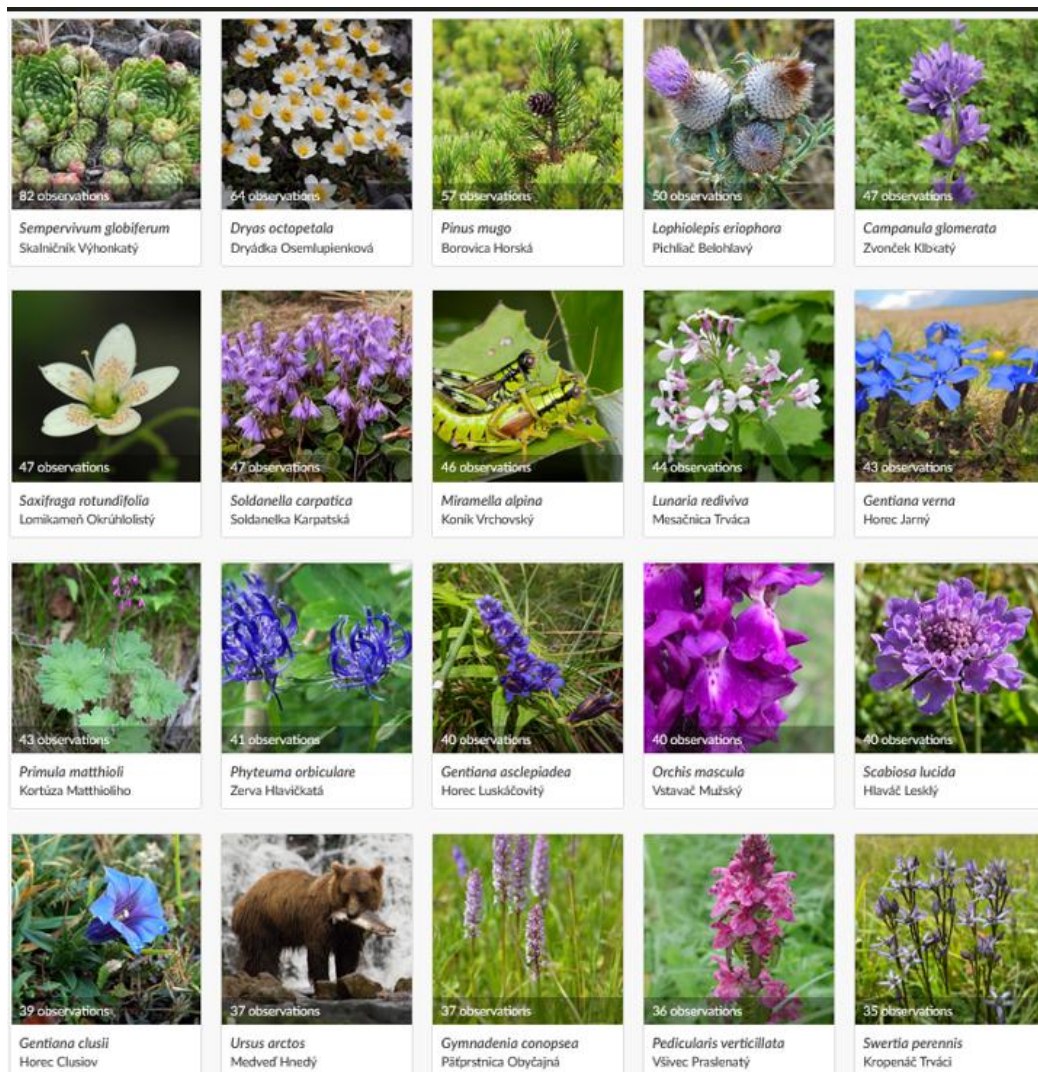


Figure 26. Elements included in the iNaturalist observations in the pilot site

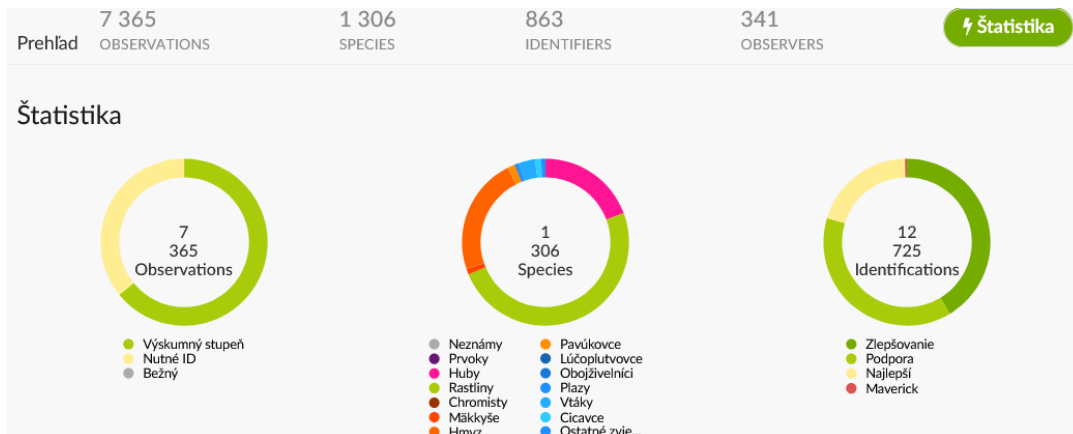


Figure 27. Visualisation of Citizen science project

Observations submitted by park visitors and volunteers significantly expanded the spatial coverage of plant records. In several cases, these observations helped us detect previously undocumented localities of rare species or confirm their continued presence in areas that had not been surveyed by experts. Some citizen scientists also recorded representatives of wildlife (Figure 26 and Figure 27).

3.1.2. Conclusions and Recommendations

Our approach demonstrated that combining expert botanical monitoring with an iNaturalist project can create a complementary monitoring system. While expert surveys ensured methodological consistency and data quality, citizen science observations broadened spatial coverage and improved the detection of rare plant species across the national park. The iNaturalist project also served as an important outreach tool. By involving visitors and volunteers in biodiversity documentation, we increased public awareness of the park's rare flora and encouraged responsible nature observation.

While iNaturalist is a valuable tool for expanding the spatial coverage of plant monitoring, there are several limitations we have encountered:

- The geographic coordinates recorded by users are not always accurate, which can make it difficult to determine the exact location of rare plants.
- By informing visitors about the presence of rare plants, we may expose these species to disturbance or collection.
- Most observations are concentrated along trails and accessible sites. As a result, areas away from paths are often underrepresented.
- Although expert validation helps, some observations may be misidentified

Despite these limitations, iNaturalist remains a useful complement to our expert monitoring, helping to detect new populations and engage the public in conservation efforts.

3.2. Botanical survey to determine cenological impact

Protected Area: Bükk National Park Directorate

Project Partner: BNPD

Botanical surveys were meticulously conducted in the Hór-valley (Figure 28) and Tar-kő peak (Figure 29) to assess the cenological impacts of tourism. The botanical surveys carried out by an external expert aim to provide an impact assessment of trampling damages and the introduction of invasive species along tourist routes. The sampling sites are around the Suba-lyuk cave in Hór valley and where hikers rest around Tar-kő peak with vegetation in different forests and on grassland types at the centre of the study. The monitoring



activity encompasses a habitat mapping of sample sites, a mapping of tourism impacts and an assessment of the impact of tourism on vegetation.

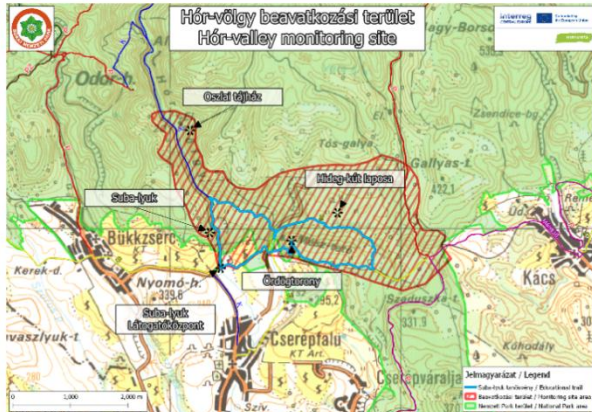


Figure 28. Hór-valley pilot site

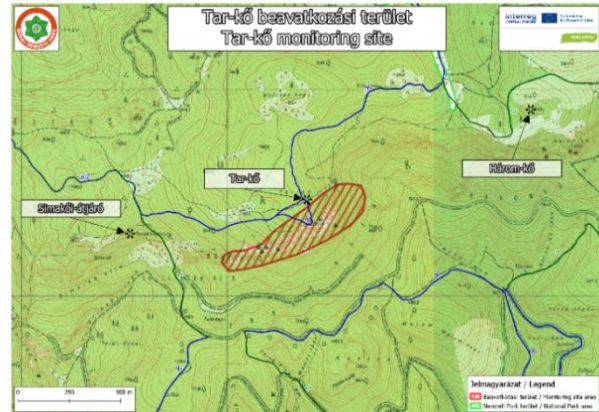


Figure 29. Tar-kő pilot site

3.2.1. Site Analysis and Species Composition

At the **Hór-völgy I (Rocky Grassland)** transect, 8 new species were identified compared to the 2024 baseline, while 14 species recorded in 2024 were not detected in 2025. Total species counts were 67 in 2024 and 61 in 2025. These fluctuations are considered typical seasonal variations rather than permanent trends. Notable, however, is the appearance of *Senecio vernalis*, an expanding weed not previously recorded in the local flora. While its presence is a negative phenomenon, it is likely due to regional expansion rather than tourism. Detected specimens were weeded out while in bloom to prevent further spreading.

At **Hór-völgy II (Thermophilous Oak Forest)**, species counts dropped from 40 (2024) to 32 (2025). This decline, including the disappearance of 15 species, is likely attributed to early and prolonged drought conditions clearly visible by May and June. The trodden path affects quadrats II/2 and II/3, where species numbers fell from 30 to 23.

At **Hór-völgy III (Slope Forest)**, species counts remained stable (17 in 2024, 19 in 2025). Interestingly, in quadrat III/1, which is directly affected by the tourist stairs, the species count increased from 4 to 9.

At the **Tar-kő IV (Beech Forest)** transect, species numbers increased from 38 to 46. However, in quadrat V/2, where the footpath crosses, the count dropped from 34 to 25, with several disturbance-tolerant and weed species appearing (*Echium vulgare*, *Euphorbia cyparissias*, *Myosotis arvensis*).

At **Tar-kő VI (Rocky Grassland)**, species numbers decreased from 65 to 51. In the affected quadrat (VI/5), the count remained at 27, but with a high proportion of weeds and disturbance-tolerant species.

3.2.2. Comparison of Coverage and Frequency

Changes in plant coverage and frequency were diverse and showed no singular dominant trend. In **Hór-völgy I**, *Allium flavum* doubled its frequency, while *Acinos arvensis* showed minimal changes unlikely to be linked to tourism.

In **Hór-völgy II and III**, weed-like species such as *Anthriscus cerefolium* and *Galium aparine* saw significant increases in coverage, with *Anthriscus* becoming a dominant species in all quadrats by 2025. Similarly, *Lapsana communis* appeared as a new weed-like presence.

At **Tar-kő VI**, significant increases were noted in the coverage of *Capsella bursa-pastoris* (from 0.2 to 17), *Draba nemorosa*, and *Poa bulbosa*, despite a general decrease in the total number of species across the transect.



3.2.3. Social Behavior Types and Phenology

In most sites, the ratio of species belonging to natural plant communities versus weeds changed proportionally with the total species count. In **Tar-kő V (Steppe Meadow)**, however, weeds increased from 3 to 6 species, alongside an increase in the coverage of disturbance-tolerant plants. Phenological data (the study of periodic plant life cycle stages) showed that the drought in 2025 impacted flowering. In **Hór-völgy II**, the number of species reaching the generative (flowering) phase in the foot-traffic-affected quadrats decreased, while in **Tar-kő V**, 22 species showed a decrease in flowering frequency.

3.2.4. Mapping of Tourism Impact

3.2.4.1. Hór-völgy

The valley floor is dominated by a gravel road used by hikers and cyclists. A steep, marked path leads to the Suba-lyuk Cave (Figure 30). Beyond the cave, unmarked paths lead to makeshift latrines and lookout points. In the forest, these paths are visible, but they "diffuse" (spread out) upon reaching the grasslands, meaning trampling is scattered rather than concentrated. In 2025, new infrastructure (railings, benches, and concrete stairs) was installed near the cave. The cave interior remains heavily disturbed due to intense trampling.

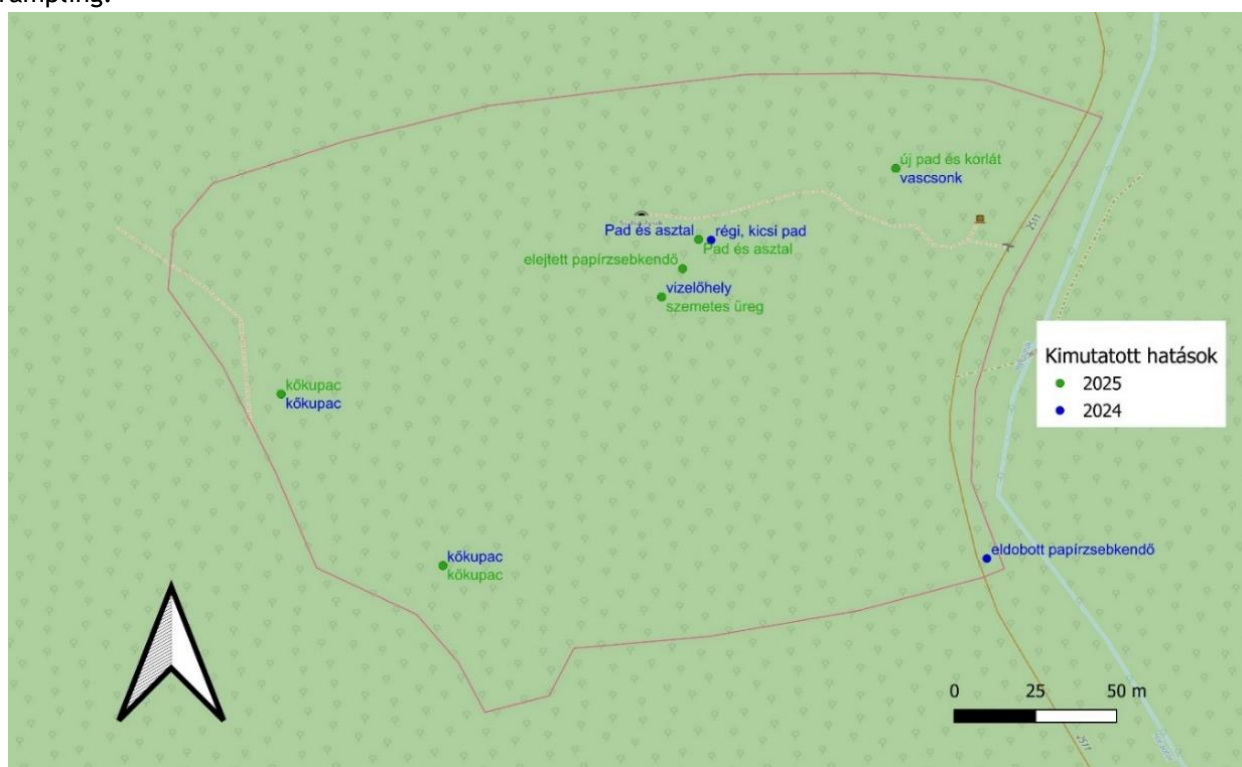


Figure 30. Tourism impacts identified at the Hór-völgy sampling area (2024–2025)

3.2.4.2. Tar-kő

The area is primarily affected by the intersection of major hiking trails. Significant trampling is evident near the lookout points, where the grassland composition has changed. Evidence of human presence includes fire pits, litter, and areas used as informal latrines. Near the **Tar-kő Rock Shelter**, impacts are minimal and difficult to distinguish from game trails, though bare soil remains at the entrance due to historical excavations (Figure 31).

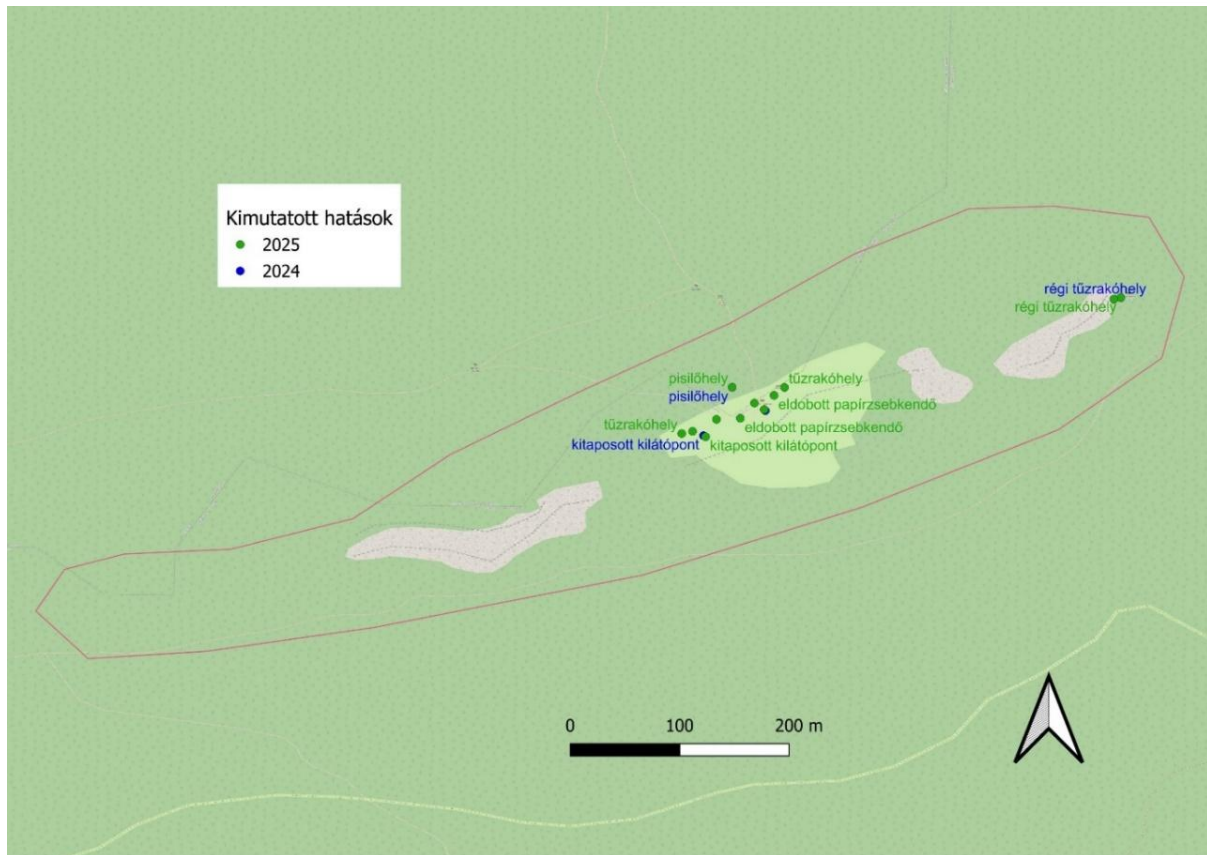


Figure 31. Tourism impacts identified at the Tar-kő sampling area (2024–2025)

3.2.5. Habitat Mapping of the Study Areas

The delineation of individual **habitat patches** was conducted using aerial imagery (Bing, Google) and handheld GPS devices. Aerial photographs were primarily utilized to define the boundaries between forest and grassland, and to a limited extent, to differentiate between specific forest and grassland types. The differentiation of these types was typically carried out in the field by walking the perimeter of the given habitat stands and recording the tracks.

The processing of the collected and recorded data, as well as the creation of the **digital habitat maps**, was performed using **QGIS software version 3.34.8**.

Within the designated area in **Hór-völgy**, 17 habitat patches were identified (Figure 32). The vast majority of these are natural rocky habitats, though the gravel road running along the valley floor is also present. In this area, a total of six natural and one artificial habitat types occur.

In the designated area at **Tar-kő**, 26 habitat patches were identified (Figure 33). Most are natural rocky habitats, with disturbed (trampled) habitats occurring in small areas. A total of eight natural and one artificial (secondary) habitat types occur in this region.



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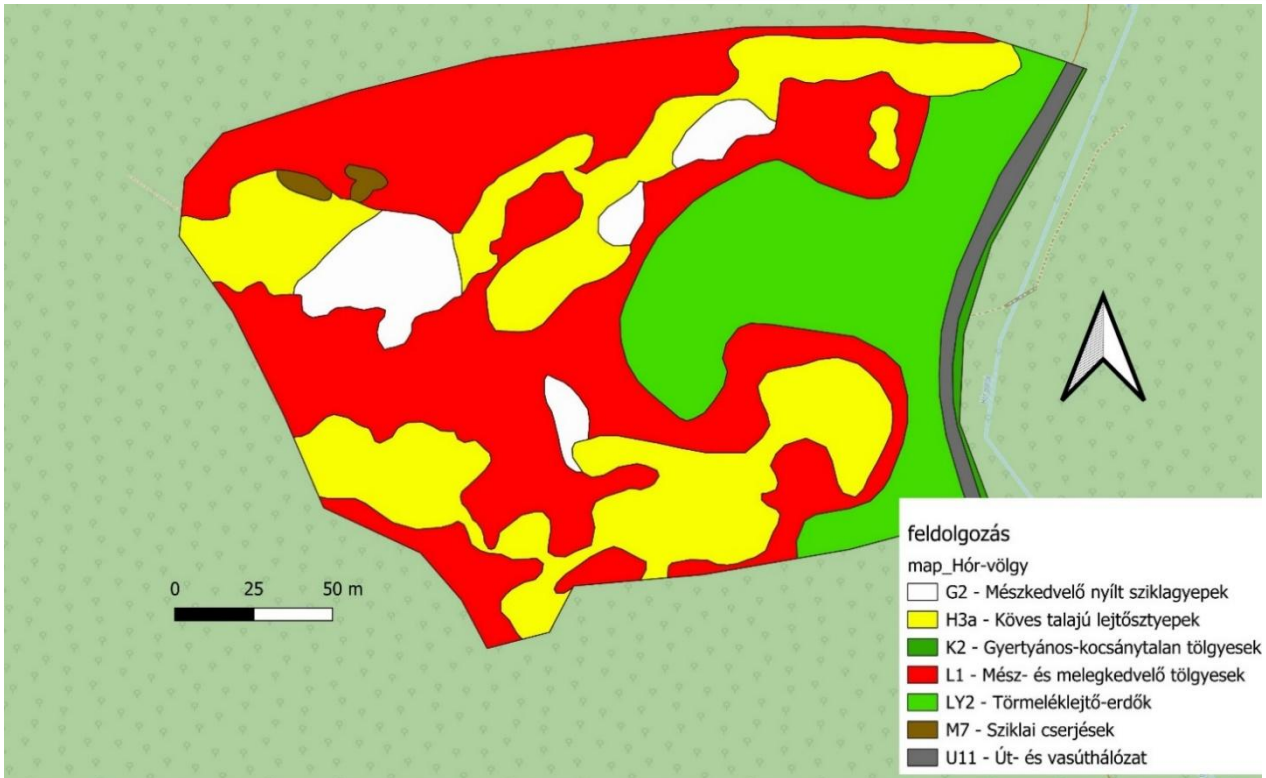


Figure 32. The habitat map of the Hór-völgy study area according to the Á-NÉR classification

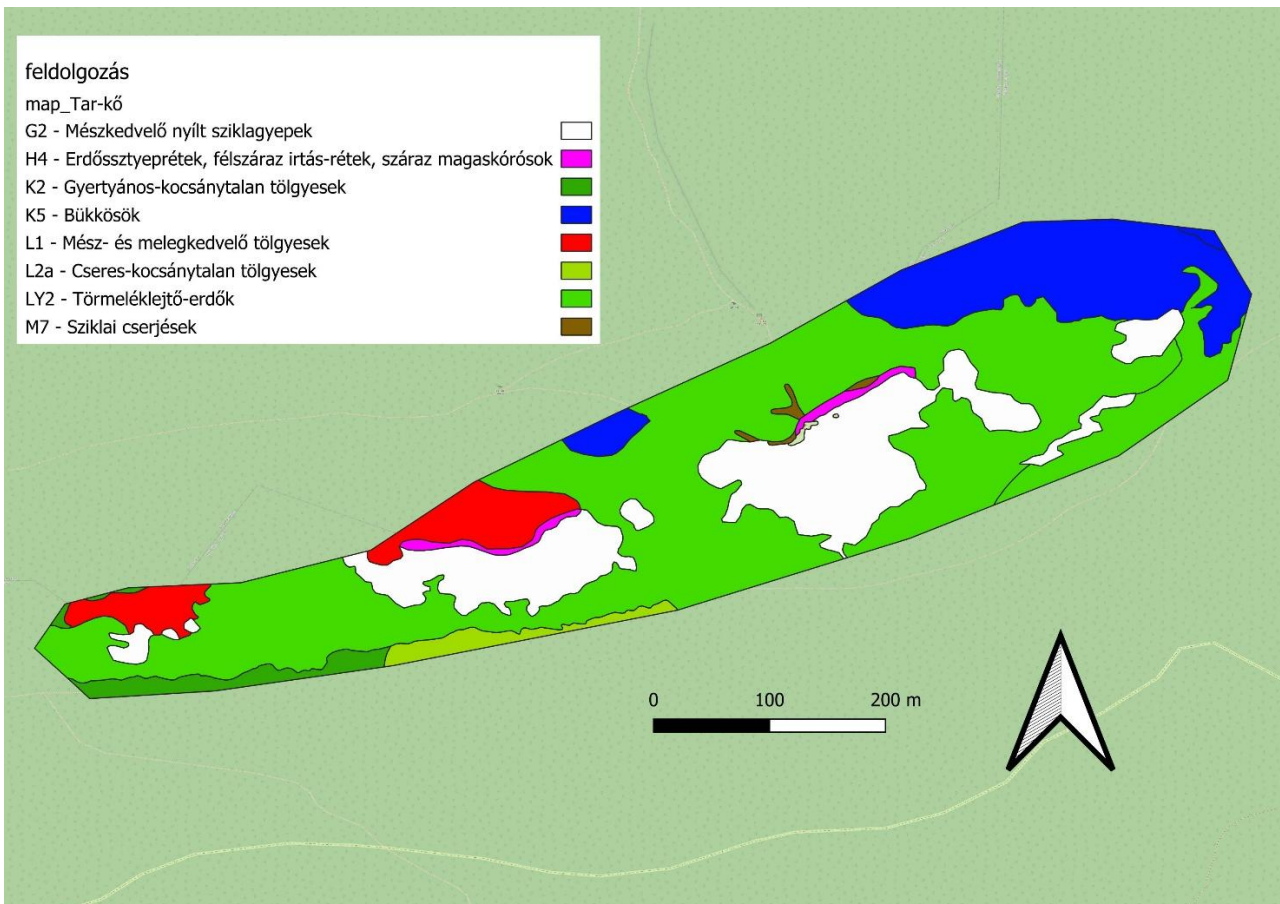


Figure 33. The habitat map of the Tar-kő study area according to the Á-NÉR classification



3.2.6. Summary and Conclusions

The 2024-2025 study utilized habitat mapping (large-scale), impact mapping (meso-scale), and coenological transects (small-scale) to assess tourism.

Meso-scale: High-traffic attractions (Suba-lyuk, Tar-kő lookout) show concentrated trampling. Despite infrastructure upgrades (stairs, railings), visitors frequently stray from designated paths. There are currently no signs warning visitors about the sensitivity of the protected habitats.

Small-scale: The direct impact of footpaths is limited to a 0.5-1 m wide zone of bare soil and a 1-2 m wide buffer where weeds and disturbance-tolerant species appear. The primary risk is these paths acting as **invasion hotspots** for non-native species into high-natural-value areas.

Environmental Factors: The study highlights that weather (specifically the 2025 drought) and long-term climate change currently exert a more significant influence on vegetation composition than local tourism.

These two years of data serve as a baseline. Continued monitoring is required to clearly distinguish between annual environmental fluctuations and the long-term cumulative effects of tourism.

The key outcomes show that the direct physical impact of footpaths on plant associations is detectable but spatially restricted, mostly confined to a 0.5 to 1-meter wide band characterized by bare soil and the appearance of disturbance-tolerant weed species. However, distinct trends of degradation were observed near the trails; for example, in the Hór-valley thermophilous oakwood transect, the invasive weed *Anthriscus cerefolium* saw an approximately twenty-fold increase in cover between 2024 and 2025, becoming the dominant species. Similarly, in the Tar-kő steppe meadow transect, the number of natural association species decreased, while the number of weed species doubled.

The most severe limitation to this analysis was the continuous, extreme drought experienced in 2025, which drastically altered species composition and phenology across all sites. This macro-environmental climatic factor heavily masked the localized impacts of tourism, making it challenging to attribute all observed vegetative declines solely to trampling. Nevertheless, the analysis concludes that while trampling has a narrow physical footprint, the footpaths act as critical invasion corridors for non-native and weed species, slowly degrading the high natural value of the inner stands.

3.3. Botanical survey to assess anthropogenic pressure

Protected Areas: Tuscan-Emilian Apennine National Park

Project Partner: PNATE

At the pilot sites of Pietra di Bismantova and Fonti di Poiano, **botanical surveys** were conducted by a botanist specifically appointed for this task, with the aim of assessing the impact of visitor presence and passage during the tourist season.

An initial field survey made it possible to identify the main critical issues, define the sample areas and environments to be investigated, and establish the survey methodology. Monitoring activities were carried out at two distinct times, at the beginning of the peak tourist season (May 2025) and at its end (late September 2025), in order to compare the collected data and assess the impact of anthropogenic pressure.

At the Poiano Springs site, the analysis also relied on a substantial body of pre-existing data, both historical and recent, particularly those derived from the LIFE Gypsum project, which were used as a baseline for interpreting vegetation dynamics. In this area, two types of herbaceous habitats with different degrees of aridity were selected, allowing for a comparative assessment of trampling effects on vegetation.

As for Pietra di Bismantova (Figure 34), the initial plan to use transects was revised following a preliminary site assessment, leading to the adoption of an approach based on three homogeneous case studies. Surveys were therefore concentrated in the most heavily visited areas, where the impacts on plant species and ecosystems were most evident.

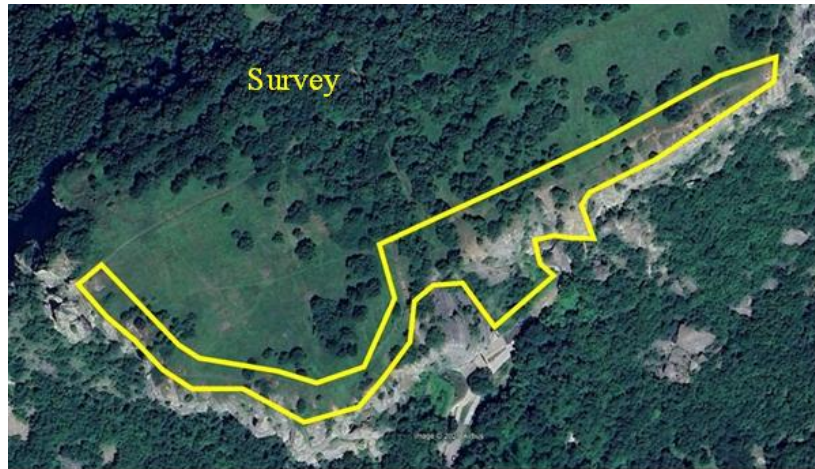


Figure 34. Areas covered by the botanical surveys at the Pietra di Bismantova pilot site

3.3.1. Quantitative and qualitative findings

Collected data were organized as plant species checklists (Figure 35), derived from repeated field surveys conducted on selected sample areas. These data support comparative analyses over time and across sites, particularly in relation to the effects of anthropogenic pressure on floristic composition and vegetation conditions.

famiglia	taxon	for_bio	corotipo
Asteraceae	<i>Achillea millefolium</i> L. subsp. <i>millefolium</i>	H scap	Eurosiber.
Poaceae	<i>Achnatherum calamagrostis</i> (L.) P. Beauv.	H caesp	Orof. S-Europ.
Poaceae	<i>Agrostis capillaris</i> L.	H caesp	Circumbor.
Amaryllidaceae	<i>Allium sphaerocephalon</i> L. subsp. <i>sphaerocephalon</i>	G bulb	Paleotemp.
Brassicaceae	<i>Alyssoides utriculata</i> (L.) Medik. subsp. <i>utriculata</i>	Ch suffr	Medit. - NE-Medit.
Brassicaceae	<i>Alyssum alyssoides</i> (L.) L.	T scap	Euri-Medit. - Steno-Medit.
Rosaceae	<i>Amelanchier ovalis</i> Medik. subsp. <i>ovalis</i>	P caesp	Medit.-Mont.
Poaceae	<i>Anisantha sterilis</i> (L.) Nevski	T scap	Medit.-Turan.
Asparagaceae	<i>Anthericum liliago</i> L.	G bulb	Europ. - Subatl. - Submedit.
Poaceae	<i>Anthoxanthum odoratum</i> L.	H caesp	Eurasiat.
Fabaceae	<i>Anthyllis vulneraria</i> L.	H bienn - H scap - T scap	Euri-Medit. - Orof. SW-Europ.
Brassicaceae	<i>Arabidopsis thaliana</i> (L.) Heynh.	T scap	Cosmop. - Paleotemp. - Subcosmop.
Brassicaceae	<i>Arabis sagittata</i> (Bertol.) DC.	H bienn - H scap	SE-Europ.
Caryophyllaceae	<i>Arenaria serpyllifolia</i> L. subsp. <i>serpyllifolia</i>	T scap	Cosmop. - Subcosmop.
Poaceae	<i>Arrhenatherum elatius</i> (L.) P. Beauv. ex J. Presl & C. Presl	H caesp	Paleotemp.
Asteraceae	<i>Artemisia alba</i> Turra	Ch suffr	S-Europ. - Steno-Medit. - Submedit.
Fabaceae	<i>Astragalus monspessulanus</i> L. subsp. <i>monspessulanus</i>	H ros	Steno-Medit.
Gentianaceae	<i>Blackstonia perfoliata</i> (L.) Huds.	T scap	Euri-Medit.
Poaceae	<i>Brachypodium genuense</i> (DC.) Roem. & Schult.	H caesp	Endem. Ital.
Poaceae	<i>Brachypodium pinnatum</i> (L.) P. Beauv.	H caesp	Eurasiat.
Poaceae	<i>Bromopsis erecta</i> (Huds.) Fourr.	H caesp	Paleotemp.
Apiaceae	<i>Bunium bulbocastanum</i> L.	G bulb	W-Europ.
Campanulaceae	<i>Campanula medium</i> L.	H bienn	NW-Medit.
Campanulaceae	<i>Campanula rapunculus</i> L.	H bienn	Eurasiat. - Paleotemp.
Asteraceae	<i>Centaurea triumfettii</i> All.	H scap	Europ.-Caucas. - Orof. S-Europ.

Figure 35. Plant species checklist for botanical survey data management

The surveys reveal that the impact of visitor presence on vegetation is highly variable and strongly dependent on local environmental conditions. In areas characterized by deeper soils and higher moisture availability, plant communities appear relatively resilient, with limited observable changes in species composition and overall structure over the monitoring period. In contrast, in more fragile environments—such as those with shallow, dry, or poorly developed soils—clear signs of disturbance emerge.

These disturbances include a reduction in vegetation cover, increased soil exposure, and localized erosion processes. In some cases, changes in species composition are observed, with an increase in species that are more tolerant to trampling and drought conditions. This suggests an early-stage shift in community structure driven by anthropogenic pressure.



In addition to these general patterns, the surveys highlight that impacts are not evenly distributed across the landscape. Instead, they tend to be concentrated in specific areas subject to intense use, such as access points, trail intersections, viewpoints, and informal paths. In these zones, repeated trampling leads to the formation of bare ground, fragmentation of vegetation cover, and the progressive widening or multiplication of trails.

Qualitative observations also indicate that certain management practices, particularly vegetation clearing or mowing conducted for tourism-related purposes, can significantly alter local ecosystems. In some cases, these interventions have resulted in the removal of shrub and herbaceous layers, increased visibility of anthropogenic structures (e.g., parking areas), and damage to protected or ecologically relevant species.

3.3.1.1. Interpretation of patterns

The observed patterns suggest that vegetation responses to visitor pressure are governed by a combination of environmental sensitivity and intensity of use. Areas with more developed soils and favorable moisture conditions exhibit greater resistance to disturbance, while marginal environments are more vulnerable and show faster and more pronounced degradation.

Importantly, the results indicate that even predominantly pedestrian use can generate significant ecological effects, especially when concentrated spatially and repeated over time. The formation of informal trails and the expansion of existing ones represent a key mechanism through which visitor pressure translates into habitat alteration. Furthermore, the interaction between direct disturbance (trampling) and indirect human activities (such as vegetation management or infrastructure maintenance) appears to play a crucial role in shaping vegetation dynamics. In some cases, these combined pressures may lead to the loss of sensitive species or to long-term changes in habitat structure.

3.3.1.2. Implications for monitored phenomena

From a conservation perspective, the findings highlight the need to consider not only the overall number of visitors, but also the spatial distribution of use and the specific characteristics of the affected environments. Sites with lower visitor numbers but higher ecological sensitivity may be equally, or even more, vulnerable than more frequented areas.

The results also emphasize the importance of regulating visitor movement, particularly by limiting off-trail access and preventing the proliferation of informal paths. Targeted management interventions—such as controlled mowing practices and the protection of sensitive areas—are essential to mitigate impacts and preserve ecological integrity.

3.3.1.3. Limitations and uncertainties

The interpretation of vegetation dynamics is subject to several limitations. The monitoring period is relatively short and captures only seasonal variations, making it difficult to assess long-term trends. In addition, the spatial extent of the surveys is limited to selected sample areas, which may not fully represent the variability of the broader landscape.

Moreover, distinguishing between natural variability and anthropogenic impact can be challenging, particularly in environments where climatic conditions (e.g., drought) also influence vegetation patterns. Despite these constraints, the integration of field observations with existing baseline data provides a robust framework for identifying emerging trends and areas of concern.

3.3.1.4. Added value of the approach

The adopted methodology, based on repeated surveys and comparative analysis, allows for the detection of early-stage changes in vegetation and provides a valuable tool for monitoring the effects of tourism over time. The combination of quantitative species lists and qualitative field observations enhances the interpretative capacity of the analysis, supporting evidence-based management decisions.



3.3.2. Conclusions and Recommendations

Vegetation monitoring highlights a clear relationship between visitor pressure and ecological response, although this relationship is strongly mediated by local environmental conditions. Areas with deeper soils and higher moisture availability show greater resilience, while fragile environments—such as shallow or dry soils—are more vulnerable to disturbance.

Impacts are spatially concentrated and include:

- Reduction in vegetation cover
- Soil exposure and erosion
- Shifts in species composition toward trampling-tolerant species

The formation of informal trails emerges as a key driver of habitat alteration. Additionally, certain management practices (e.g., vegetation clearing) can amplify ecological impacts, sometimes affecting protected or sensitive species.

Future actions should include expanding the spatial coverage of surveys to improve representativeness and extending monitoring over multiple years to better distinguish seasonal variability from long-term trends. It will also be important to prioritize monitoring in ecologically sensitive areas, even when visitor numbers are relatively low, while implementing stricter control of off-trail access to prevent the formation of informal paths. At the same time, more selective and ecologically informed vegetation management practices should be adopted. Finally, vegetation monitoring should be more explicitly linked to visitor data in order to better understand cause-effect relationships between use patterns and ecological change.

3.4. eDNA sampling to analyse dispersal of invasive plant species

Protected Area: EGTC Geopark Karawanken-Karavanke

Project Partner: CUAS

This monitoring activity focused on the early detection of invasive plant species using environmental DNA (eDNA) metabarcoding analysis in combination with citizen science. The study was conducted in the Karawanken-Karavanke UNESCO Global Geopark, a transboundary protected mountain area characterized by high biodiversity and increasing tourism pressure. The activity aimed to assess whether visitors act as potential vectors for invasive species dispersal.

The monitoring approach builds on the premise that invasive plant species pose significant ecological and economic threats, particularly when detection occurs only after establishment of highly invasive species, such as in case of Canadian goldenrod (*Solidago canadensis*) or Japanese knotweed (*Fallopia japonica*). Therefore, the activity emphasized pre-invasion monitoring by identifying traces of propagules (e.g. seeds, spores, plant fragments) before visible plant populations emerge in the tourist-impacted areas. The approach to test the applicability of the given methods in the Geopark comprises tests for species detection from known target plant samples, detection of plant DNA from soil samples at the sites with known invasive plant occurrence, sampling of soils from the Geopark by the project team and sampling of soil from the ground, bikes and shoes by the citizen scientists. Sampling was conducted in three sampling campaigns in July 2023 and September 2024 along an elevational gradient on Petzen/Peca mountain.

Sampling comprised control samples of plant tissue and soil from known invasive species locations to validate detection, soil collected from trails, forest ground, and defined transects (0-3 cm depth, both trail sides), and visitor associated soil and debris from hiking shoes and mountain bike parts (Figure 36). A total of 111 samples were collected (including controls), of which a substantial share was contributed by 40 citizen scientists. Participants used custom sampling kits developed by the project team containing sterile tools, collection tubes, sample collection label and instructions. Samples were collected continuously during the campaigns and stored under controlled cooling conditions before laboratory processing.



Figure 36. Sampling operations for eDNA analysis

Laboratory and analytical workflows followed molecular ecology protocols that consisted of DNA extraction from soil samples using commercial kits with subsequent DNA extract quality and quantity control (i.e., gel electrophoresis, fluorometric quantification), polymerase chain reaction (PCR) targeting the internal transcribed spacer 2 (ITS2) region specific for plants, followed by high-throughput sequencing of the DNA library and taxonomic assignment using available reference sequences information from NCBI Genbank. Finally, data was filtered and compared using statistical analyses.

To assess invasive species in the list, a list of invasive species up to date recorded in Austria was downloaded from EASIN database. All the records were double-checked for their occurrence in the region in the Global Biodiversity Information Facility database (GBIF).

3.4.1. Results, Assessment, and Interpretation

A total of 88 samples (excluding negative laboratory controls) yielded usable data, detecting 431 plant species across the study area. On average, approximately 118'000 DNA sequences per sample were obtained, with species richness ranging from 1 to 78 species per sample. Notably, around 50% of the detected species occurred only once, indicating a large number of rare detections. Among the sample types, shoe samples contained the highest number of unique taxa (118), followed by transect and soil samples. Statistical analysis revealed significantly higher species richness in shoe samples compared to soil and path samples, with a p-value of less than 0.01.

Common plant species, such as *Plantago* sp., *Festuca rubra*, and *Urtica dioica*, were consistently detected across samples, confirming the reliability of the eDNA metabarcoding method in detection of common species. However, community composition varied between substrates. Shoes acted as mobile collectors of plant material, trail soils reflected local deposition patterns, and bike samples exhibited more distinct assemblages. Invasive species were detected in 17 samples, with *Impatiens glandulifera* being the most frequently identified species. Other non-native and potentially invasive species included *Erigeron annuus*, *Ambrosia artemisiifolia*, and *Robinia pseudoacacia*. These detections were split between trail samples and visitor-associated samples, particularly shoes. Most invasive species detections occurred at lower elevations (below 1200 meters), with limited presence at higher altitudes. Control samples confirmed the detection capability of the method, although certain species, such as *Fallopia japonica*, were not detected, highlighting methodological limitations.

The combination of environmental and visitor-derived samples provides compelling evidence that visitors act as vectors for plant DNA dispersal, potentially transporting it across the landscape. Trails and infrastructure can act as corridors for the spread of invasive species. Based on these outcomes, the use of eDNA can enable the detection of early-stage or low-density presence of such species that are may sometimes not be visible through traditional survey methods. Visitor-associated samples, especially shoes, showed high diversity and invasive species presence, indicating potential contribution of tourism in



facilitating dispersal. Several limitations and uncertainties were identified during the study. Marker limitations prevented the resolution of some taxa to the species level, such as *Heracleum* spp.. False negatives were observed, with species such as *F. japonica* not being detected despite their known presence. The use of eDNA metabarcoding enabled non-invasive, high-throughput biodiversity assessment. Yet, integration with citizen science significantly expanded spatial coverage, allowing for a more comprehensive analysis.

3.4.2. Conclusions and Recommendations

The study demonstrates that combining eDNA metabarcoding with citizen science is a feasible and effective approach for monitoring plant biodiversity and detecting invasive species DNA across tourist-visited mountain area. This method provides sensitive detection of both common and rare taxa, offering valuable insights into possible dispersal pathways linked to human activity. Visitor-associated vectors, particularly footwear, play a significant role in transporting plant material, underscoring the need to assess potential targeted management in the future. Despite certain methodological limitations, the approach shows strong potential as an early warning system for invasive species detection and biodiversity monitoring.

The combined eDNA-citizen science approach has proven effective for early detection and broad-scale monitoring of plant biodiversity and invasive species. With the given approach it is possible to expand it into monitoring programs in protected areas. To enhance future data collection efforts, temporal replication through seasonal sampling as well as laboratory optimization for detection of further invasive species of interest should be conducted. The monitoring should be associated to in-field identification either through experts or by trained personnel and citizens. Based on such comprehensive outcomes, preventive measures, such as boot cleaning stations and bike wash facilities (already implemented at Petzen), could be considered to reduce the risk of plant material transport by visitors.

3.5. iNaturalist app to track invasive species

3.5.1. Case study #1

Protected Area: Bükk National Park Directorate

Project Partner: BNPD

The iNaturalist citizen science project was utilized to track the spread of invasive plant species across the national park by having users upload photos and GPS coordinates.



Figure 37. iNaturalist project created for the activities in the Bükk National Park Directorate area

An examination of the species distribution within the dataset reveals a highly targeted collection effort. The dataset encompasses 1,126 total observations representing 62 distinct species, all of which belong



exclusively to the Kingdom Plantae. The floristic profile is predominantly characterized by known non-native, invasive, and aggressively spreading plant species, directly reflecting the specific objectives of the regional monitoring project.

The distribution of observations is heavily skewed toward a few highly successful invasive species that currently dominate the regional landscape. The most frequently recorded species by a significant margin is the Indian Pokeweed (*Phytolacca acinosa*), representing 249 observations. This is followed by the Tree-of-heaven (*Ailanthus altissima*), a notorious and fast-growing invasive tree, which accounts for 116 records.

Other prominently distributed species include the Common Milkweed (*Asclepias syriaca*) with 52 observations, Canada Goldenrod (*Solidago canadensis*) with 47, Annual Fleabane (*Erigeron annuus*) with 46, and Spotted Spurge (*Euphorbia maculata*) with 46. Woody invasive plants are also well-represented by the Box Elder (*Acer negundo*) with 36 records and the American Hackberry (*Celtis occidentalis*) with 30 records. The overwhelming prevalence of these specific species highlights their widespread establishment in the Bükk mesoregion and underscores their priority status for local botanical monitoring.

A spatial density analysis derived from the geographical coordinates of the observations reveals distinct localized hotspots for these invasive species across the Bükk Region mesoregion (Figure 38). The primary density hotspot is heavily concentrated in and immediately surrounding the city of Eger (approximately 47.90° N, 20.37° E). This dense clustering indicates that these plant populations proliferate most successfully within urban-wildland interfaces, where continuous human activity, infrastructure development, and land disturbance frequently facilitate the introduction and rapid spread of alien species.

In addition to the primary Eger cluster, secondary, slightly more diffuse hotspots extend eastward along the southern foothills of the Bükk Mountains. These secondary concentrations are particularly notable around the municipalities of Noszvaj, Szomolya, and Mezőkövesd.

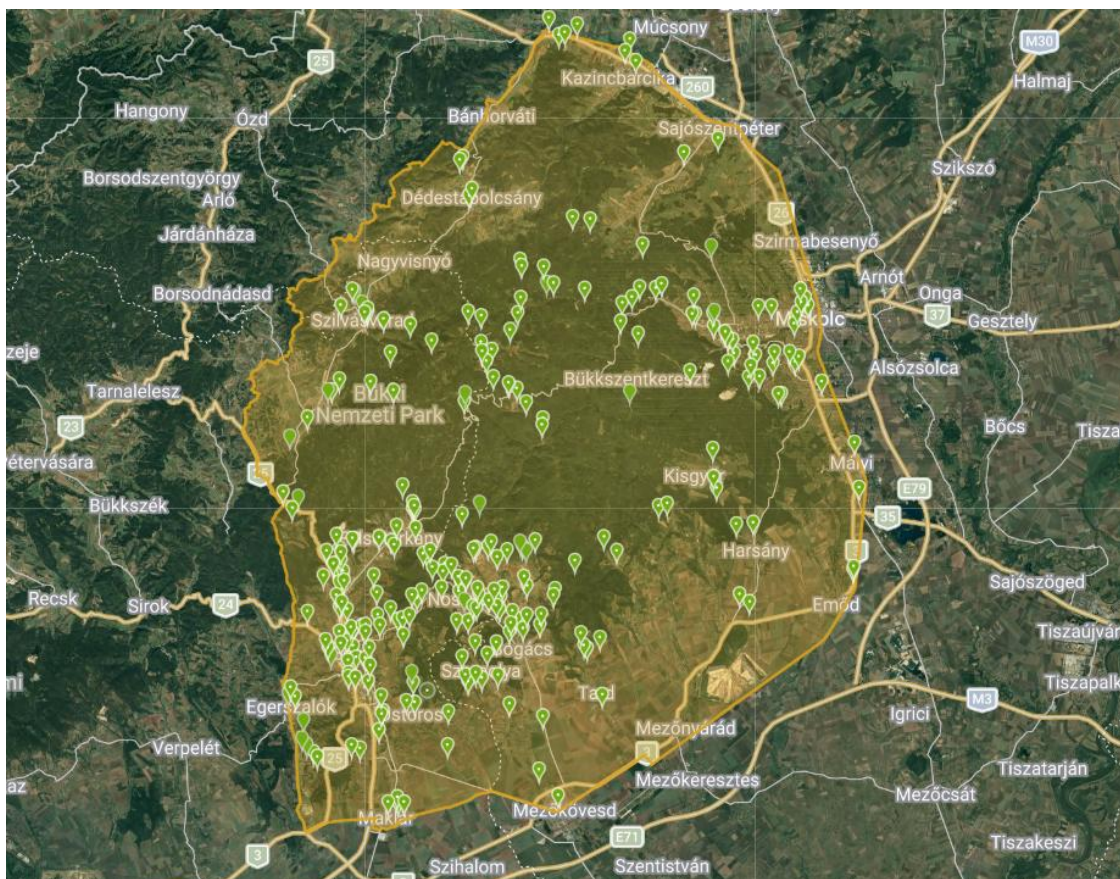


Figure 38. Spatial distribution of observations collected



From a broader habitat perspective, the spatial distribution of these observations closely tracks human infrastructure, such as road networks and settlements, as well as the disturbed transitional zones situated at the boundaries of the Bükk National Park. In stark contrast, the deep, undisturbed interior regions of the national park exhibit a significantly lower density of observations. This spatial disparity strongly suggests that while these invasive species thrive in edge environments, transitional ecotones, and disturbed soils, they face substantial ecological barriers when attempting to penetrate the mature, undisturbed native forest habitats of the protected interior. However, it should also be noted that this distribution pattern may partially reflect the concentration of observer effort along easily accessible trails and settlement borders.

The key outcome was the collection of hundreds of verified observations detailing numerous invasive species encroaching on protected habitats. A clear spatial trend emerged showing that observations were heavily clustered around highly populated and easily accessible areas, such as the outskirts of Eger, rather than reflecting the true ecological distribution of the plants. The primary limitation of this dataset is its reliance on ad-hoc public use, which inherently creates a spatial bias favoring popular tourist routes and urban borders. The analysis dictates that for this tool to be scientifically robust for monitoring remote pilot sites, data collection must be deliberately structured by engaging park rangers, researchers, and trained guides to survey the underrepresented, deeper zones of the park.

3.5.2. Case study #2

Protected Area: Lower Kamenjak

Project Partner: PIK

Vegetation monitoring was conducted via the iNaturalist application, which aims to engage visitors in mapping the locations and abundance of invasive alien species along trails. The app allows visitors to input invasive species name, location, date and abundance. All the data is collected in an online database. Also, promotional leaflets about invasive alien species in the Lower Kamenjak area have been printed in 4 languages (Croatian, English, German, Italian) and distributed to visitors, and several workshops were held to educate the community about alien invasive species.

Currently, there are 59 observations of invasive alien species reported by community members, which have identified 7 invasive alien species (Figure 39).

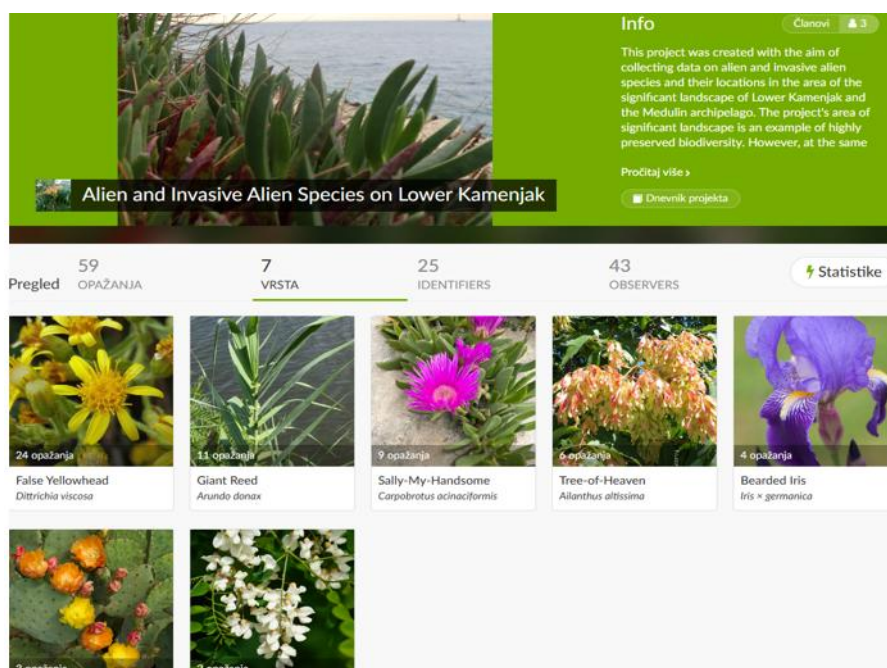


Figure 39. iNaturalist observations for Alien and Invasive Alien species on Lower kamenjak



Some of those identified are several significant invasive species: *Ailanthus altissima* (Tree of Heaven), *Aster squamatus*, *Carpobrotus acinaciformis*, *Conyza canadensis*, *Phyllostachys* sp., and *Robinia pseudoacacia* (Black Locust), which pose a threat to local biodiversity, since their rapid spread displaces native plants, alters natural habitats and reduces biodiversity overall. The main limitation of the citizen science approach is that, when talking about the area of Lower Kamenjak, visitors mainly come to rest and recreate, and so they neglect the nature protection part, and thus do not participate in the alien species identification.

The monitoring can be broadened to protected species monitoring (orchids, fungi), try to boost local community engagement in tracking protected species and educate them to be able to distinguish them themselves. Visitor engagement should be broadened by holding multiple workshops, awareness raising events, educations, and also rewarding engagement in the species identification project.

3.6. Citizen Scientist: custom-made direct approach

Protected Area: EGTC Geopark Karawanken-Karavanke

Project Partner: EGTC GEOPARK

In the HUMANITA project, the Geopark primarily focused on **identifying non-native and invasive alien species** in the whole Geopark area, their locations, threats, impact on habitats and appropriate measures to address them in the future. **Invasive alien species** and **non-native species**, alongside climate change, urbanisation and pollution, pose the greatest threat to biodiversity, and the Geopark region is not immune to this effect (Figure 40).



Figure 40. Examples of Invasive Alien Species and non-native plant species in Karawanken-Karavanke UNESCO Global Geopark

Our goal was to **connect regular scientific surveys with a citizen science approach**, including visitors, the public, and volunteers, thereby increasing spatial coverage and the likelihood of **detecting and collecting data on observations of invasive alien and non-native species**. At the project's onset, we established a monitoring framework based on previous expert botanical surveys, which had provided limited coverage of the area. **We identified a set of target invasive alien plant species** throughout the entire Geopark and **developed standardised field protocols**. These methods included **recording the size of affected areas**, identifying plant species, assessing habitat characteristics, filling the gaps, and, most importantly, **ensuring the accuracy of location data**.

In December 2023, we started the Citizen Scientist project using the iNaturalist app.



Preliminary analyses of this approach, particularly with a single application like iNaturalist, have revealed **several warning signs that suggest limited expectations for a positive outcome**. This concern was later confirmed by the number and quality of observations collected. The warning signs included: Low local engagement with the application, Low average rate of observation submissions, Inaccurate user-reported observation locations, Incomplete observation datasets, and insufficient clarity in user species identification.

Despite a variety of parallel activities—such as numerous workshops, excursions, fieldwork, leaflets, posters, invitations, promotional events, and social media campaigns designed to promote the project goals and involvement at the citizen science platform "Österreich forscht"—the impact was minimal after one year. During this time, there were **only 121 observations, with just 50 recorded in 2024**.

3.6.1. Citizen Scientist - direct approach | © Urosh Grabner 2023/2024

In **November 2024**, we launched a parallel project called **Citizen Scientist** (Invasive Alien Plant Species and non-native plant species) - **direct approach**.

This initiative aims to create a comprehensive database or map of all non-native plant species found in the Geopark Karawanken-Karavanke area. The primary motivation for developing a new Citizen Scientist approach was to **facilitate the collection of observations that could increase in number at any given time**. This approach aims to expand the geographic range of these observations while maintaining a high standard of accuracy. It also seeks to provide high-quality and useful data on the presence of non-native plant species in the Karavanke Geopark area, ultimately **ensuring better outcomes in the research efforts**.

The innovative concept for Citizen Scientist - direct approach, was thoughtfully developed by our Geopark colleague, Project Manager and photographer Urosh Grabner. This initiative demonstrates a commitment to environmental stewardship and seeks to engage the public in meaningful discussions about sustainability practices. Urosh's unique combination of project management expertise and artistic vision has resulted in an approach that not only gives results but also educates and inspires attendees to collaborate with appreciation and protection of our natural ecosystems.

The strategy focuses on **connecting with individuals from specific interest groups related to outdoor activities** such as hiking, photography, guiding, or simply being nature enthusiasts. The main approach is **direct, personal interaction customised to each person's specific interests**, creating meaningful connections with those already engaged in the topic.

Additionally, raising awareness and involving selected volunteers has also sparked interest among secondary participants. These participants, through the main information channel, offer clues about the locations and confirmations of non-native species in the environment, sharing valuable insights through active volunteers or direct contacts.

The process consists of **three main phases**:

- Gathering data and clues from individuals through brief, productive interviews (a simple invitation to the coffee).
- Identifying non-native plant species and confirming locations (field work or digital proof).
- Entering the collected data into a database and GIS location (Geopark Karawanken-Karavanke).

Set of data obtained:

- **Species**
- **infected area** (if it can be determined);
- **number of plants** (flat estimate example (depends of the species): 5, 10, 50, 100, more than 10, etc...);
- **location (GIS)** - within a precision range of up to 10 meters;



- **first year of observation recording** (specific date not necessary);
- **assessment of whether it is a wild or cultivated species;**
- **observer** (person who confirmed the location with evidence can also stay anonymous if wanted - GDPR);
- **measure** (whether the area has already been subjected to measures to remove or limit the species or not);
- **evidence** (photo material, video material, in person, ...);
- **notes** (additional general information or remarks).

Even though the approach was used for marking invasive alien plant species, and other alien plant species. **We have already introduced the system into the testing process of obtaining useful data for locating species and habitats of indigenous plant and animal species.** The suitability of the system is demonstrated for a set of verified useful locations for any visual finding in the targeted area (e.g., illegal waste dumps (bio or artificial), geological findings, water bodies, habitats, illegal activities, etc.) In short, the range of the set is limited only to the visual evidence approach.

Additionally, new phases are in the making:

- Creating an API or dedicated app with preset entries of known species for easier data entry and species identification.

3.6.2. Results, Assessment, and Interpretation

To date, more than **32'000 confirmed locations** of non-native plant species have been recorded in the database for the Geopark Karawanken-Karavanke (Figure 41). The majority consists of Invasive Alien Species. Altogether, **over 90 non-native plant species** have been identified, and there are still more than 15,000 clues pending verification. Each month, we receive several new tips that require confirmation and regularly fill gaps in the database and co-create the final image of the digital map of the Geopark with confirmed locations.

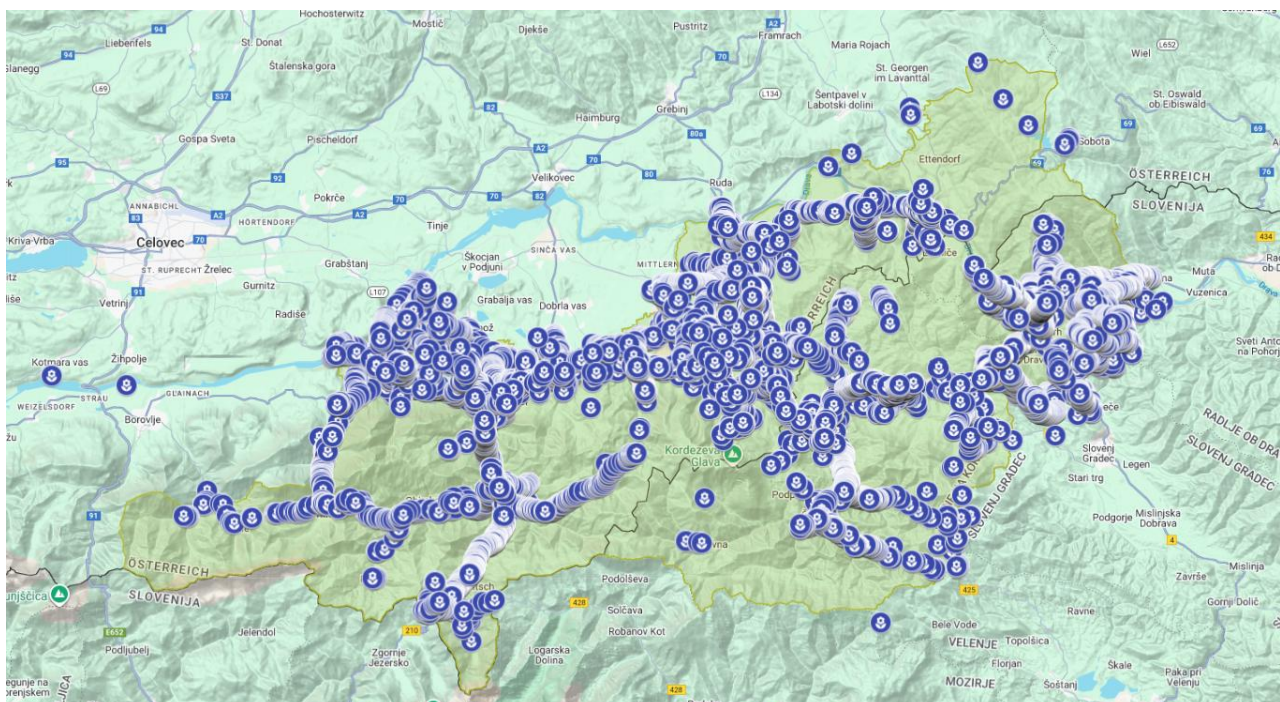


Figure 41. Map of confirmed locations of Non-native and Invasive Alien plant species in the Geopark Karawanken-Karavanke using the Citizen Scientist – direct approach.



Based on the data we have collected so far, we estimate that there are **between 50,000 and 100.000 locations with non-native plant species within the Geopark area**. This estimate considers gaps in data from less accessible regions, as well as unsurveyed locations that may not have been included and unconfirmed data that still need to be inspected.

No physical "samples" were collected throughout the process, except for individual photo materials used to identify species. Once the species and location were confirmed, the photos were not archived due to the large amount of data. In this context, "samples" refer to digital databases used for further analysis and creating the digital map of all collected data in the future.

Through the concept of a set of confirmed locations, we have also identified a set of the most common alien species that dominate the Geopark area. These are **Annual Fleabane** (*Erigeron annuus*) with currently over 6,500 confirmed locations, **Black Locust** (*Robinia pseudoacacia*) with over 1,800 confirmed locations, **Canada Goldenrod** (*Solidago canadensis*) and **Giant Goldenrod** (*Solidago gigantea*) combined form over 4,500 known locations, **Himalayan Balsam** (*Impatiens glandulifera*) with almost 3,000 known locations, **Horseweed** (*Erigeron canadensis*), over 850 known locations, **Japanese Knotweed** (*Reynoutria japonica*), which together with **Giant Knotweed** (*Reynoutria sachalinensis*) and **Bohemian Knotweed** (*Reynoutria × bohemica*) forms over 2,500 known locations, **Large-leaved Lupine** (*Lupinus polyphyllus*) with almost 300 known locations, **Small Balsam** (*Impatiens parviflora*) with over 600 confirmed locations, **Staghorn Sumac** (*Rhus typhina*) and **Tree-of-Heaven** (*Ailanthus altissima*) together form over 500 known locations, and **Yellow Oxeye** (*Telekia speciosa*) with over 350 confirmed locations.

It is also worth mentioning the presence of critical, **aggressive invasive alien plant species**, such as **American Pokeweed** (*Phytolacca americana*), **Bamboos** - Genus *Bambusa*, **Common Evening-Primrose** (*Oenothera biennis*), **Common Ragweed** (*Ambrosia artemisiifolia*), **Cutleaf coneflower** (*Rudbeckia laciniata*) - *Goldquelle*, **Jerusalem Artichoke** (*Helianthus tuberosus*), **Orange Day-Lily** (*Hemerocallis fulva*), and **Shaggy Soldier** (*Galinsoga quadriradiata*).

The extensive floods of 2023 contributed to the presence and spread of certain non-native species in the area surrounding the Geopark. These floods literally washed some species from gardens and parks into natural habitats. It is important to note that, in addition to these non-native species—primarily garden and park plants—that have remained unusually prevalent in nature after two years, we have also confirmed the presence of two highly toxic species. These are **Jimsonweed** (*Datura stramonium*), which has been found in over 20 locations, and **Snow-on-the-mountain** (*Euphorbia marginata*), which has been identified in over 50 locations.

The locations of confirmed observations also show the **pattern of observer/human movement** (paths, road connections, trails, etc.). The next step is to **pinpoint and address gaps in remote, hard-to-reach areas** to verify or dismiss the presence of non-native species, along with planning actions for containment, removal, and ongoing monitoring of non-native species. Some of those locations were already inspected and have confirmed minor presence of individual non-native and Invasive alien plant species; however, this is a continuous process, as the transfer of biological material can occur at any time.

The methodology used can also be applied to identify and catalogue different plant and animal species within the Geopark. Additionally, this approach can be adapted by any other organisation or individual looking to gather a large amount of useful data in a clear and transparent format adjusted to their needs. This technique streamlines the process of digitising the entire area, creating a comprehensive repository of valuable information. By systematically identifying these species, we can enhance our understanding of the region's biodiversity and ecological interactions. This initiative not only enriches the data available for researchers and conservationists but also facilitates informed management practices that promote the preservation of the unique ecosystems found within the Geopark.

A flat-rate analysis between the two used approaches (namely, iNaturalist and Citizen Scientist - direct approach) shows a large gap in the dataset's result, as well as in the quality of the observations obtained (Figure 42).



Area: Karawanken-Karavanke UNESCO Global Geopark

Flat rate comparative analysis

Period: 2024/2025

Approach	Observations	NEW	Confirmed	Timeframe	Accuracy					Species	Performance score Value coefficient
					Not recorded	< 10 m	< 100 m	< 500 m	> 1 km		
CS – iNaturalist	313	285	231 (40)	> 2 years	69	148	23	24	49	24	0,15% / 0,04%
CS – direct approach	32.115	All	All	8 months	/	All	/	/	/	> 90	32,12%
Prediction:	100.000										100%

Figure 42. A flat-rate analysis comparing data from two Citizen Scientist approaches

3.6.3. Conclusions and recommendations

Due to its more personal approach, the system performs significantly better than distant, impersonal digital data collection via applications. In this way, the participant has a greater sense of belonging and the value of their own contribution. The feeling of participation and appreciation of the effort and work of the individual participant is at a higher level than the impersonal distanced, digital collaboration.

Monitoring data acquisition is important and demands more time and energy compared to using an app. This highlights both the positive and negative aspects of the approach. While the initial phase of collecting data, information, or clues is faster and more extensive than any app, the second and third phases are more time-consuming but yield better confirmed results - easily eliminating inaccurate information with more verified location accuracy (even additional discoveries of the IAS on the way). The key factor is having a well-organised logistical design for verification through zoning the area of interest effectively.

3.6.3.1. Relevant pointers and recommendations

- **Start with the people that you know**, trust, connect with, and you have positive energy between you. Nature photographers, hikers, guides, nature lovers... friends, acquaintances, even colleagues...
- **Take some time.** Invite them for coffee (but not in your office, make it informal - choose a friendly environment). Don't attack them with what you want from them. Don't talk just about the work and what you need. Ask them how they are, where they were, and what they saw (these are pieces of information that will connect you to your cause). Connect in a way that you will listen and guide them through their own activities in nature, on what result you are aiming at.
- **Take as many notes as you can.** It is not a digital approach; it is a good, reliable old-school approach. Draw a map of locations if needed (let the observer do the same). The result is awarded.
- **Create a bond.** Reward to the participants. Some items, like T-shirts from your organisation, bottles of water, etc., are most welcome to give.
- Since the system coordinates the verification of clues and indicators in the wider area of interest, **the limitations are primarily of a time or nature.** The initial stage of the process requires more individual work and time. The process is not designed so that individuals can independently participate in it, but rather the involvement of individuals is carried out on a personal level, which requires more time for communication and the transfer of information via verbal background. However, as the system becomes established, the work also normalises. The advantage of the system is that it has no time limit. Data entry is circular and is constantly being updated. In our case, the assessment of location acquisition was set at a flat estimate of 100,000 locations of non-native species in nature. With the help of the established digital system of the iNaturalist application (where over 10 workshops were conducted and constant advertising of the purpose, invitations to active users of the application, etc.) we managed to acquire around 40 useful locations in two years (a total of just over 300 locations, not all of which are useful due to poor location accuracy, which in some cases deviates by a kilometer or more). With a direct approach and a currently limited number of participants, in just over half a year of active



operation, we have acquired over 32,000 confirmed locations of non-native plant species (within a radius of less than 10 meters) and identified more than 90 non-native plants in nature.

More effort and time are also spent on species identification, because it is, at the moment, a **manual approach** (however, once the system is up and running, and the participant is trained, the time is significantly reduced, and data entry is faster). The result also goes far beyond the app-based approach, as it does not limit the hints to the position that the observer independently determines, but to the wider surroundings, where the observer transfers the relevant information to the result.

3.6.3.2. Criticalities

- **Collected data can be inconsistent or inaccurate** (especially locations), leading to extra time and effort for verification (which is included in this case in phase two of the verification approach).
- Obtaining data from individuals **requires multiple interactions with individuals**, which can occasionally present a time coordination challenge.
- All three phases of this approach involve **a lot of time-consuming tasks**, so having a well-organised logistical plan is crucial to prevent unnecessary delays and redundant efforts.

3.6.3.3. Opportunities and future developments

- The potential exists to establish a **Citizen Scientist Geopark Community** that, with proper training, could greatly enhance monitoring efforts in various areas of interest by gathering consistent, detailed, and localised data.
- Increasing the potential for general **public awareness** of Invasive Alien Plant Species. Learning about individual invasive alien species and their impact on non-native species in natural habitats and ecosystems.
- To create a **comprehensive database** and **digital map of IAS** for the entire Karawanken-Karavanke Geopark area with the help of the community.
- Non-formal education programs/courses, including external/internal experts and active participants.



4. Erosion monitoring

4.1. Multi-scale UAV-based photogrammetric survey

Protected Area: Tuscan-Emilian Apennine National Park

Project Partner: UNIPR

The activity focused on monitoring the impact of tourist pressure on mountain trails and surrounding protected environments through multi-temporal UAV-based photogrammetric surveys. The main objective was to evaluate the effects of recreational activities in terms of soil erosion, trail morphology alteration, and trampling phenomena, combining landscape-scale interpretation with detailed quantitative terrain analysis.

Mountain trail degradation is a complex and spatially heterogeneous process. It manifests at different scales: from diffuse trampling in open grassland areas to localized incision along narrow forested paths. For this reason, the monitoring framework was structured around two complementary acquisition strategies:

- **High-altitude UAV surveys (~80m)**, designed to cover broad, open areas and support qualitative and semi-quantitative assessment of trampling patterns and trail network evolution.
- **Low-altitude UAV surveys (~30m)**, designed to follow specific trail segments at very high spatial resolution, enabling quantitative multi-temporal comparisons based on Digital Terrain Models (DTMs).

High-altitude surveys allow the identification of areas where visitor pressure is most intense and where trampling or trail widening is occurring. Low-altitude surveys can then be applied to these critical areas to perform quantitative analyses of terrain change, including the extraction of elevation profiles and the estimation of volumetric variations associated with erosion processes. Together, these complementary datasets provide a comprehensive representation of trail degradation dynamics, linking large-scale spatial patterns with localized geomorphological changes occurring along the monitored paths.

The monitoring activities were carried out in three pilot areas within the Tuscan-Emilian Apennine National Park, located in the northern Apennines of Italy (Figure 43). These sites were selected in order to represent different environmental contexts, visitor pressures, and trail morphologies within the protected area.

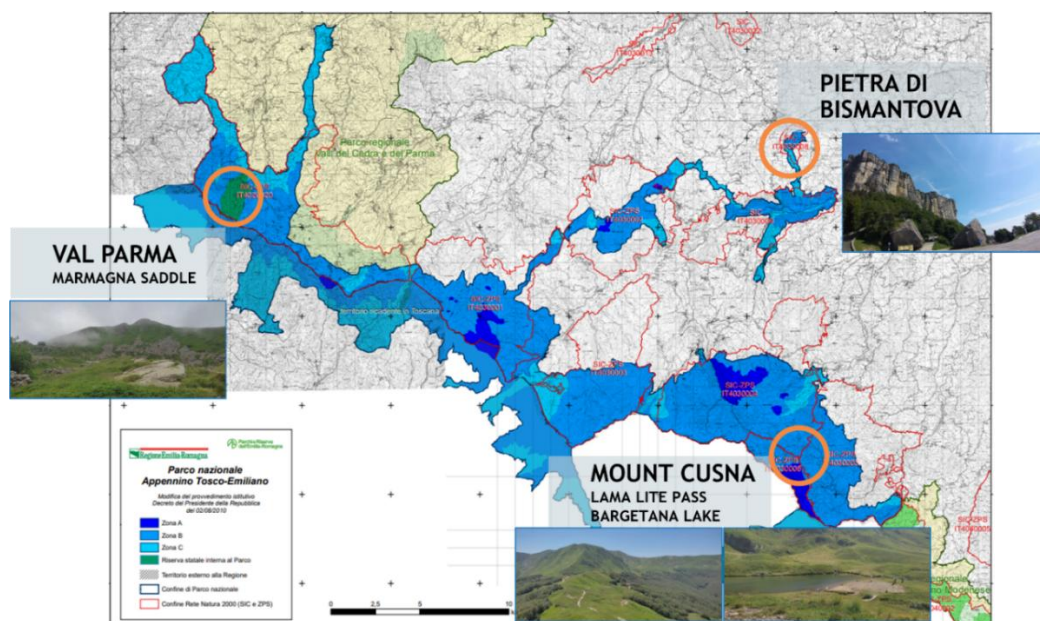


Figure 43. Pilot sites location



The first site is Pietra di Bismantova, an isolated sandstone plateau characterized by steep cliffs and a wide grass-covered summit. This location is one of the most popular tourist destinations within the park, attracting a large number of hikers and climbers. The summit area hosts several viewpoints and open spaces where trampling phenomena frequently occur outside the official trail network.

The second monitored area is located in the Val Parma sector near the Marmagna Saddle, a high-altitude environment characterized by alpine meadows and rocky terrain. The trail network in this area connects several mountain routes leading toward Mount Marmagna and the surrounding ridgelines. Due to its geomorphological characteristics and seasonal visitor flows, the site represents a suitable environment for analysing erosion processes along exposed mountain paths.

The third pilot site is situated in the Mount Cusna area, focusing in particular on the surroundings of Lama Lite Pass and Lago Bargetana. This area includes a complex network of hiking trails crossing open alpine landscapes and glacial landforms. The presence of the lake and panoramic viewpoints attracts a significant number of visitors, creating localized trampling and informal path formation in addition to the official trail system.

All aerial surveys were conducted before and after the summer season of years 2023, 2024, and 2025, using a DJI Mavic 3 Enterprise equipped with:

- A 20 MP RGB camera with mechanical shutter
- An integrated RTK positioning module
- A DJI D-RTK 2 GNSS mobile base station

Due to limited connectivity in mountainous environments, real-time GNSS corrections were transmitted locally from the mobile base station. The position of the base station was first surveyed and marked as a stable reference point. To improve vertical consistency and multi-temporal alignment, the base station position was introduced as a Ground Control Point (GCP) in the adjustment process. This significantly reduced systematic bias and improved vertical repeatability across epochs. Flights were planned with nadir strips and 80% longitudinal and lateral overlap to ensure geometric robustness and repeatability.

4.1.1. Results, Assessment, and Interpretation

The results obtained from the surveys 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

4.1.1.1. High-altitude surveys: Multi-Temporal Orthophoto Analysis

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.

A clear example of the capability of the areal UAV monitoring approach to detect trampling dynamics is provided by the multi-temporal orthophoto comparison performed at the Pietra di Bismantova site (Figure 44). The figure shows two orthophotos acquired in different monitoring epochs over the plateau area located near the cliff edge, which is one of the most frequently visited zones of the site.



Figure 44. Multi-temporal comparison performed on two orthophotos collected on April 2024 and October 2024 – Pilot site: Pietra di Bismantova

The comparison highlights several relevant changes in surface conditions and path morphology. While the main trail connecting the access point to the central plateau remains clearly identifiable in both epochs, the later acquisition reveals a more complex pattern of surface disturbance. In particular, several secondary tracks become visible across the grassy surface, forming a network of informal paths connecting the main trail to viewpoints located near the cliff edge.

These secondary tracks are particularly evident in the central portion of the plateau, where the orthophoto shows multiple parallel trajectories generated by repeated pedestrian movement across the grassland. Although these tracks are not associated with substantial vertical incision, their presence indicates progressive vegetation disturbance and soil compaction caused by frequent trampling.

The spatial pattern of these disturbances suggests a typical behaviour observed in heavily visited natural sites: visitors tend to deviate from the main trail to reach panoramic viewpoints or to shorten walking routes, progressively generating new lines of passage. Over time, repeated foot traffic reduces vegetation cover and exposes the soil surface, potentially initiating subsequent erosion processes. From a geomorphological perspective, this stage represents an early phase of trail degradation, where the impact is primarily expressed through vegetation disturbance rather than measurable terrain lowering. For this reason, orthophoto analysis plays a crucial role in identifying such processes, which may remain undetected when relying exclusively on elevation models.

Another relevant observation concerns the apparent widening of the main trails. In the more recent orthophoto, the disturbed area surrounding the official paths appears slightly wider, suggesting that lateral trampling is progressively extending the trail footprint. These observations confirm that high-altitude UAV orthophotos are particularly effective for detecting early-stage tourist impacts, especially in grass-covered environments where erosion does not immediately produce measurable vertical changes.

UAV-derived orthophotos are also highly useful for comparing the actual ground conditions with the officially mapped trail network. Figure 45 illustrates this approach for the area surrounding Lago Bargetana, where the orthophoto is overlaid with the trail system extracted from existing cartographic datasets.

The high spatial resolution of the orthophoto allows the mapped trails (shown in red) to be directly compared with the paths visible on the terrain. The main routes correspond well with the most clearly defined tracks, confirming the overall reliability of the official trail network. At the same time, the orthophoto reveals several additional paths that are not included in the mapped dataset. In the example shown, a number of secondary tracks connect different segments of the official trail network (dashed yellow lines).

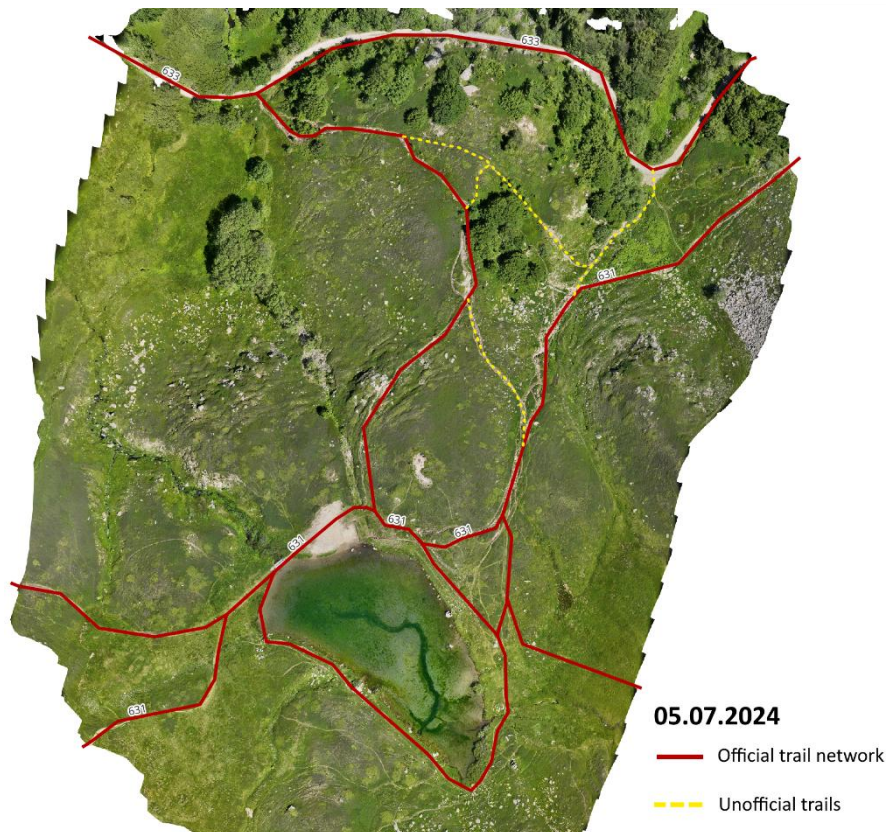


Figure 45. Orthophoto overlapped with official trail network traces to identify unofficial paths – Pilot Site: Mount Cusna, Bargetana Lake

This comparison highlights the value of UAV orthophotos as an objective reference layer for assessing the correspondence between mapped trails and the actual patterns of visitor movement. Identifying informal paths is particularly relevant for protected area management, as it allows early detection of zones where visitor behaviour diverges from the intended trail system and where trampling or erosion processes may develop.

4.1.1.2. Low-Altitude Surveys: Quantitative Linear Analysis of Trail Incision

In addition to the areal monitoring carried out through high-altitude flights, several low-altitude UAV surveys were conducted along selected trail sections in order to obtain high-resolution terrain models suitable for quantitative analysis of erosion processes. These surveys were performed by flying the UAV at low altitude along the trail axis, allowing the acquisition of dense image blocks and the generation of Digital Terrain Models (DTMs) with centimetric or sub-centimetric spatial resolution. The primary objective of this approach is to enable multi-temporal comparisons of terrain morphology by analysing DTMs generated from surveys conducted in different epochs. After co-registration of the models, elevation differences between the surfaces can be calculated, allowing the identification of localized erosion or deposition patterns along the trail corridor.

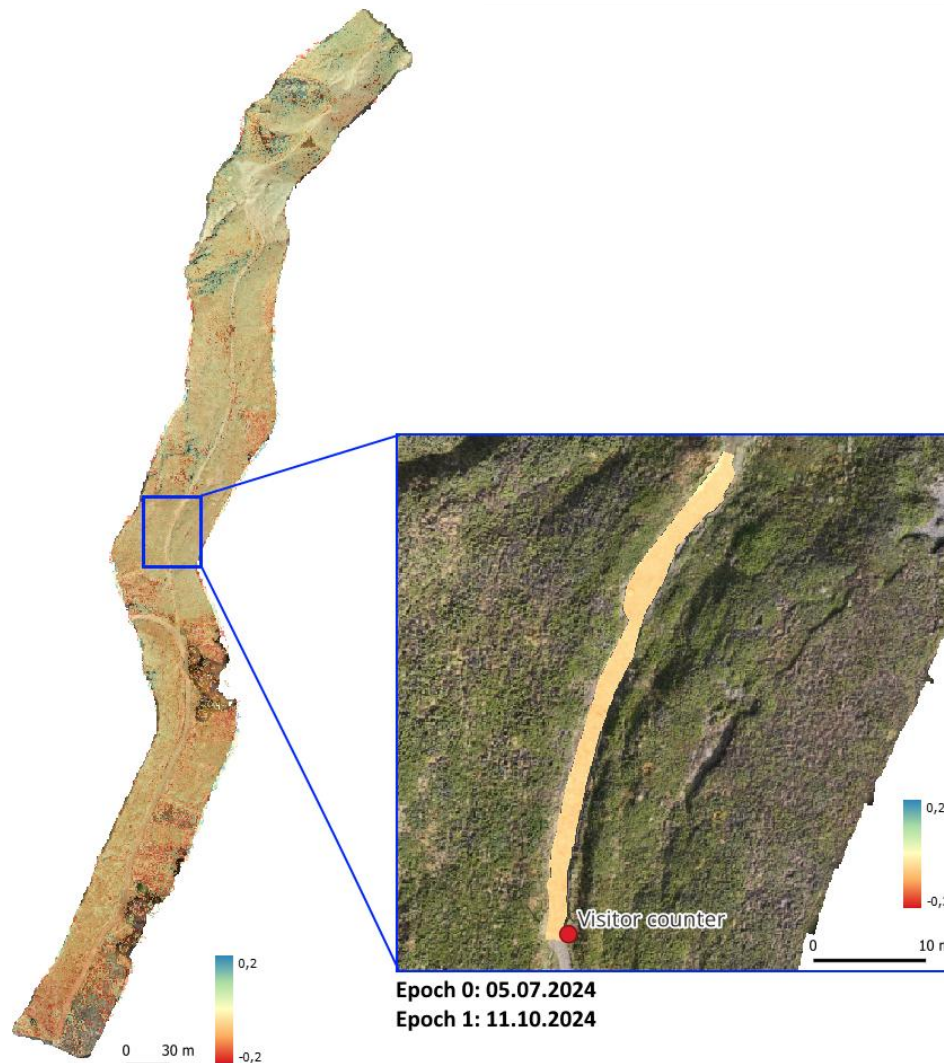


Figure 46. Elevation differences assessed from a multi-temporal comparison between two DTMs collected on July 2024 and October 2024, with a focus on a specific section of the trail close to a visitor counter – Pilot site: Mount Cusna, Lama Lite pass

The effectiveness of low-altitude UAV surveys for quantitative terrain analysis is clearly illustrated by the case study conducted at the Lama Lite Pass. The comparison between DTMs acquired in different epochs allows detailed assessment of surface changes along the monitored trail segment. The DTM difference map (Figure 46) highlights spatial patterns of erosion and deposition along the trail corridor. Negative values (erosion) are mainly concentrated along the central path, where repeated foot traffic causes progressive surface lowering.

A more detailed interpretation is provided by the extraction of transverse elevation profiles along selected sections of the trail (Figure 47). The comparison between profiles derived from two different acquisition dates (July and October 2024) shows a consistent lowering of the trail surface in all analysed sections. In particular, the central portion of the trail exhibits a clear incision, with vertical differences reaching approximately 5 cm, while the lateral areas show minor variations. The shape of the profiles also indicates a progressive increase in cross-sectional asymmetry, suggesting that erosion is not uniformly distributed but influenced by local slope conditions and preferential flow paths. In some sections, the displacement of material toward one side of the trail is clearly visible, reflecting the combined effect of trampling and surface runoff.

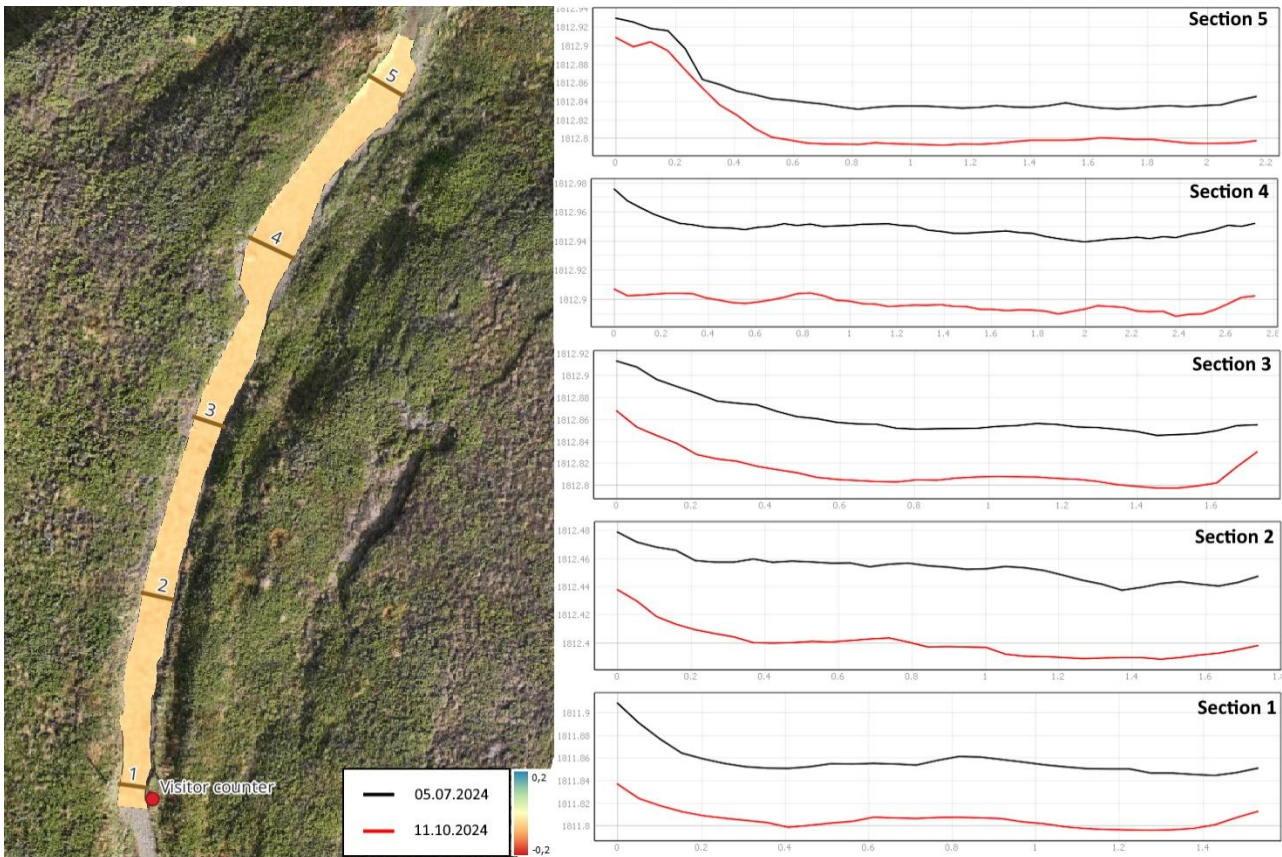


Figure 47. Profile variation in five different sections – Pilot site: Mount Cusna, Lama Lite pass

Multi-temporal UAV-derived Digital Terrain Models also enable the estimation of volumetric changes, providing an integrated measure of soil loss and material redistribution within selected areas. The Val Parma case study, specifically the low altitude flight on the trail leading to the Marmagna Saddle, provides a clear example of this approach. A focused analysis was conducted on a selected trail segment (Figure 48), where elevation differences were integrated to estimate the total volume of removed material with a dedicated QGIS utility. The resulting value of approximately 2.97 m³ provides a direct measure of soil loss associated with the analyzed portion of the trail; by evaluating the area of the selected segment, which amounts to 55 m², gives an average soil loss value of 5.4 cm/m² during the considered time span.

The integration of DTM differencing and profile analysis provides a comprehensive understanding of trail evolution. While difference maps allow the spatial distribution of changes to be identified, profile comparisons enable a more precise quantification of morphological modifications. Together, these approaches confirm that low-altitude UAV surveys can effectively capture small-scale erosion processes and support detailed monitoring of trail degradation over time.

It is important to note that not all elevation differences correspond to actual soil loss. Leaf accumulation, displaced stones, organic debris, or small branches may generate artificial positive signals in DTM differencing. For this reason, visual cross-validation with orthophotos is recommended.

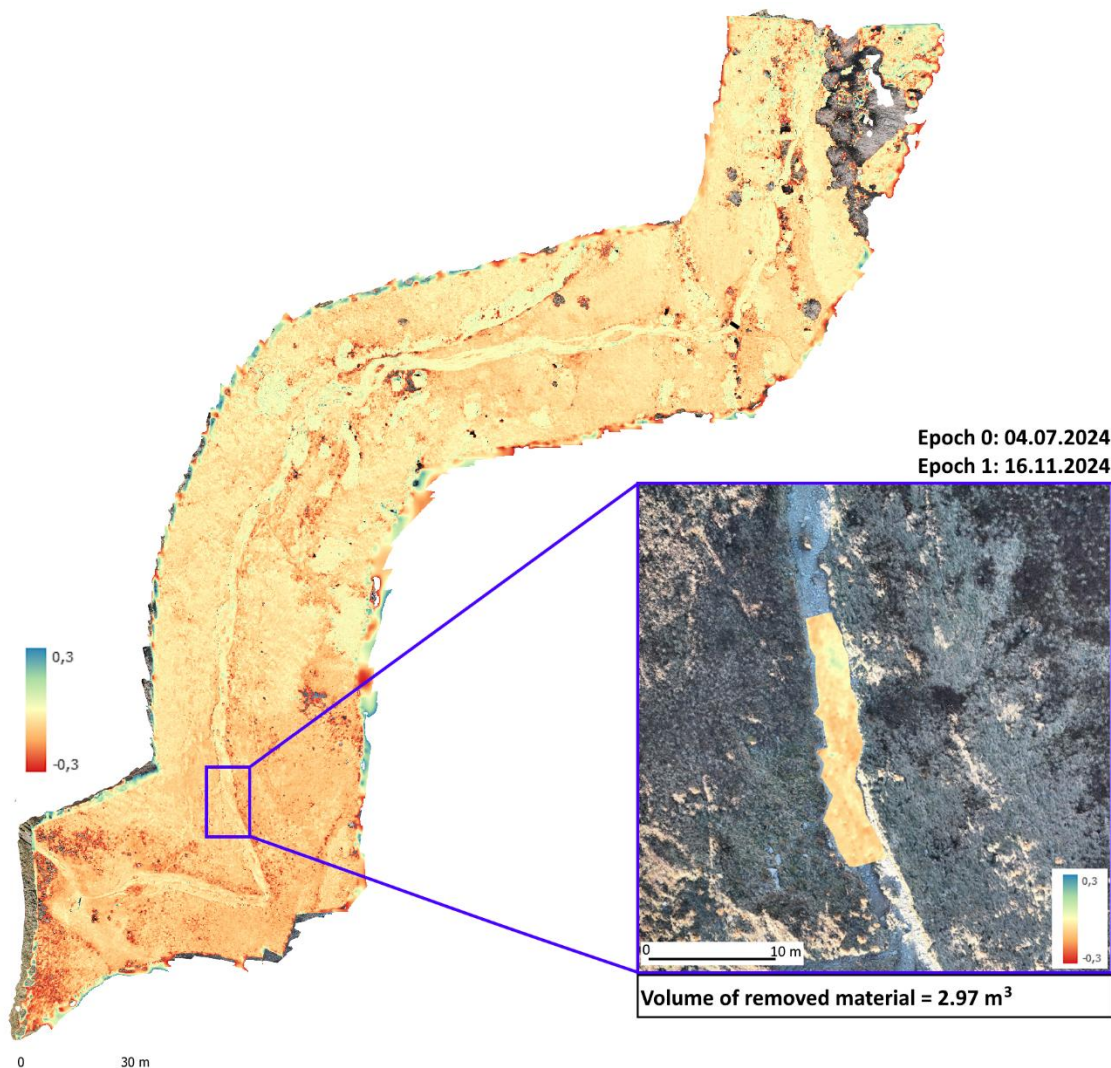


Figure 48. Elevation differences assessed from a multi-temporal comparison between two DTMs collected on July 2024 and October 2024, with a focus on a specific section of the trail for the determination of volumetric changes – Pilot site: Val Parma

4.1.2. Conclusions and Recommendations

The monitoring activities carried out within the selected pilot sites demonstrate the effectiveness of UAV-based photogrammetry as a flexible and scalable tool for analysing trail degradation processes in protected mountain environments. By integrating surveys conducted at different spatial scales, the adopted methodology allows both the spatial distribution and the physical magnitude of tourist-induced impacts to be investigated.

High-altitude UAV surveys proved particularly useful for providing a comprehensive overview of the monitored areas and for identifying zones where visitor pressure generates visible surface disturbance. The comparison of multi-temporal orthophotos makes it possible to detect trampling patterns, trail widening, and the formation of informal paths, even in environments where vertical terrain changes remain limited. In this context, orthophotos represent a valuable reference layer for assessing the correspondence between the official trail network and the actual routes used by visitors, as shown in the case of the Lago Bargetana area.

Low-altitude UAV surveys complement this approach by enabling a more detailed analysis of terrain morphology along selected trail segments. The generation of high-resolution Digital Terrain Models allows multi-temporal comparisons to be performed with sufficient precision to identify localized changes in the



trail profile. Through the extraction of longitudinal and transverse elevation profiles, it becomes possible to quantify how repeated pedestrian or cycling activity gradually modifies the cross-sectional shape of the trail, producing incision, lateral sediment displacement, and progressive surface deformation.

In addition to profile-based analyses, the comparison of DTMs acquired in different epochs also allows the estimation of volumetric changes within selected areas. This approach provides a more comprehensive indicator of erosion intensity, as it considers the overall balance between material loss and deposition rather than isolated elevation differences. The case study conducted in the Monte Cusna - Lama Lite Pass area demonstrates how this type of analysis can be used to quantify terrain alterations associated with concentrated visitor activity.

From a broader perspective, the results confirm that trail degradation processes often develop gradually through the interaction between trampling, vegetation disturbance, and sediment redistribution. Early stages of impact are typically expressed through surface disturbance detectable in orthophotos, while more advanced stages involve measurable morphological changes that can be captured through detailed DTM comparisons. The combined use of high- and low-altitude UAV surveys therefore provides a robust methodological framework for monitoring recreational impacts in protected areas. This approach supports a more complete understanding of how visitor pressure influences trail conditions over time thanks to the multi-scale analysis of the relevant areas. These outcomes contributed to the publication of a scientific paper, authored by University of Parma members, that explores and underlines the advantages of this kind of approach to investigate erosion effects on mountain areas¹.

Future monitoring campaigns will further extend the available time series of observations, improving the ability to detect long-term trends and seasonal variability. The continued integration of multi-temporal UAV datasets will also facilitate the development of more advanced analytical approaches, including automated change detection and improved volumetric estimation of erosion processes. These developments will contribute to strengthening the scientific basis for trail management and conservation strategies within the park.

4.2. UAV-based LiDAR survey

Protected Area: Malá Fatra National Park

Project Partner: UNIZA

The activity consisted of monitoring the deformation of hiking trails. Data collection for this study was performed using the Lidaretto system, specifically a configuration mounted on a DJI Matrice 300 RTK drone (Figure 49). The system integrates a LiDAR sensor manufactured by Hesai together with a GNSS receiver and an inertial measurement unit (IMU). One measurement epoch consisted of a continuous flight over the observed locality. The flight sequence consisted of several phases. The initial phase included static system initialization, during which the system was powered on and allowed time for GNSS stabilization, together with verification of HDOP/PDOP values. This was followed by a dynamic excitation phase, consisting of periodic movement of the platform within the selected locality. In this study, the maneuver was performed in a figure-eight pattern. The purpose of this phase was to stabilize the IMU solution and improve GNSS/IMU sensor fusion. The next phase consisted of the actual data acquisition. Data were collected at a speed not exceeding 6 m/s and at a flight altitude of up to 40 m. Each locality was surveyed according to a predefined flight plan passing directly above the hiking trails, with data collected in both directions (forward and backward).

¹ Bruno N., Valletta A., Segalini A., Roncella R. (2024) Low-cost techniques for soil erosion monitoring on mountain trails. International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences XLVIII-2/W8-2024, 53-60. <https://doi.org/10.5194/isprs-archives-XLVIII-2-W8-2024-53-2024>

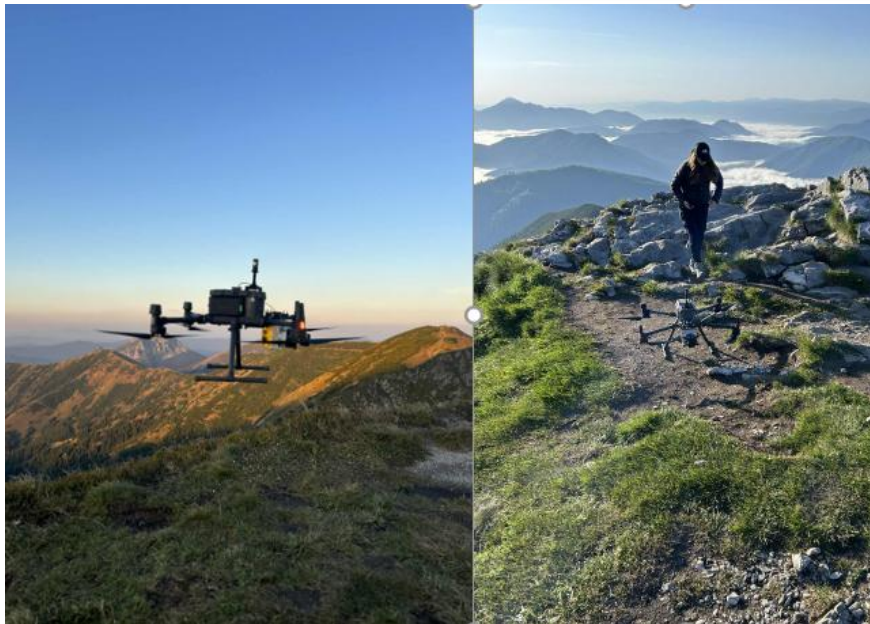


Figure 49. Lidareto Measuring System deployed on site

After the main data acquisition phase, a repeated IMU stabilization phase was performed. Once the drone landed, the acquisition sequence was completed with a final static phase to ensure GNSS stabilization. For this study, selected segments of hiking trails in Malá Fatra National Park were chosen for testing. Individual trail segments were selected based on specific attributes. Four localities were selected: Chleb, Velký Kriváň, Kopiská, and Chrapáky. Their names are derived from local toponyms or from the mountain peaks to which the trails lead. The Chleb and Velký Kriváň localities belong to the most frequently visited areas of the national park, partly due to the presence of a cable car operating in the saddle between these sections. From a geological and geomorphological perspective, these areas are underlain by limestone, dolomite, and quartzite, with occurrences of black limestones interbedded with gray dolomites. These locations are characterized by shallow soils, which increases the importance of capturing and preventing surface erosion processes.

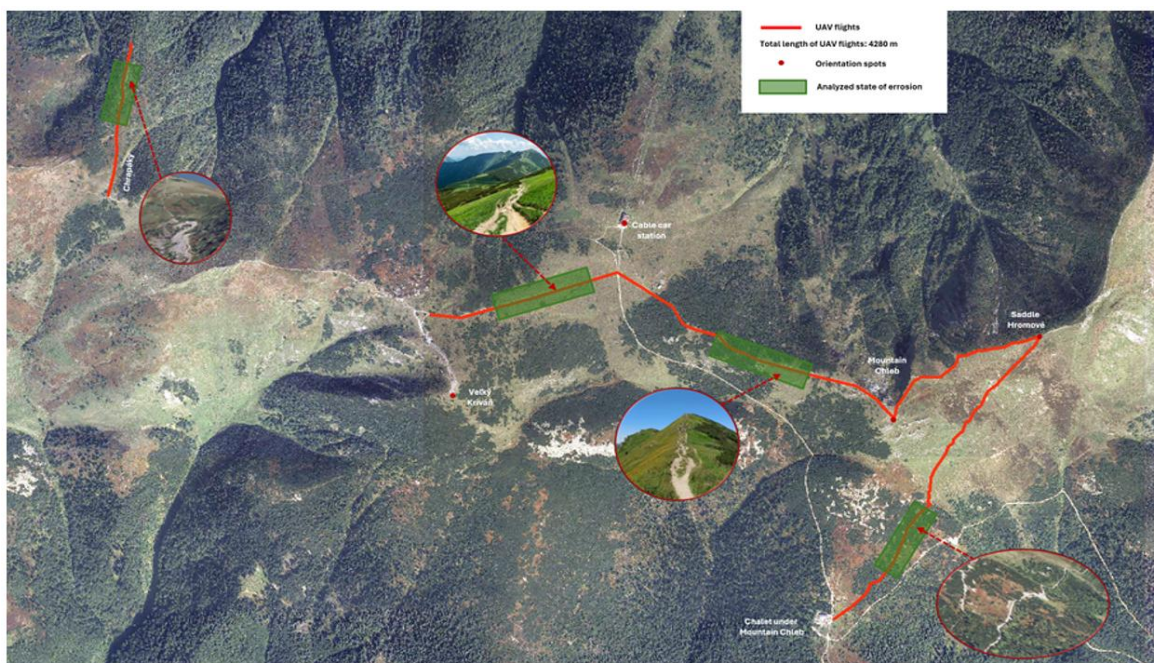


Figure 50. Observed locations



The Kopiská and Chrapáky localities (Figure 50) were selected primarily due to their specific slope conditions and geological substrate, which influence the occurrence and intensity of surface erosion. In these cases, the trails are located on steep slopes (approximately 20% on average) with a nappe structure that contains shear planes and debris zones, making them particularly susceptible to erosion. Measurements processed in this study were conducted in September 2023, May 2024, September 2024, and October 2025. The aim was to capture the condition of the sites at the end of the hiking season and before its beginning, in order to identify seasonal changes. Although there is no official winter closure in the area, the intensity of tourism from October to April is significantly lower than during the summer months.

The acquisition process produced a raw dataset consisting of LiDAR data, raw GNSS data combined with IMU measurements for trajectory computation, and RINEX data obtained from the SKPOS network service used for correction calculations. Data processing was performed in several software environments. The first step involved processing in Inertial Explorer, whose role was to compute the trajectory of the measurement system. Subsequently, in the Lidareto Creator environment, the LiDAR measurements were time-synchronized with the computed trajectory and known orientation, and a point cloud was generated in the Slovak reference coordinate system S-JTSK. The resulting point cloud was then exported for further analysis. During post-processing, only data located within a 90 m radius from the LiDAR sensor were calculated and exported. The dataset was subsequently clipped to predefined areas of interest, where deformation and changes were analyzed.

4.2.1. Results, Assessment, and Interpretation

The accuracy of the resulting point cloud primarily depends on the IMU technology, and therefore directly on the accuracy of the computed trajectory. The manufacturer Lidareto specifies the following system parameters:

- Hesai XT32M2X LiDAR - 32 channels, maximum range 300 m, typical ranging accuracy ± 1 cm, up to three returns
- NOVATEL OEM7 GNSS receiver - supports GPS, GLONASS, Galileo, and BeiDou signals with post-processing accuracy of 1-2 cm
- MEMS IMU integrated in the SPAN solution - post-processing accuracy (heading/pitch/roll) $0.010^\circ / 0.005^\circ / 0.005^\circ$

Under the defined conditions, the internal accuracy of the resulting point cloud did not exceed 3.3 cm.

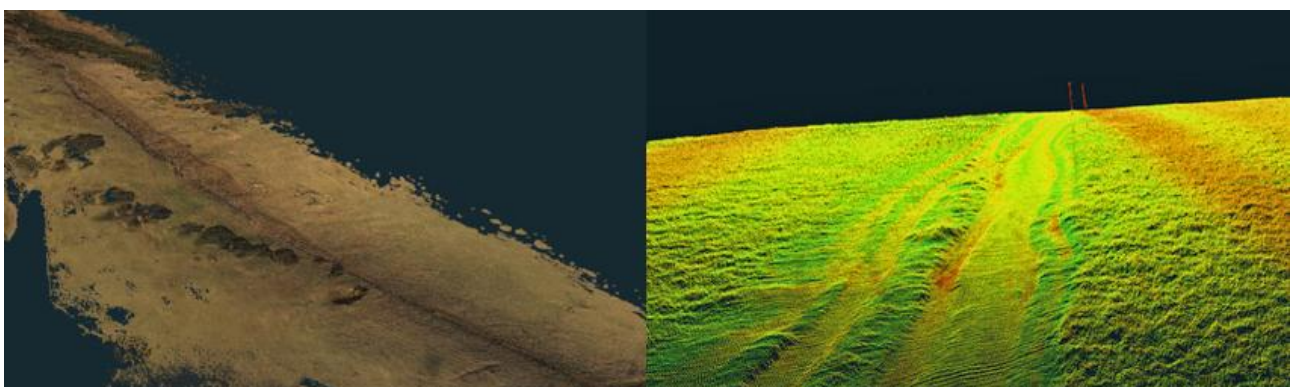


Figure 51. Resulting point cloud

During the processing and comparison of the results, several important findings emerged. One of the key observations is that the system is capable of detecting deformations exceeding several centimeters. Based on the obtained results, changes of 6 cm or more can be considered reliable and distinguishable from measurement uncertainty. However, the results are influenced by systematic effects, which should ideally be eliminated through mathematical corrections. The most significant of these is a systematic shift of the



entire point cloud. Although the point cloud exhibits an internal accuracy of approximately 3.3 cm, its external accuracy, which is associated with georeferencing, is lower and introduces a systematic influence affecting the entire dataset. For this reason, when calculating differences between two point clouds, the resulting discrepancy should be divided into two components: systematic and random effects. The systematic component is primarily caused by georeferencing errors and other systematic influences. This error can be mitigated through appropriate post-processing and mathematical corrections, such as applying a seven-parameter transformation.

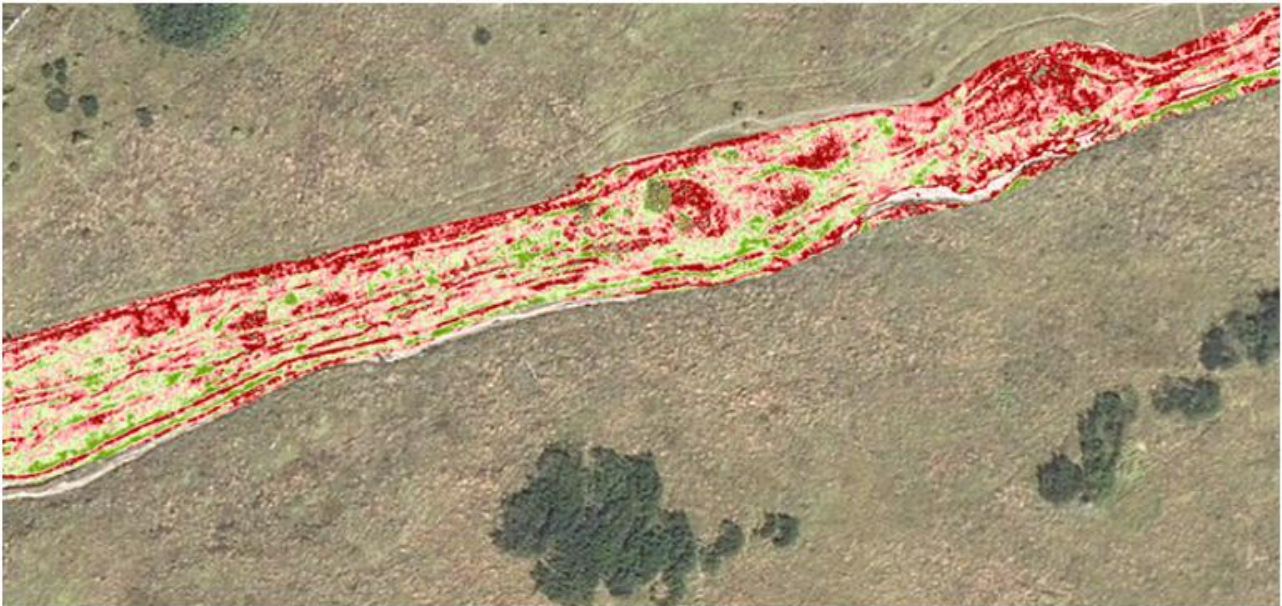


Figure 52. Example of the deformation between two epochs (Sep. 2023, May 2024)

After removing systematic effects, the remaining random component represents the actual terrain changes occurring between individual measurement epochs (Figure 52). The results indicate that deformation tends to occur primarily in locations where the terrain surface is elevated relative to the previous trail surface. However, based on the current number of measurement epochs, it is not yet possible to reliably quantify the individual influence of tourism intensity and weather conditions on the observed erosion processes. Nevertheless, the results suggest a correlation between the magnitude of deformation and weather conditions during the season.

4.2.2. Conclusions and Recommendations

The applied methodology based on UAV-mounted LiDAR proved to be suitable for monitoring morphological changes and deformation of hiking trails. The system demonstrated the ability to reliably detect terrain changes exceeding approximately 6 cm, which confirms its applicability for monitoring erosion processes and surface deformation in mountainous environments. The high density of the resulting point cloud and the internal precision of approximately 3.3 cm allow for detailed spatial analysis of trail surfaces. However, the results also indicate that systematic influences related mainly to georeferencing can affect the interpretation of detected changes. After appropriate correction of these systematic shifts, the method provides a reliable basis for identifying real terrain changes between measurement epochs.

Future data acquisition could benefit from more frequent measurement epochs, ideally capturing conditions both before and after the main hiking season as well as after significant precipitation events. Increasing the temporal resolution of measurements would help better distinguish between seasonal erosion processes and short-term changes caused by weather extremes. In addition, maintaining consistent flight parameters and acquisition geometry across all epochs is essential for minimizing systematic discrepancies between datasets. The use of additional ground control points or reference surfaces could further improve georeferencing stability and reduce systematic shifts in the resulting point clouds. Further analytical



improvements may include more advanced point cloud alignment and normalization techniques to minimize systematic errors before deformation analysis. Applying robust co-registration methods, including iterative closest point (ICP) or multi-scale cloud comparison algorithms, could increase the reliability of change detection. Additionally, separating systematic and random components of differences between point clouds should remain a key analytical step, as the random component represents the actual terrain deformation. Integrating statistical analysis or spatial modelling techniques could also help quantify the relationship between detected deformation patterns and environmental factors such as weather conditions or tourist activity.

4.3. UAV photogrammetry for informal trail detection

Protected Area: Lower Kamenjak

Project Partners: UNIPR, PIK

The monitoring activity carried out at the Kamenjak pilot site focused on assessing the impact of visitor pressure on protected dry grassland ecosystems, with particular attention to the formation of informal trails and soil degradation processes. Unlike mountain trail environments, where erosion is often expressed through vertical incision, dry grasslands are primarily affected by surface trampling, vegetation disturbance, and soil fragmentation. These processes progressively alter habitat structure and reduce vegetation cover. The main objective of the monitoring activity was therefore to identify critical areas of trail formation and surface disturbance, rather than to quantify detailed volumetric erosion. The focus was placed on detecting spatial patterns of human-induced impact and understanding how visitor movement modifies the landscape over time.

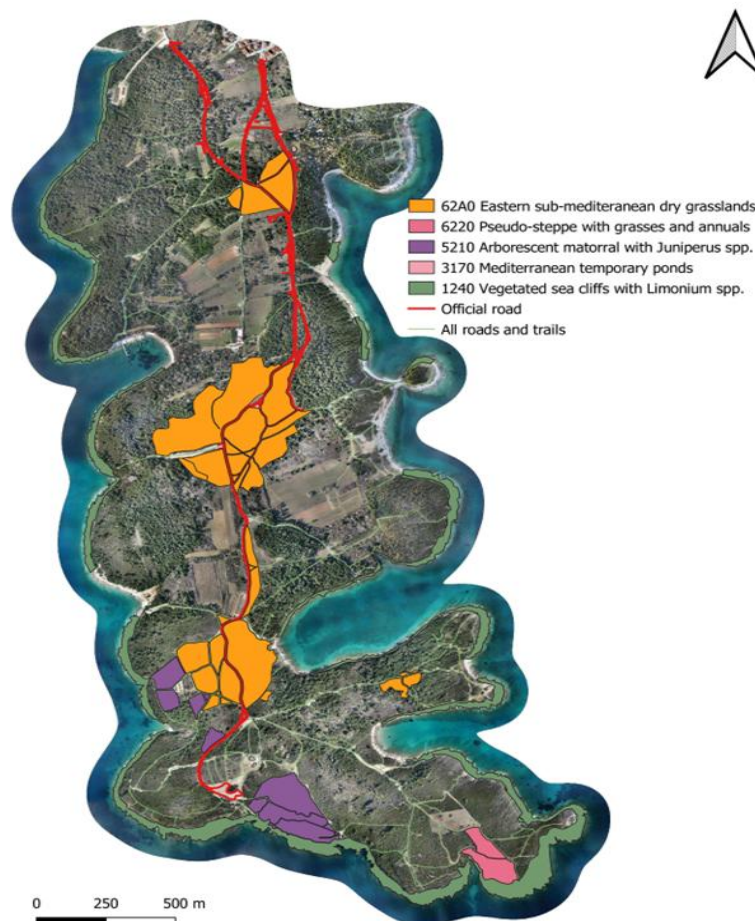


Figure 53. Overview of relevant areas in the Lower Kamenjak region



The monitoring framework was based on low-altitude UAV photogrammetric surveys conducted over five selected areas within the Lower Kamenjak region (Figure 53). These areas were chosen to represent different levels of visitor pressure and varying degrees of existing disturbance within the protected grassland environment. The monitoring activity was structured following a multi-temporal approach, and the analysis focused primarily on orthophoto comparison, as this approach proved most effective for detecting trampling-related changes in grassland environments.

4.3.1. Results, assessment, and interpretation

The comparison of orthophotos acquired in different epochs clearly highlights the progressive formation of informal trails across the monitored grassland areas. In several locations, areas that initially showed continuous vegetation cover evolved into visible linear features corresponding to repeated pedestrian movement. These paths are typically not aligned with the official trail network and tend to develop as shortcuts between existing routes or as direct access paths to points of interest.

A representative example of the monitoring results is provided by Site A, the closest one to the entrance, where the UAV-derived orthophoto was compared with the officially mapped road network (Figure 54). The official paths, shown in red, correspond to the main access routes and are clearly identifiable in the orthophoto. At the same time, the high spatial resolution of the UAV data reveals a significantly more complex pattern of surface use. Several informal trails can be identified within the surrounding vegetated areas (yellow dashed lines), which are not included in the official mapping. These “wild” trails form a dense network of connections between the main routes, often cutting across the grassland to create shortcuts or alternative access paths. The spatial pattern suggests that visitor movement is strongly influenced by access nodes, resulting in radiating path systems that extend from high-use areas.

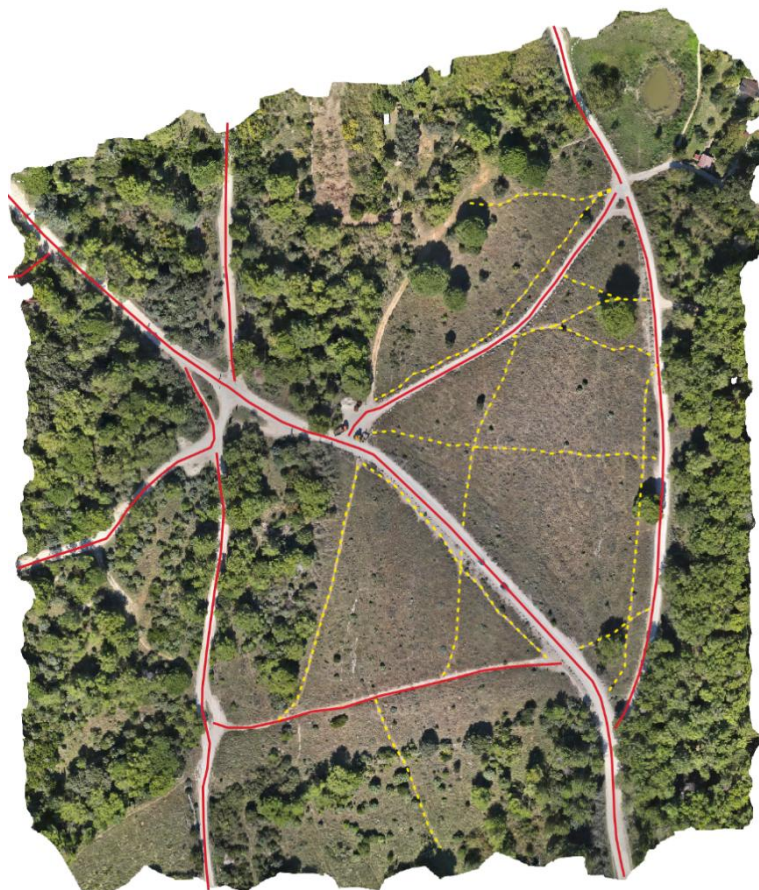


Figure 54. Overlapping between official roads and orthophoto surveyed in Site A for the identification of unofficial paths



The multi-temporal comparison of orthophotos (Figure 55) further highlights the dynamic nature of these processes. Between the first acquisition (September 2023) and subsequent monitoring campaigns, several changes can be observed. Some informal paths become progressively more visible and continuous, indicating repeated use and vegetation degradation, while others appear to partially recover depending on seasonal conditions. In particular, the central grassland area shows a gradual increase in the density and continuity of disturbance features, suggesting an intensification of trampling. These observations confirm that informal trail networks evolve over time and may stabilize if visitor pressure persists.

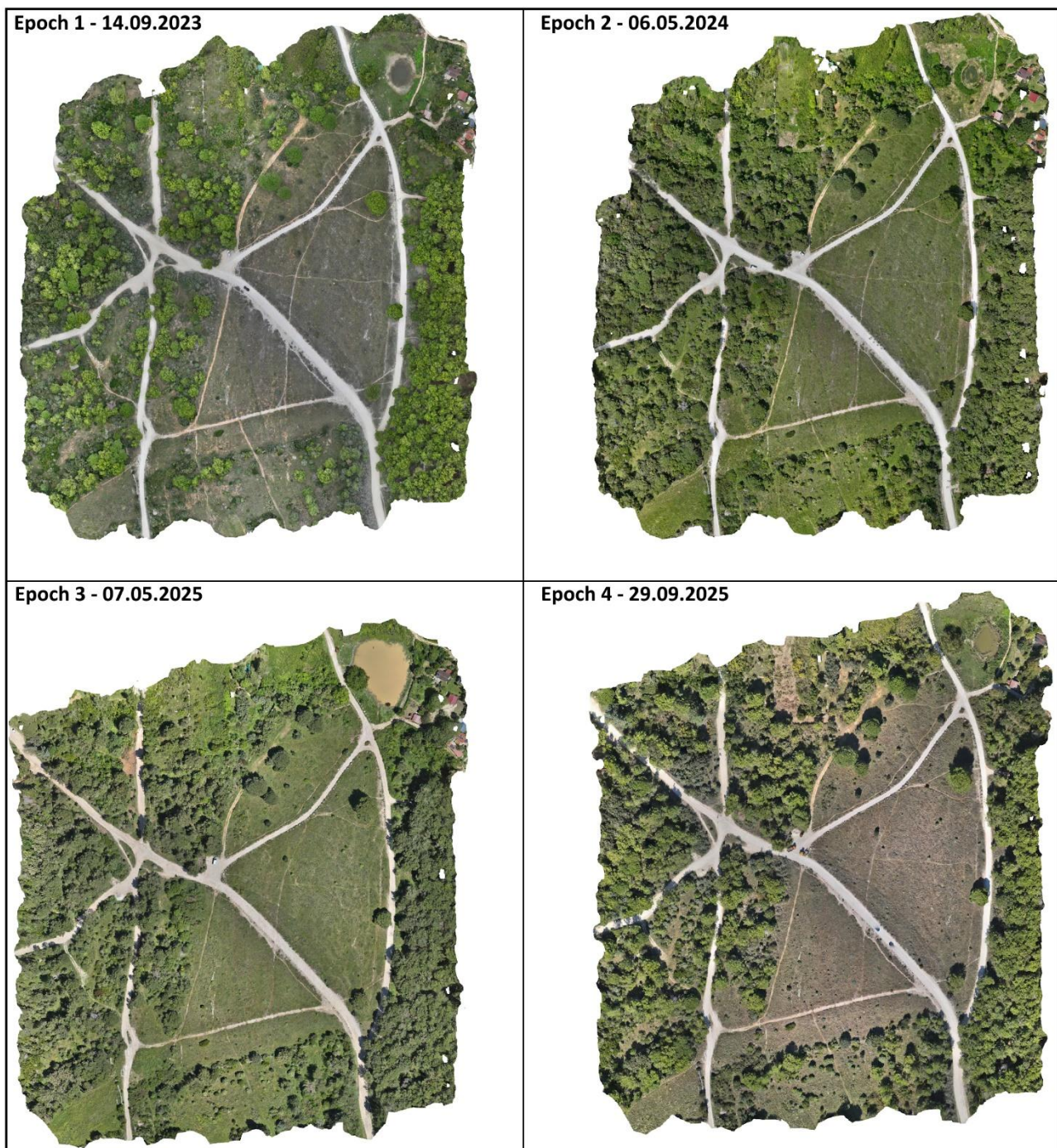


Figure 55. Multi-temporal comparison between orthophotos collected at Site A

A complementary example is provided by Site D, located towards the end of the peninsular area, which represents a more structured and heavily used area located near a parking zone (Figure 56). Compared to



Site A, this site shows a stronger interaction between formal infrastructure and informal movement patterns. The orthophoto comparison highlights both seasonal variability and longer-term changes in surface conditions. The area shows an initial presence of multiple informal paths and bare soil zones, followed by partial vegetation recovery likely linked to seasonal regrowth. However, this recovery is not persistent, as subsequent observations reveal a renewed expansion of disturbed surfaces.

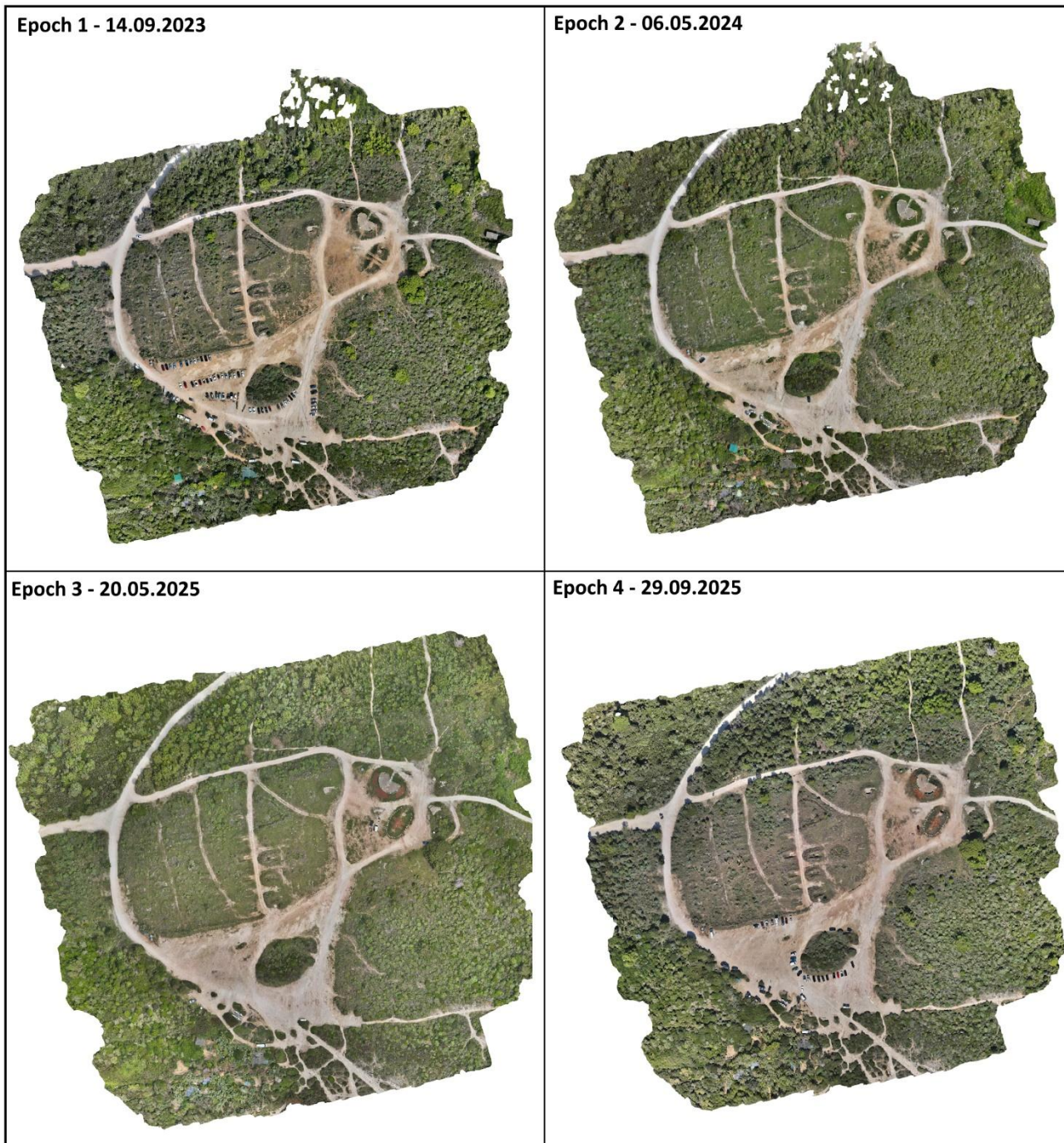


Figure 56. Multi-temporal comparison between orthophotos collected at Site D

4.3.2. Conclusions and recommendations

The monitoring activity carried out at the Kamenjak pilot site demonstrates the effectiveness of UAV-based photogrammetry for assessing visitor-induced impacts on protected dry grasslands.



In parallel, a topographic control network was established along the trail to assess the potential geometric robustness of models derived from spherical imaging. These analyses are currently ongoing and represent a key direction for future development. At present, the method is primarily used for qualitative interpretation, focusing on visual inspection of trail conditions and surrounding environments.

4.4.1. Results, Assessment, and Interpretation

For the purposes of the present analysis, a subset of 149 panoramic images was selected from the full dataset, which includes more than 1300 equirectangular images. This subset provides effective spatial coverage of the entire trail segment and allows efficient evaluation of trail and environmental conditions, while significantly reducing data handling and processing requirements. Each panoramic image is associated with spatial and temporal metadata, including coordinates, altitude, acquisition date, and survey identification. This allows the dataset to be integrated within a broader monitoring framework. The dataset is therefore represented within an interactive visualization system (part of the Humanita dashboard) where each acquisition point is georeferenced and linked to its corresponding panoramic image (Figure 58).

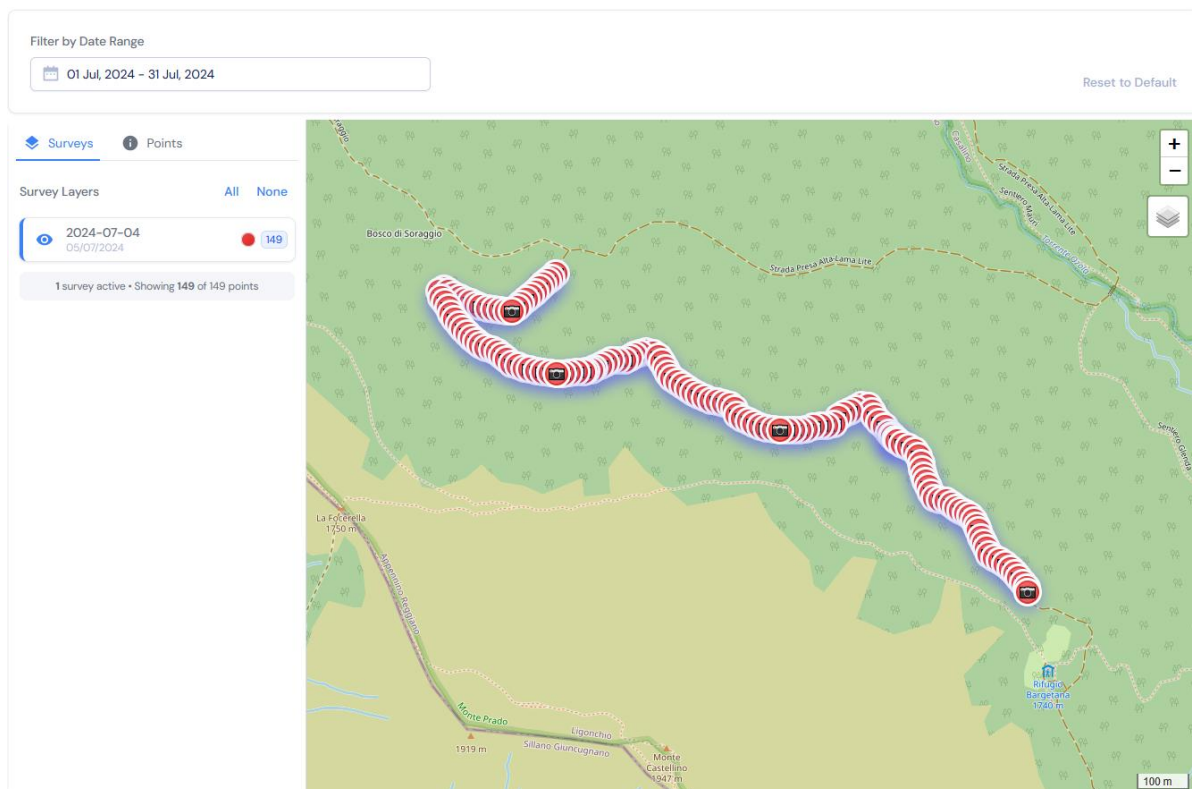


Figure 58. Georeferenced markers corresponding to each equirectangular image of the spherical imaging survey

The interface allows users to filter surveys by date and visualize the spatial distribution of acquisition points, providing an immediate overview of coverage along the monitored segment. By selecting a point, the system opens a **360° panoramic viewer**, where the image can be explored interactively. Users can rotate the view, zoom in, and examine the full surroundings of the acquisition point. Metadata such as coordinates, altitude, and acquisition date are displayed alongside the image.

The panoramic imagery collected along the Monte Cusna trail reveals a wide range of conditions reflecting both anthropogenic impacts and natural processes. In several sections, the trail surface shows clear signs of **mechanical degradation**, particularly in areas affected by vehicle passage (Figure 59). These zones are characterized by surface incision, compaction, and exposure of coarse material, indicating a significant impact on the trail conditions. Such conditions can highlight specific segments where maintenance interventions may be required.

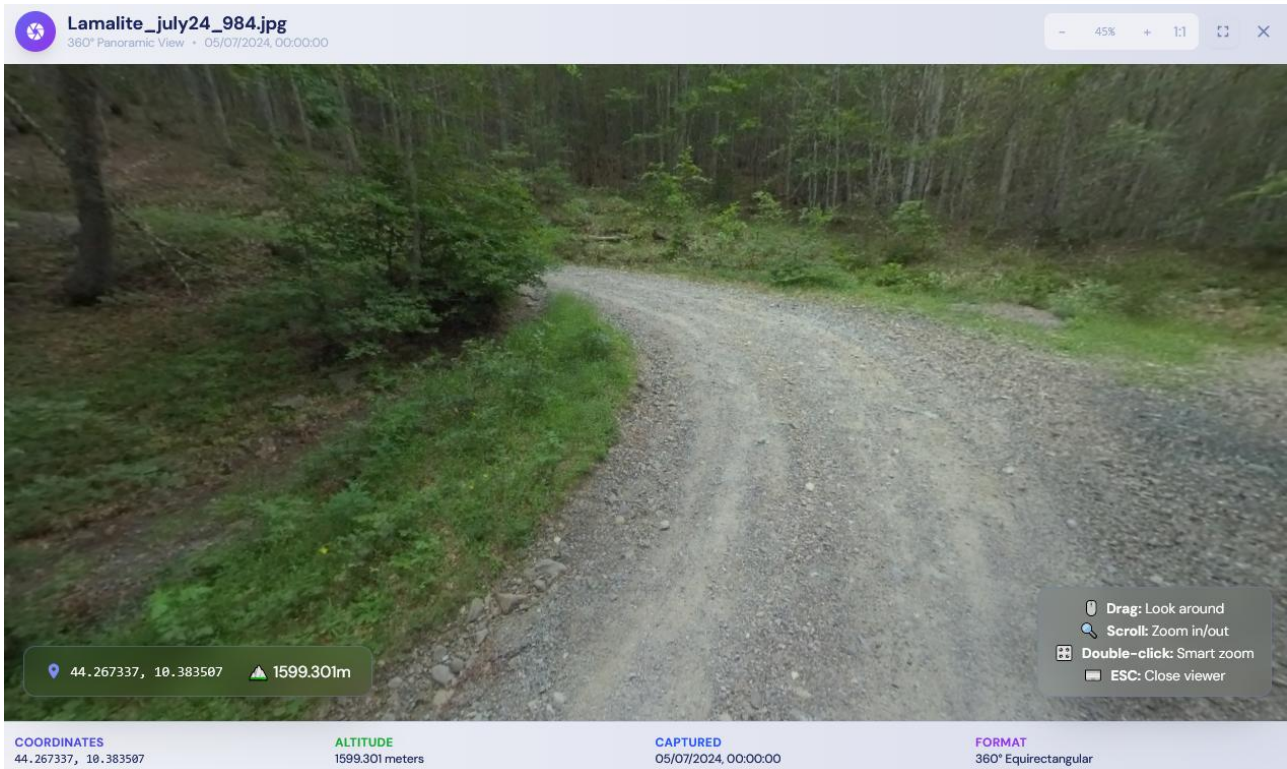


Figure 59. Example of trail degradation captured through spherical imaging

In addition to direct trail impacts, the imagery also documents **erosion processes in the surrounding environment** (Figure 60). Localized soil displacement, small-scale slope instability, and exposed roots can be observed adjacent to the trail. Although these features are not always directly linked to visitor activity, they provide important context for understanding broader landscape dynamics.

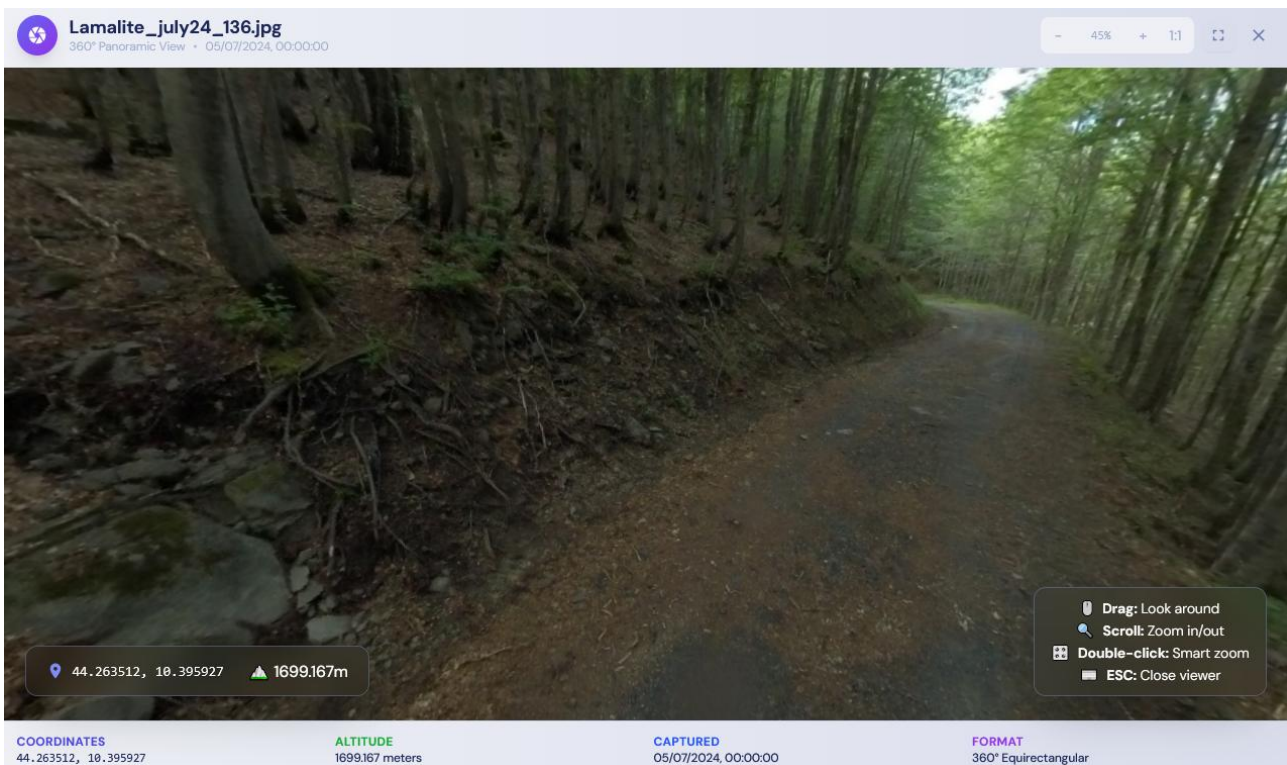


Figure 60. Example of erosion processes in the surrounding environment close to the road



4.4.2. Conclusions and Recommendations

The spherical imaging activity carried out at the Monte Cusna pilot site demonstrates the potential of ground-based panoramic acquisition as a valuable component of trail monitoring systems. The results confirm that spherical imaging is particularly effective in forested and densely vegetated environments, where UAV-based surveys may be limited by canopy cover and reduced visibility of ground features. While aerial photogrammetry provides accurate terrain models from above, spherical imaging captures the environment from a ground-level perspective, enabling detailed observation of vertical features such as embankments, drainage channels, and vegetation structure.

Preliminary results also indicate the potential for extending this methodology toward quantitative applications. The availability of a topographic control network and the dense acquisition geometry suggest that spherical datasets could be used to generate 3D models and perform comparisons between different epochs. Although these applications are still under investigation, they represent a promising direction for integrating spherical imaging within a more comprehensive monitoring framework that combines qualitative and quantitative approaches.

4.5. Mean soil erosion rate assessment with dendrochronological techniques

Protected Area: Tuscan-Emilian Apennine National Park

Project Partner: UNIPR

The research activities carried out focused on an experimental study assessing the soil erosion process in a natural environment subject to tourist frequentation. The main objective of the conducted research was to estimate the **mean soil erosion rate** over the last decades along highly frequented trails in forested sites where tree roots were visible at the surface, exposed to light/air, and trampling. To achieve this objective, an overall assessment of tree growth conditions was also performed by sampling the stems of unaffected trees of the same species of the affected ones and growing in their vicinities, in order to evaluate the possible presence of growth anomalies related to climate and climate extremes in the reference chronologies. This study was approached both through a dendrogeomorphological method, based on the microscopic analysis of growth increments and anatomical features of stem and root samples, and through a digital approach, involving the analysis of microtopographic data using GIS software.

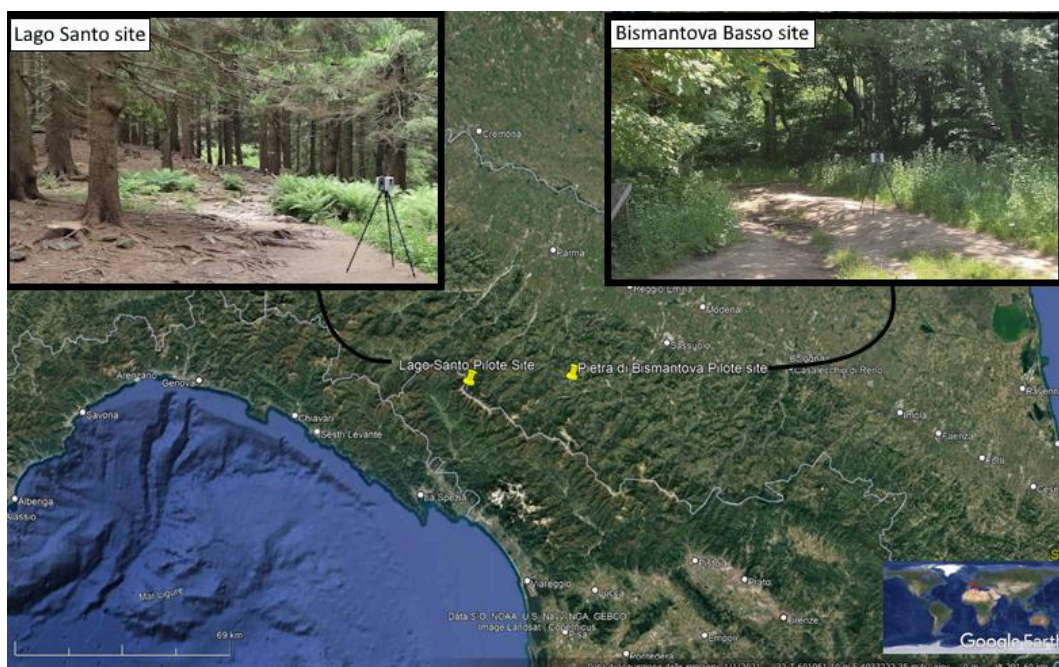


Figure 61. Pilot sites location



Two areas were selected (Figure 61), where soil erosion was evaluated along highly frequented trails:

- Pietra di Bismantova → the analysis focused on two separate sites, located in the lower (Basso site) and the upper (Alto site) portion of the forested trail leading to the top of the Pietra
- Lago Santo → a single site was identified in the area, located on the densely forested trail connecting the Lago Santo to the Marmagna saddle

Climatic conditions specific of the study sites were either reached through on-site air and soil temperature monitoring or by analyzing high-resolution temperature and precipitation series from the closest meteorological stations managed by the Regional Environmental Protection Agency (ARPAE).

4.5.1. Collected data

Microtopographical data: In order to measure the eroded surface area and root height before root sampling, it was necessary to produce a digital representation of the site's surface, technically known as a Digital Surface Model (DSM). Laser scanning techniques using a Leica RTC360 instrument and photogrammetry with a Nikon D3X camera were employed to capture high-resolution images. For the construction of high-resolution DSM models several pictures along the analysed trails have been taken as well and then processed by means of photogrammetric techniques. These images, after appropriate processing, enabled the creation of an orthophoto. This DSM was then used for microtopographic analysis via GIS software. The exact position of the roots and other elements (pebbles, outcropping rocks, small broken branches, leaves) have been identified. The codes of each root was assigned before cutting the sample.

Root samples along the trails: Small portions of roots were sampled following standardized protocols described in scientific literature². The cut of the roots was facilitated by a Metabo electric saw, and the samples were collected and coded, saving also the root orientation information. Root sampling is performed cutting a disc perpendicular to the root axis, and marking the upper portion of the root bark with a pen in order to record its position before removing the disc.

Cores from the tree stems: Cores were collected from trees of the same species found along the trail and growing in their vicinities, under the same climatic conditions. Sampling was performed following standard procedures³ using Pressler's increment borers with a Metabo impact driver equipped with WSL adapters and torque amplifier. All couples of samples extracted from each stem were coded and the location of all trees was georeferenced with a Garmin60 GPS.

Data of air and soil temperatures: These information were collected since September 13, 2023 with a frequency of 30 minutes, using Watchdog 1000 dataloggers set up and managed by the SpecWare 9 software. The sensors for air temperature allowed also the collection of relative humidity and were protected by a solar shield. The sensor for soil temperature was put at -15 cm from the surface, being the upper soil portion of soil presenting roots under normal growth conditions. As only 10'038 data is stored in the datalogger's memory, data download in the field has been repeated at least two times per year. Moreover, also the batteries were replaced when necessary. Series of daily temperature (max and min), total daily precipitation, half-hour total precipitation were downloaded from external database, in order to complete the overall assessment of the climatic conditions at the study sites also in the past years, up to 2010. The closest meteorological stations were Castelnovo Ne' Monti (1.5 km horizontal distance and 310 m vertical distance from the Pietra di Bismantova pilot site) and Lagdei (1.6 km horizontal distance 330 m 310 m vertical distance from the Lago Santo pilot site).

² Bodoque J. M., Ballesteros-Cánovas J. A., Rubiales J. M., Stoffel M. (2019). Laboratory and field protocol for estimating sheet erosion rates from dendrogeomorphology. *Journal of Visualized Experiments*, 2019(143).

³ Speer J.H. (2012). *Fundamentals of tree-ring research*. University of Arizona Press, pp. 219-230



4.5.2. Results, interpretation, and assessment

4.5.2.1. Preliminary operations and methodological notes

For each type of data collected and samples, specific handling is required in order to proceed with the analysis.



Figure 62. Root sample

The root samples collected during fieldwork underwent processing at the Laboratory of Dendrochronology of University of Parma. A drying process was done by putting the samples in the oven for one week at a temperature of 60°C. This step is performed to stabilize the samples, prevent subsequent deformation, darkening, and mold growth, thereby slowing wood degradation. After drying, these root portions were cross-sectioned to obtain small discs approximately 2 cm thick, ensuring easier handling. The final phase of raw sample preparation involved belt-sanding the samples with progressively finer abrasive paper, up to P600 grit, to achieve the smoothest and flattest surface possible. This facilitated the observation and marking of annual growth rings (Figure 62).

The raw wooden cores extracted from the stems underwent the same drying process. A sharp transverse surface of the cores was obtained using the WSL core-microtome, thus allowing a clear observation of the tree rings and their measure. All samples were fixed on woody supports by gluing them (Figure 63), thus letting the following measure of the ring widths by digital imaging and under the microscope using hardware and software facilities of the Laboratory of Dendrochronology (A3 high-resolution scanner, LINTAB® Rinntech measurement table, microscope, and Tsap software). Digital measurements were performed using the CDendro and CooRecorder software, using a performant pc for image storage and handling. A series of dated ring widths was therefore obtained from each sample, with an accuracy of 1/1000 mm.



Figure 63. Silver Fir cores collected at Lago Santo pilot site

Root-exposure height is measured on horizontal or inclined surfaces while avoiding areas affected by sediment deposition or scour. Root sections are analyzed to determine anomalous wood and bark thickness, considering either high or low soil mechanical impedance, and the number of rings formed since exposure is counted. The soil erosion rate is then calculated by dividing the eroded soil thickness by the years since root exposure, applying formulas specific to the mechanical conditions of the soil.

For each sampled root, a topographic profile was constructed and the mean soil slope at both sides of the roots was obtained. Surface slope was extracted not in the vicinity of the root in order to avoid accumulation of materials at the root in the upslope direction and scour erosion at the root in the downslope direction. After determining the height of the root measured parallel to the upslope and downslope surfaces, all necessary measurements were extracted.

The methods for the construction of reference chronologies constructed for each study site, follows the standard approaches when needing to extract a common growth signal from the forest stand, thus removing individual age growth trends, biological disturbances, etc, allowing to evaluate growth patterns primarily driven by climate.

Raw growth series have been processed visually and statistically for removing potential dating errors using the COFECHA software. At each site we built a chronology by smoothing the raw series with a cubic spline with rigidity fixed at 67% of the series length using the ARSTAN software (ver. 44 h3). Detrended indexed series were obtained from each raw series by computing the ratios of measurements for each year vs. the



modelled growth. A biweight robust mean was then applied to all the indexed series finally obtaining the site chronologies. The obtained site chronologies were then truncated at sample replication < 5 cores per year.

4.5.2.2. Mean soil erosion evaluation

The microtopographic analysis was performed in GIS environment for extracting the root heights above the soil surface. A couple of cases at the Bismantova Basso site is hereafter reported (Figure 64). As evident, from these two examples, an accurate analysis of the topographic features of each roots was necessary. In all cases the erosion measurement was obtained as the mean height measured on the left and on the right of the root section, however some cases showing too anomalous conditions were removed. Also too anomalous conditions found in root samples led to the exclusion of the sample.

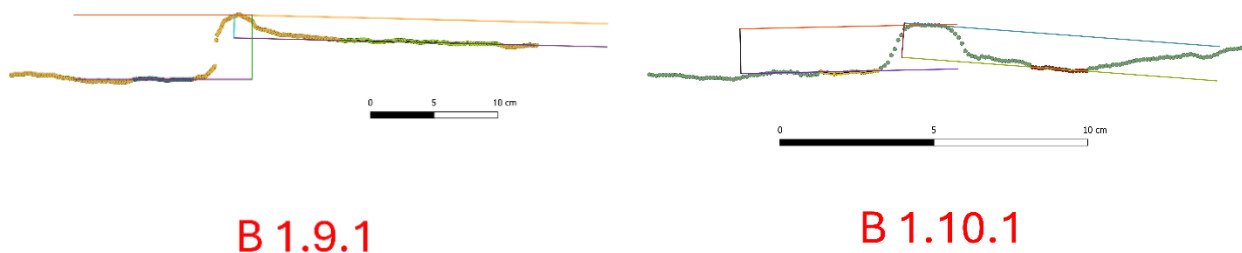


Figure 64. Two examples of root height derived from microtopographic data

The following data were obtained after measuring all topographic profiles, and measuring all the necessary root discs variables, considering the overall direction of the slope and of the roots. Data of soil erosion rate exceeding ± 1.5 standard deviation were discarded.

For the Bismantova Basso site (Table 1 and Figure 65), since roots were sampled in 2023, at this site most of them were exposed to light because of soil erosion since 2015. The first root was exposed in 2009.

Table 1. Soil erosion rate for Bismantova Basso pilot site

Root disc ID	Thickness of eroded soil (mm)	Years of root exposure (yr)	Soil erosion rate (mm/yr)
B 1.1.1	8.11	6	1.35
B 1.2.1	21.54	4	5.39
B 1.3.1	53.8	14	3.84
B 1.4.1	44.5	12	3.71
B 1.5.1	40.27	13	3.10
B 1.6.1	33.64	5	6.73
B 1.7.1*	38.58*	3*	12.86*
B 1.2.2	22.64	6	3.77
B 1.8.1	24.84	6	4.14
B 1.8.2	22.46	5	4.49
B 1.9.1	33.06	8	4.13
B 1.10.1	10.60	4	2.65
	Mean values	8	3.94
	St. deviation	3.7	1.39

* Roots not considered in the estimation of mean soil erosion rates.

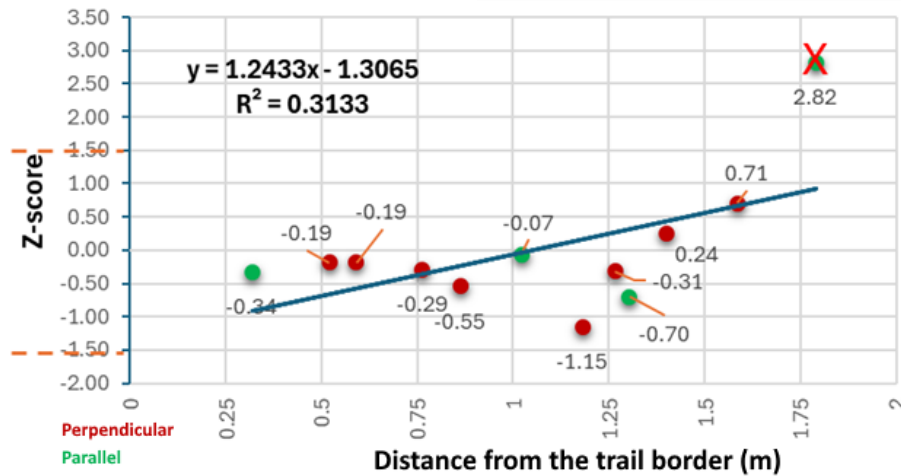


Figure 65. Soil erosion rates expressed as z-scores, and roots ordered according to their distance from the trail border (Pilot site: Bismantova Basso)

Regarding the Bismantova Alto site (Table 2 and Figure 66), since roots were sampled in 2023, at this site most of them were exposed to light because of soil erosion since 2019. The first root was exposed in 2014.

Table 2. Soil erosion rate for Bismantova Alto pilot site

Root disc ID	Thickness of eroded soil (mm)	Years of root exposure (yr)	Soil erosion rate (mm/yr)
B 2.1.1	10.41	2	5.20
B 2.2.1	48.34	9	5.37
B 2.2.2	17.78	3	5.93
B 3.1.1	19.98	5	4.00
B 3.2.1*	27.90*	4*	6.97*
B 3.3.1*	18.80*	7*	2.69*
B 3.4.1	-	-	-
B 3.5.1	15.36	4	3.84
B 3.6.1	-	-	-
B 3.7.1	9.55	2	4.77
	Mean values	4	4.85
	St. deviation	2.6	0.81

* Roots not considered in the estimation of mean soil erosion rates.

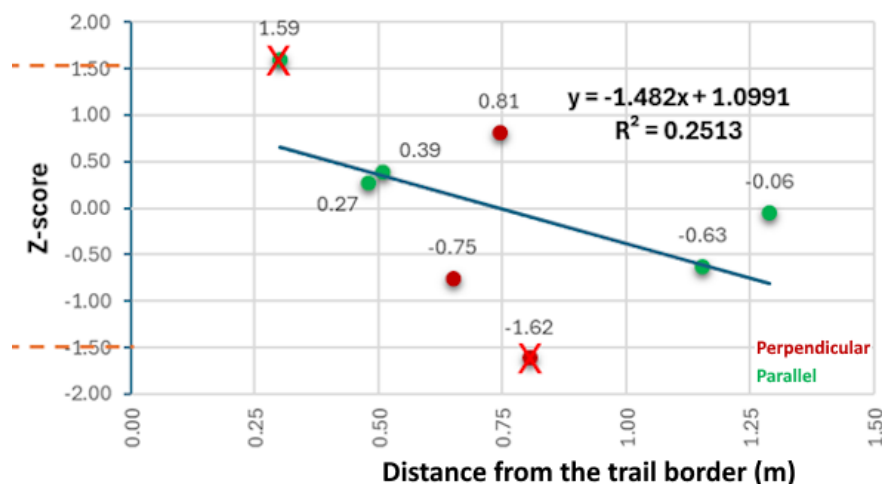


Figure 66. Soil erosion rates expressed as z-scores, and roots ordered according to their distance from the trail border (Pilot site: Bismantova Alto)



Finally, for what concern Lago Santo site (Table 3 and Figure 67), since roots were sampled in 2023, at this site most of them were exposed to light because of soil erosion since 1995. The first root was exposed in 1980.

Table 3. Soil erosion rate for Lago Santo pilot site

Root disc ID	Thickness of eroded soil (mm)	Years of root exposure (yr)	Soil erosion rate (mm/yr)
L 1.1.1	27.63	23	1.20
L 1.2.1	28.24	37	0.76
L 1.2.2	22.91	43	0.53
L 2.1.1	23.21	15	1.55
L 2.2.1	17.64	31	0.57
L 2.2.2	19.46	21	0.93
L 2.3.1*	36.94*	19*	1.94*
L 2.4.1	25.85	20	1.29
L 2.5.1	21.88	38	0.58
L 2.6.1	39.57	25	1.58
	Mean values	28	1.00
	St. deviation	9.6	0.42

* Roots not considered in the estimation of mean soil erosion rates.

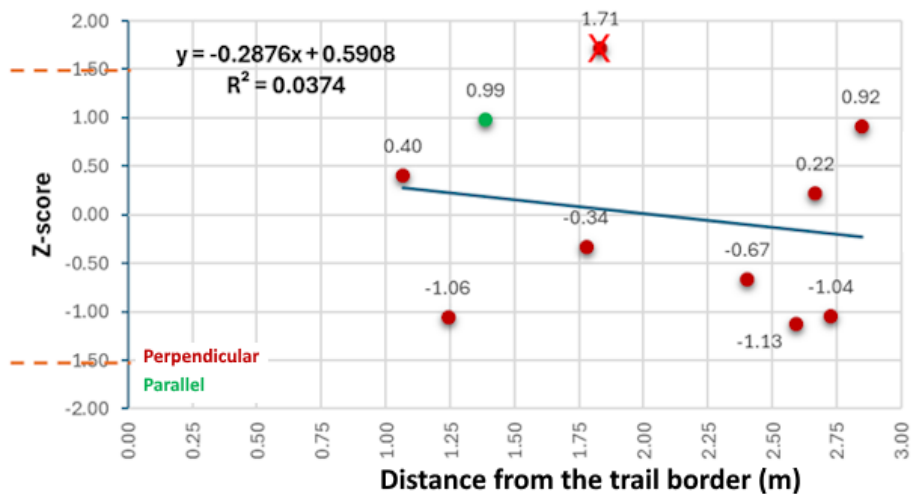


Figure 67. Soil erosion rates expressed as z-scores, and roots ordered according to their distance from the trail border (Pilot site: Lago Santo)

Outcomes of the analyses, namely the years of root exposure and the mean soil erosion rate for each pilot site are reported in Figure 68. Overall, at the two pilot sites we obtained contrasting results for what concerns the years of root exposure and of mean soil erosion rates. Within the Bismantova site, however the two subsites evidenced similar environmental conditions.

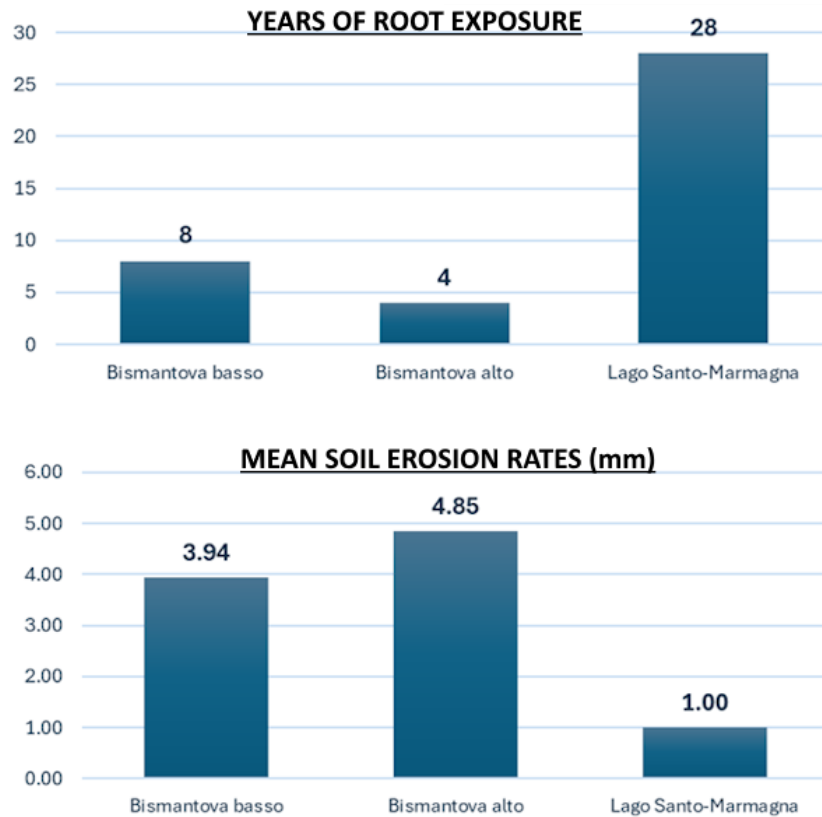


Figure 68. Years of root exposure and mean soil erosion rates

4.5.2.3. Tree-growth chronology

Regarding the two reference chronologies constructed for Field maple *Acer campestre* (at the Bismantova pilot site) and the Silver fir *Abies alba* (Lago Santo pilot site), it was possible to assess the growth pattern of the forest stand for the preceding decades. The decreasing growth trend in the tree rings is physiological and related to tree age. Data interpretation took advantage of meteorological datasets retrieved from on-site dataloggers (e.g., Figure 69), and weather stations located near pilot sites and managed by the Regional Environmental Protection Agency (e.g. Figure 70).

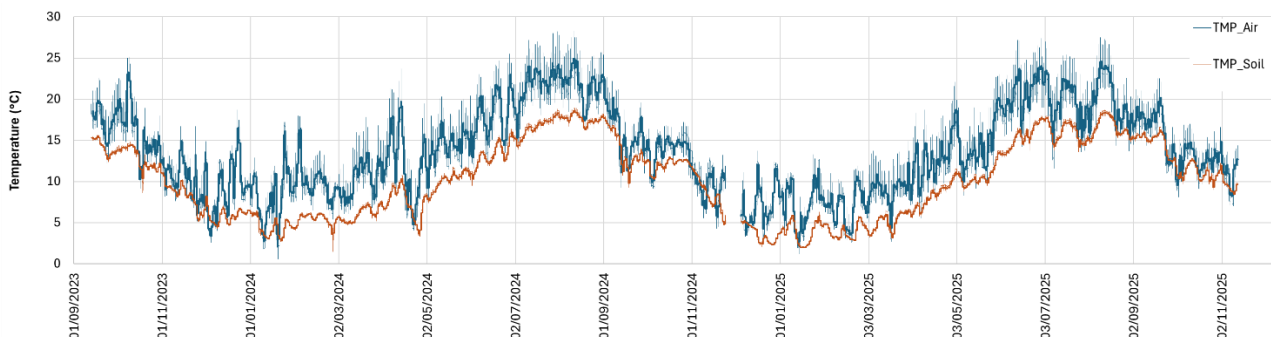


Figure 69. Monitoring of air and soil temperature at the Bismantova pilot site spanning from September 2023 to November 2026 with a 30-minute sampling frequency

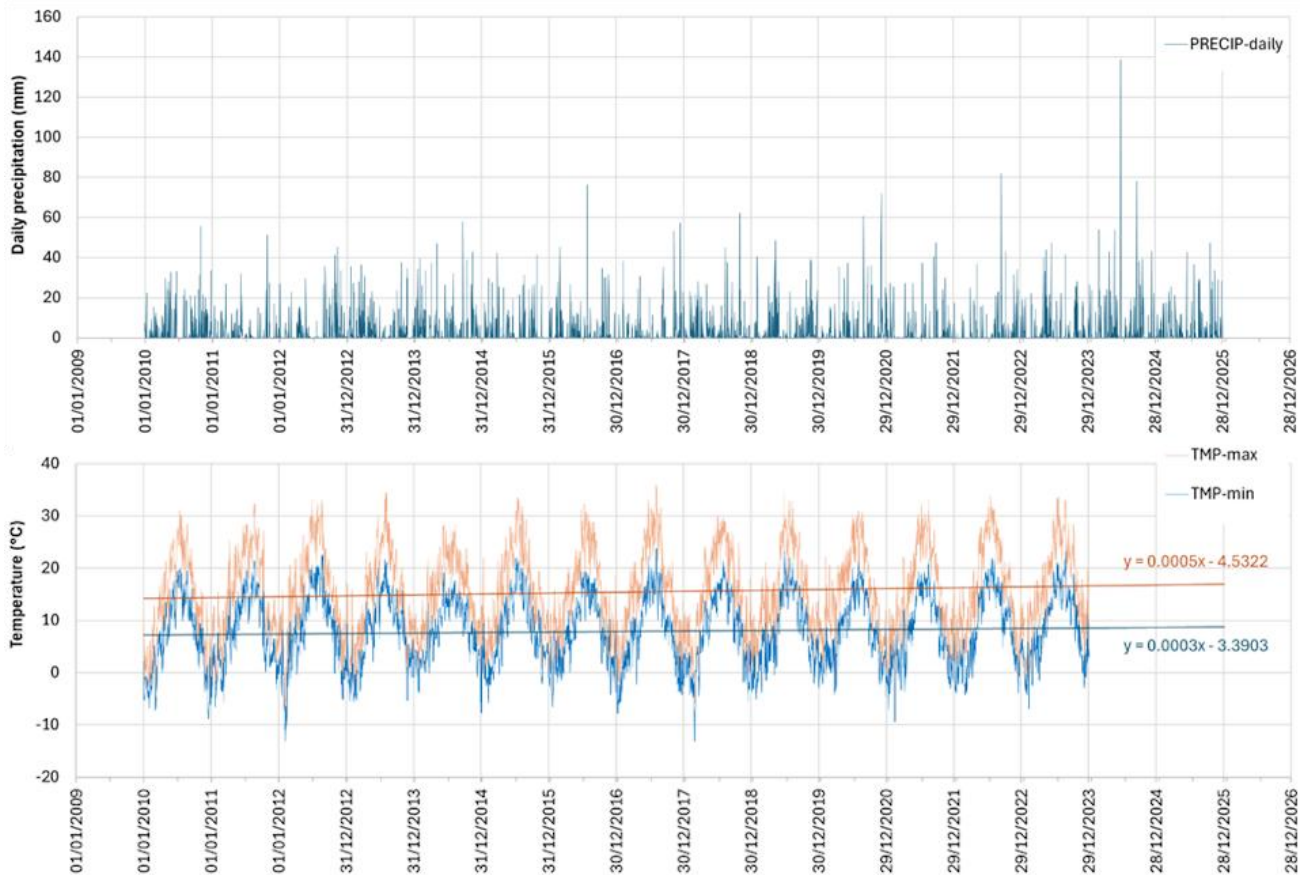


Figure 70. Daily rainfall, maximum and minimum temperature measured by the Castelnovo ne' Monti weather station from 2010

Standard chronology for Field Maple data (Figure 71) display periods of growth stress are recorded in the mid 1980s and after the summer 2003 during which a heat wave invested the whole Europe. This growth stress lasted up to 2007. Field Maple trees at this site are sensitive to April and June precipitation, whereas no temperature variables significantly correlated with tree growth. This is expected, being the Bismantova pilot site a temperate-moist site. Precipitation of April and June positively correlates with tree-ring growth ($r = +0.34$).

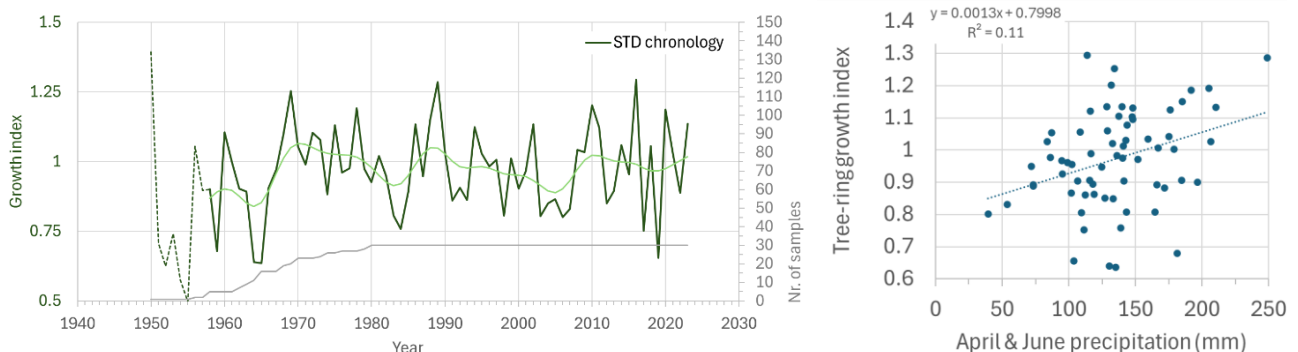


Figure 71. Standard chronology for Field Maple, and rainfall measured by the closest meteorological station for April and June – Pilot site: Pietra di Bismantova)

Standard chronology at the Lago Santo pilot site for Silver Fir (Figure 72) indicate periods of difficult growth in the 1970s, 1990s and after the 2003 heat wave, whose negative effect lasted up to 2008. Significant correlations between climatic variable and tree-ring growth at this site were found only for precipitation variables. In particular, the precipitation of January and of May negatively correlates with tree-ring growth of Silver fir ($r = -0.33$ for both variables).

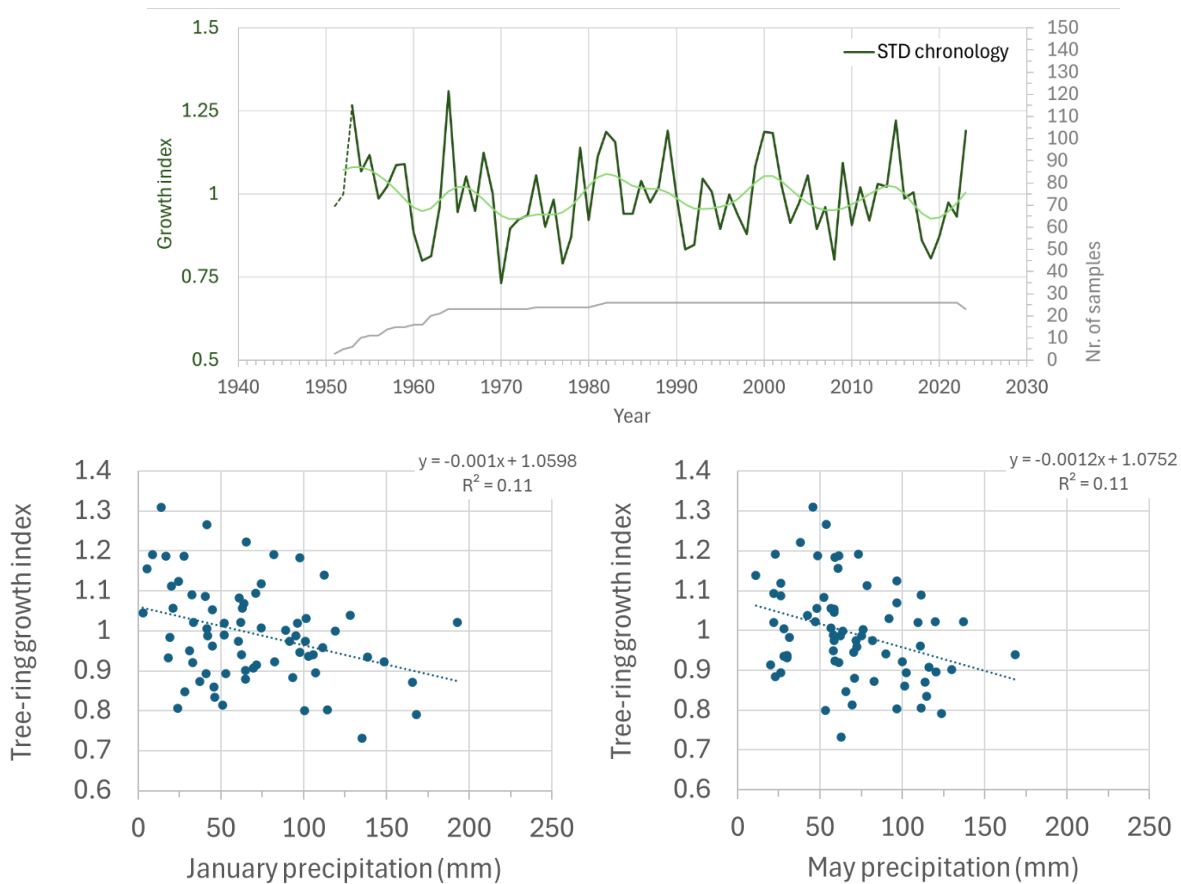


Figure 72. Standard chronology for Silver Fir, and rainfall measured by the closest meteorological station for January and May – Pilot site: Lago Santo

4.5.2.4. Topographic profiles

At the sito di Bismantova both Basso and Alto sites showed a mean erosion rate of approximately 4.4 mm/yr of soil loss. At Basso site, root exposure has involved most of the sampled roots since 2015 but it showed slightly lower mean erosion rates (3.94 ± 1.39 mm/yr), whereas at Alto site slightly higher mean erosion rates were found (4.85 ± 0.81 mm/yr) and most of the roots were impacted only four years later, in 2019.

The topographic profiles conducted along the trail direction and at three different transversal positions evidenced that Basso site (Figure 73) has a slightly higher slope (6.97°) than Alto site (Figure 74) and it is slightly bending on the left (when going upslope) and a concave shape in its lower-left portion. This shape of the topographic surface may account for the higher erosion rates found towards the right, at increasing distance from the left trail border where the tree stems are found. This depression, acting as a watershed for the surrounding areas, results in a concentrated water flow, which therefore may concentrate both water fluxes and materials.



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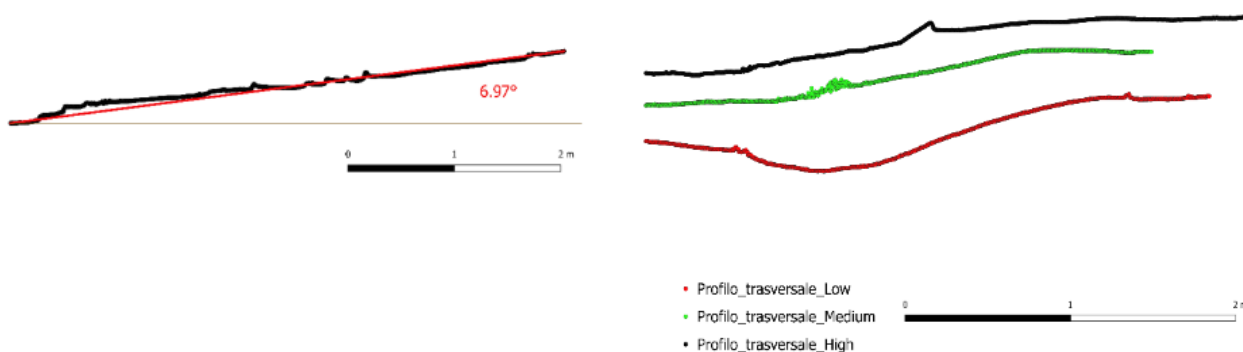


Figure 73. Bismantova Basso topographic profiles of the trail

The sito Alto has a lower slope (4.69°), and shows an almost flat condition in trasverals sections. At this site, higher erosion rates were found towards the tree stems positioned on the right.

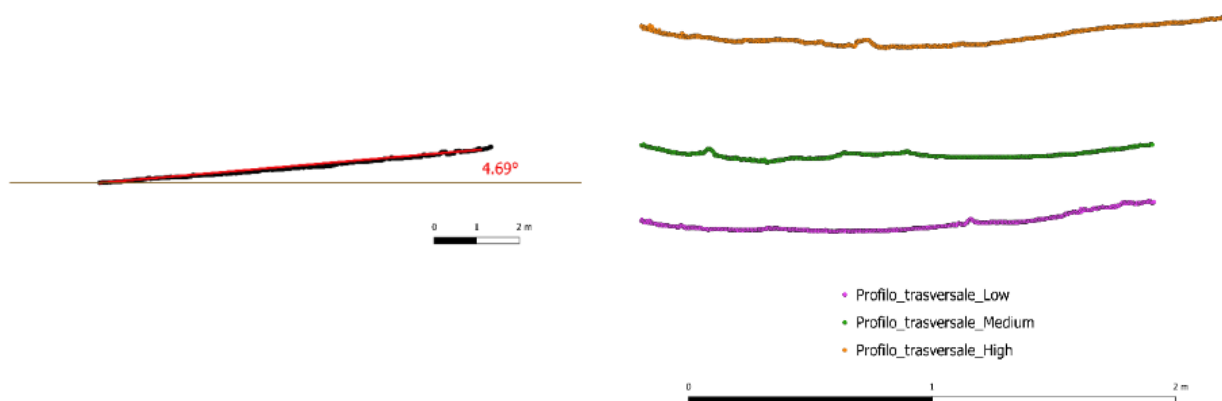


Figure 74. Bismantova Alto topographic profiles of the trail

At the Lago Santo site the mean erosion rates were evaluated at 1.00 ± 0.42 mm/yr, a much lower than at Bismantova value than the Bismantova site. At this site, soil erosion has impacted most of the trees already since 1995, the first exposed root dating back to 1980. At this site the erosion process has therefore started much earlier than at the Bismantova site. The slope of the trail (4.64°) is comparable with that of Bismantova Alto, and the trail is slightly bending towards the right (Figure 75). The roots showed a high scatter in erosion rate values, however a higher erosion rate is found closer to the tree stems towards the left.

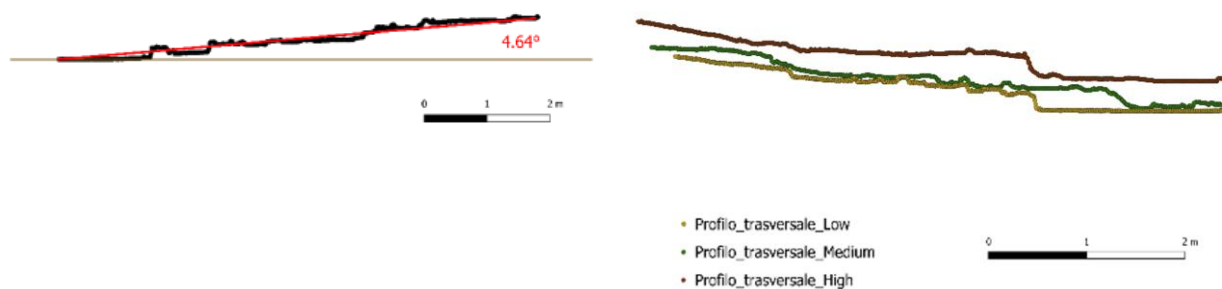


Figure 75. Lago Santo topographic profiles of the trail



Regarding the analysis of tree-ring growth sensitivity to climate, over the period 1950-2023 both sites evidenced that precipitation variables are driving growth processes more than temperature. As both sites are under temperate conditions, tree growth is not strongly limited by temperature. However, the exceptional hot and dry conditions of summer 2003 were recorded at both sites with a growth decay and the negative effects lasted also for some years later.

At the Bismantova site Field maple tree-ring growth is directly driven by the combination of April and June precipitation. If higher amounts of precipitation occur in these months, the Field maple is positively impacted in growth processes. Instead, at the Lago Santo site, Silver fir is negatively impacted if higher amounts of precipitation occur in January or in May. At this site the maximum precipitation amounts are recorded in October and November.

4.5.3. Conclusions and Recommendations

From our analysis it emerged that the two investigated sites are differently impacted by soil erosion.

The Lago Santo site started earlier showing this phenomenon, since 1980, however the overall balance of soil loss is almost negligible (-1.0 mm/yr).

At the Bismantova site, instead, the process has more recently impacted the area, since 2009, but the soil loss is much higher, ranging from 3.94 mm/yr (Bismantova Basso) and up to 4.85 ± 0.81 mm/yr at the Bismantova Alto. This implies that different strategies may be adopted and a special focus should be dedicated to the Bismantova site. Here in fact, despite the lower levels of precipitation, intense precipitation events may easily improve water concentration along the trail, promote runoff and sediment transport downstream.

Major uncertainties on mean soil erosion rate estimations through dendrogeomorphological approaches are related to the several factors potentially influencing soil erosion along a trail. The interaction between these factors finally leads to an overall condition of ongoing erosion and incision of the observed trails. The analyzed trails are directly impacted by tourist trampling, especially during summer months. The roots once exposed to light may also be directly damaged by people walking on them. Indeed, many roots showed anomalous growth and some of them were scarred on the upper part, and still growing only in the bottom (more protected) portion.

A technical bias of the overall approach is related to the minimum soil depth below which roots start morphological changes in response to soil erosion, even if not yet fully exposed to light. In the present approach, the value of this variable was set to 0 year. This may lead to under/overestimations of the soil erosion rates (depending on the root sensitivity to light and the permanence of a thin soil layer covering the root), although the resulting deviation in its value remains minimal. To further investigate this aspect, laboratory experiments could be conducted on the roots of the same tree species examined in this study. The aim would be to replicate, under controlled conditions, a context as similar as possible to that of the study area and thus measure the specific bias value.

Finally, the estimations of the mean soil erosion rates are evenly distributed over the whole period of root exposure, whereas seasonally the process likely proceeds with phases of erosion and deposition of materials. This implies that over very long periods of time such as at the Lago Santo site, the obtained value is related to the overall balance of soil loss over that period, without the possibility of entering in more accurate evaluations.



5. Wildlife monitoring

5.1. Camera-based wildlife observation

Protected Area: EGTC Geopark Karawanken-Karavanke

Project Partner: EGTC GEOPARK

For **wildlife observations** in areas adjacent to high-traffic visitor locations, we are utilising **20 EVOLVEO StrongVision PRO 4G cameras**. The purpose of the observation is to **verify the presence of different animal species**, identify their **habitats**, and observe their **behaviour patterns**, especially focusing on **vulnerable and endangered species**. The observations were conducted in **20 carefully selected zones** within the **Petzen/Peca mountain pilot area**, near hiking and biking trails, and the infrastructure of the cable car, for which we obtained the necessary permits from the landowners (Figure 76).

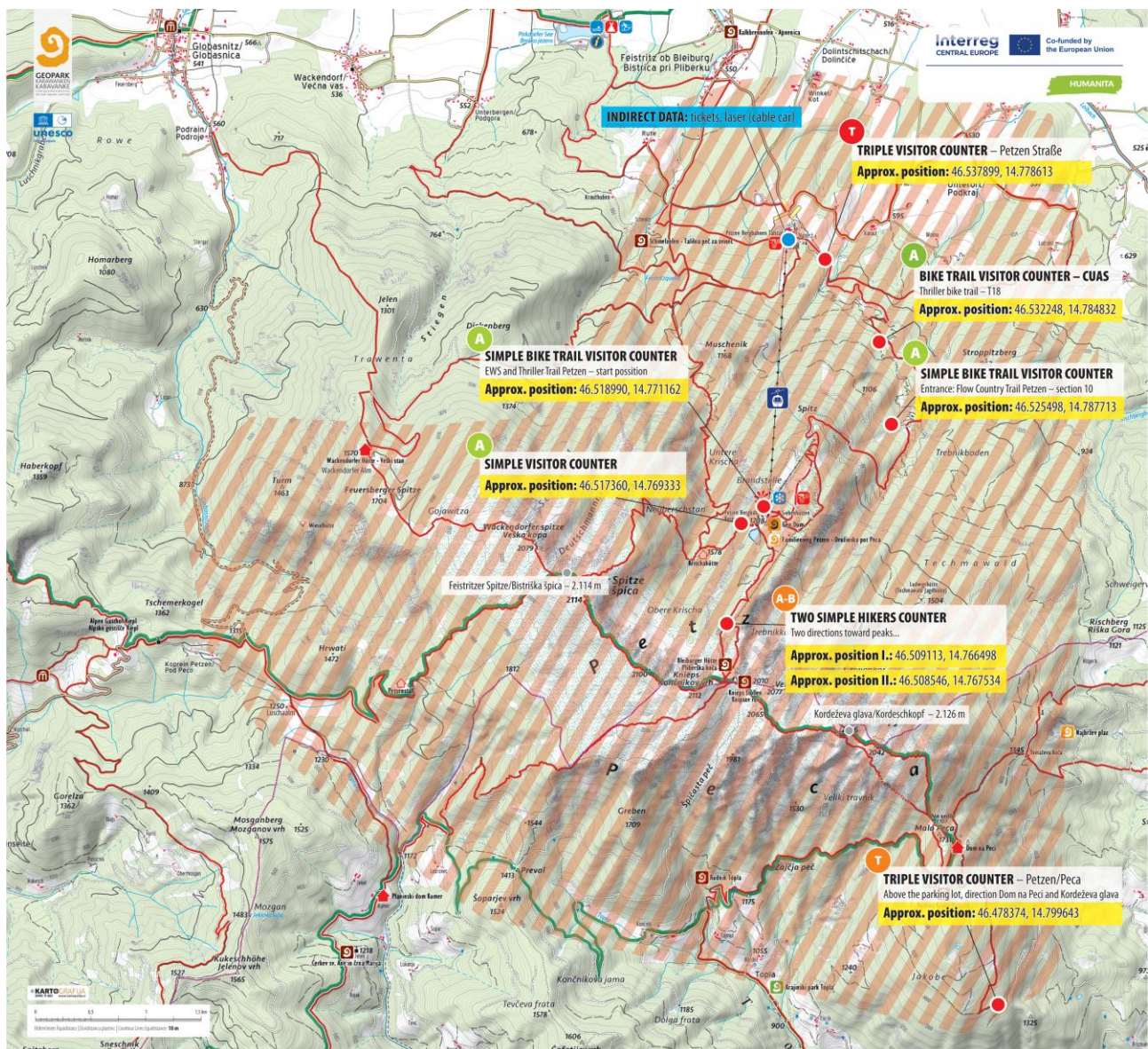


Figure 76. Location of observation zones with wildlife camera positions on the pilot site Petzen/Peca

The EVOLVEO StrongVision PRO 4G is a high-performance 4G/LTE cellular Wildlife camera designed for wildlife monitoring and observations.



- **Connectivity & Remote Access:** Utilises 4G/LTE to send photos/videos to email, FTP, or the Evolveo CAM app (Android/iOS). It supports LiveView, allowing for real-time video streaming.
- **Imaging & Video:** Records up to 4K Ultra HD video at 30 fps (up to 60 sec) and captures 30 MP images (up to 9 photos). It uses an 8 MP CMOS sensor.
- **Night Vision:** Equipped with 58 infrared LEDs (940 nm), making the flash invisible to humans and animals.
- **Power & Storage:** Powered by a 10,000 mAh rechargeable Li-ion battery for long-lasting operation. Supports SD cards up to 256 GB for local storage.
- **Durability & Design:** Features an IP65-rated waterproof and dust-resistant housing, suitable for outdoor use. It has a 2.4" TFT display for easy setup.
- **Functionality:** Includes PIR motion detection, time-lapse mode, and allows for remote management of files.
- **Detection system:**
 - Motion Sensor: 3xPIR
 - Detection Angle: 120°
 - Detection Range: Adjustable from 1 to 20 meters
 - Trigger Speed: 0.3 seconds for photos, 0.5 seconds for video
 - Delay between each detection is 1/5/10/30 seconds, 1/5/10/30 minutes (settings)

We configure our wildlife cameras to capture a combination of photos and videos to increase the chances of monitoring animals in the area. The basic settings we use for photos are high-resolution **30MP photos**, and 9 photos in sequence. For video: **4K video at 30 fps for 60 seconds** (the camera also records low-resolution backup videos at 720p), and the **PIR sensitivity is best set to medium or low**. A 256 GB memory card provides plenty of space to store all data for at least six months. The camera also supports remote data transfer via the cloud, helping to minimise physical interference in the observation area. Lithium batteries have proven to be an effective energy choice and have failed only once in 20 cases (in the testing period).

The observation area was split into three zones of interest. Using preliminary tests and field research, we decided how many cameras to place in each, and the most appropriate installation position was then identified on-site (Figure 77). The first and the lowest zone, near the valley at 770-870 meters above sea level, used a mix of 4 cameras. The second zone, around 1,400 meters, had 7 cameras, while the third and the highest zone, between 1,650 and 1,950 meters, was equipped with 9 cameras.

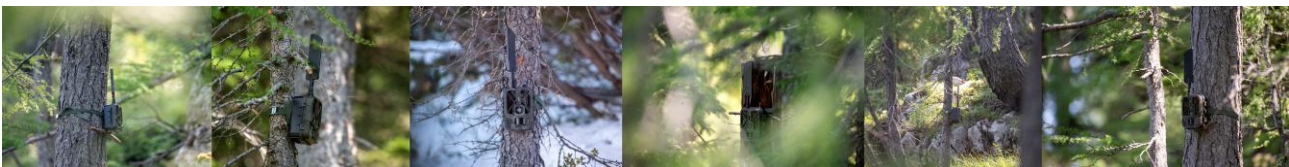


Figure 77. Examples of installing Wildlife cameras in different locations on the pilot site Petzen/Peca

5.1.1. Results, Assessment, and Interpretation

The collected information is crucial for **conservation efforts, identifying areas of various biodiversity, and assessing the impacts of human activity on wildlife.**

The initial analysis of the collected observations confirms the presence of various species exhibiting known behavioral patterns, emphasising the significant impact of human activity on their behavior. **The animals primarily inhabit their environments at night, with occasional sightings occurring early in the morning, typically until around 8 a.m., before the first hikers/visitors begin to arrive at approximately 9 a.m.**



Usually, the animals return to the spots in the evening—though not always—about an hour before sunset, settling into the quiet areas scattered around. This behavioral pattern has been observed primarily in **Northern Chamois** (*Rupicapra rupicapra*), while **Roe deer** (*Capreolus capreolus*) does not show it. They are scattered over a larger area, probably due to their smaller numbers of individuals. Mostly a solitary roe deer male or a female with cubs is caught on several locations (all together we were able to identify 3 adult males (one was hunted down in 2025), and two females from which one was with two cubs). On the other hand, we were able to identify small packs of chamois between 6 and 9 individuals and couple of solitary males. Altogether 6 cubs were identified, 9 females and 12 males. They were scattered mostly in zones two and three.

The same applies to small mammals such as the **Red squirrel** (*Sciurus vulgaris*), and the **Mountain hare** (*Lepus timidus*) which mostly emerge from their hiding places when there is no human activity nearby (early in the morning, late afternoon and evening and even at night). The **European edible dormouse** (*Glis glis*) and mice were observed at night, which coincides with their nocturnal lifestyle, the same as the **Red fox** (*Vulpes vulpes*), **European pine marten** (*Martes martes*) and **Least weasel** (*Mustela nivalis*) were caught only by nighttime.

Human activity in the observation zone generally wraps up by 5:15 PM each day, when the cable car's daily operations come to an end.

However, during bad weather or on days when there are no people around, they tend to stay in their habitats for extended periods and can even be seen on cameras during the daytime.

Throughout the observation period, we collected approximately 20,500 files. Of these, 12,600 files proved valuable with animal identification, indicating a camera detection and triggering capture rate of over 60% success.

Ten species of mammals were identified in the pilot area, including small packs of **Northern Chamois** (*Rupicapra rupicapra*), which tend to intertwine and dominate in this area. The cameras did not record any large carnivores, despite confirmation of their presence nearby. The largest carnivores captured on camera were the **Red Fox** (*Vulpes vulpes*) and the **European Pine Marten** (*Martes martes*). Additionally, the presence of the **Mountain Hare** (*Lepus timidus*) was confirmed in several higher elevation locations (shares habitat with Chamois and Black Grouse). Interestingly, the cameras also recorded the occasional presence of **bats** at altitudes between 1,600 and 2,000 meters, suggesting that their mating habitat may be close by. **Fifteen bird species** were identified, including the vulnerable and endangered **Black Grouse** (*Lyrurus tetrix*). Unfortunately, despite suitable habitats, the cameras did not capture any sightings of the **Western Capercaillie** (*Tetrao urogallus*) or any other members of the vulnerable grouse family in previously known habitats. In total, 26 animal species were identified.

The cameras were also **triggered by increased concentrations of moths and insects at night**, as well as **reptiles, amphibians, and small rodents**.

The species could **not be identified from only 19 images/videos** that caught animals (reasons: blurry shot, only part of the animal, too small, too far away). Of course, we did not try to identify any insect species, which triggered the camera 56 times (the outline shows that in most cases these are species of moths).



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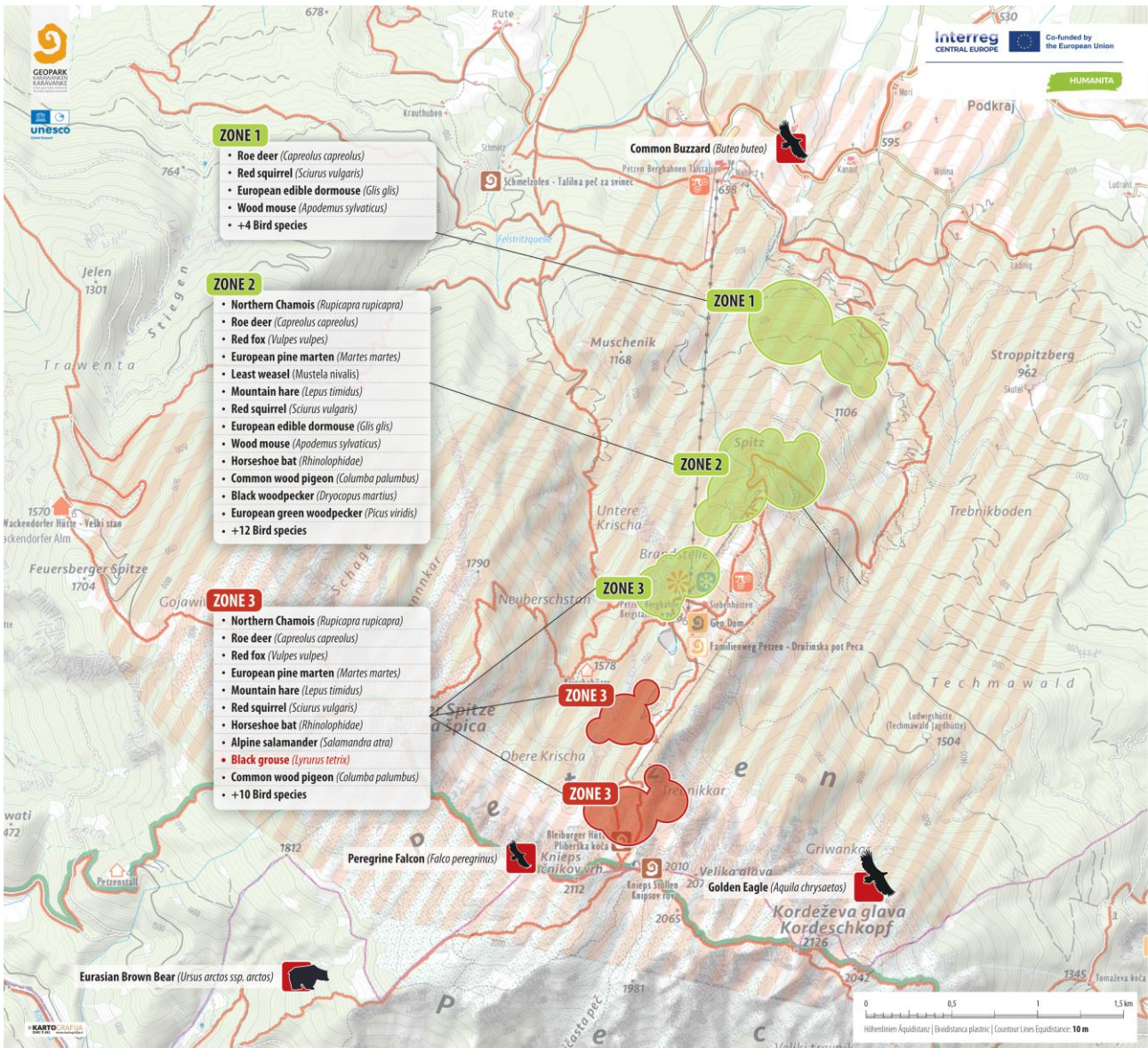


Figure 78. Identified animal species in the zones of observation in the Petzen/Peca pilot area

The collected data (Figure 78) clearly shows how the diversity in the pilot area changes with altitude. At the lowest points (zone one, 770-870 meters above sea level), results were minimal, with only occasional sightings of Roe deer (*Capreolus capreolus*), small bird species, and small mammals like Red squirrel (*Sciurus vulgaris*) and rodents such as mice and the European edible dormouse (*Glis glis*). In total, only eight species were recorded, with only 25 video/photo files indicating noticeable disturbance in the forest and possible lack of wildlife or major disturbances affecting wildlife movement. The richest diversity appeared around 1,400 meters (zone two), with 25 species identified—10 mammals and 15 bird species—and the most successful data collection at roughly 7000 files that show regular wildlife activities spread in the observation zone. At the highest points (zone three, 1650-1950 meters), 7 mammals, one amphibian and 12 bird species were recorded in about 5,600 files, including Black Grouse (*Lyrurus tetrix*), along with moths (no ID for species), bats and the Alpine salamander (*Salamandra atra*). Some examples of the animals detected by wildlife cameras are displayed in Figure 79.



Figure 79. Example of observations and the presence of wild animals on the Wildlife cameras

The following graphs show the diversity of activities by observation zone and specific time parameters. 99% of all captured wildlife activity occurs during times without human activity in or near the monitoring area. This shows a known behavioural pattern with strong pressure from human presence and its impact on wildlife.

We divided the analysis into time frames: early morning (Figure 80), during the day (Figure 81), late afternoon-evening (Figure 82), and at night (Figure 83). Finally, Figure 84 provides a flat-rate analysis of selected species across all time frames.



Pilot site: Petzen/Peca

Flat rate analysis

Period: Summer season 2025 (July – November 2025) – Early morning Wildlife activities (from sunrise till 9 AM)

No human presence!

Unidentified: 5 x / Caws: 6 x

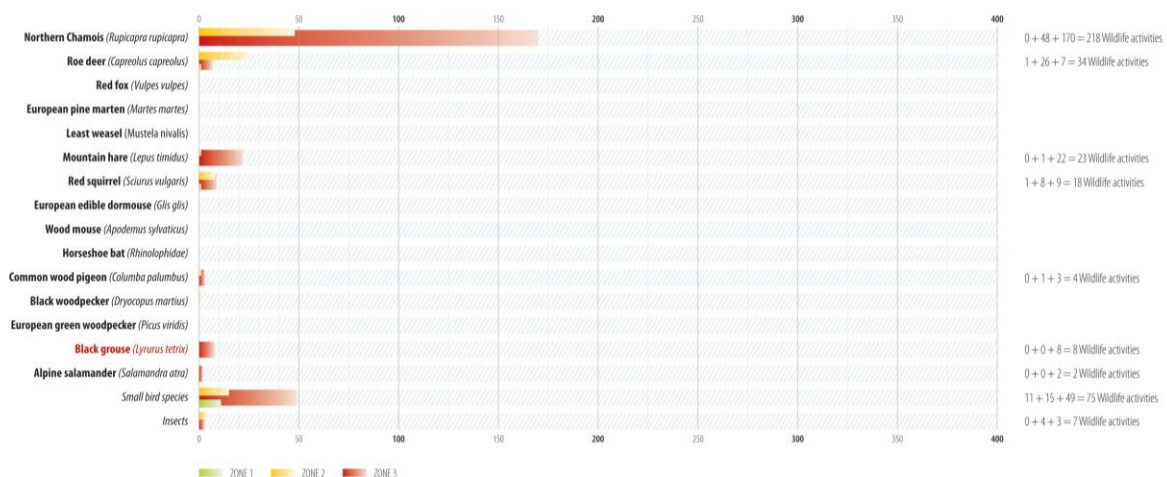


Figure 80. A flat-rate analysis comparing and combining data from three observation zones for the comparison of wildlife activities of species in the same time frame. Early morning Wildlife activities (from sunrise till 9 AM) – before operating hours and the time



Pilot site: Petzen/Peca

Flat rate analysis

Period: Summer season 2025 (July – November 2025) – Daytime Wildlife activities (9 AM till 5 PM)

*Bad weather and/or no human presence on that day!

Unidentified: 5 x / Dogs: 10 x

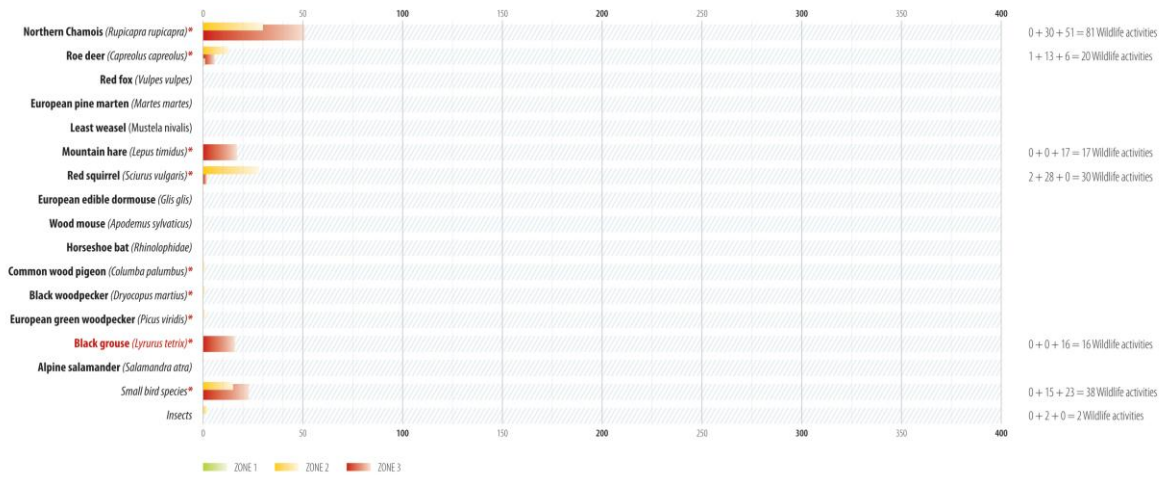


Figure 81. A flat-rate analysis comparing and combining data from three observation zones for the comparison of wildlife activities of species in the same time frame. Daytime Wildlife activities (9 AM till 5 PM) – when the intensity of visitors in the area is the highest



Pilot site: Petzen/Peca

Flat rate analysis

Period: Summer season 2025 (July – November 2025) – Late afternoon Wildlife activities (after 5 PM till sunset)

No human presence!

Unidentified: 1 x / Cows: 1 x

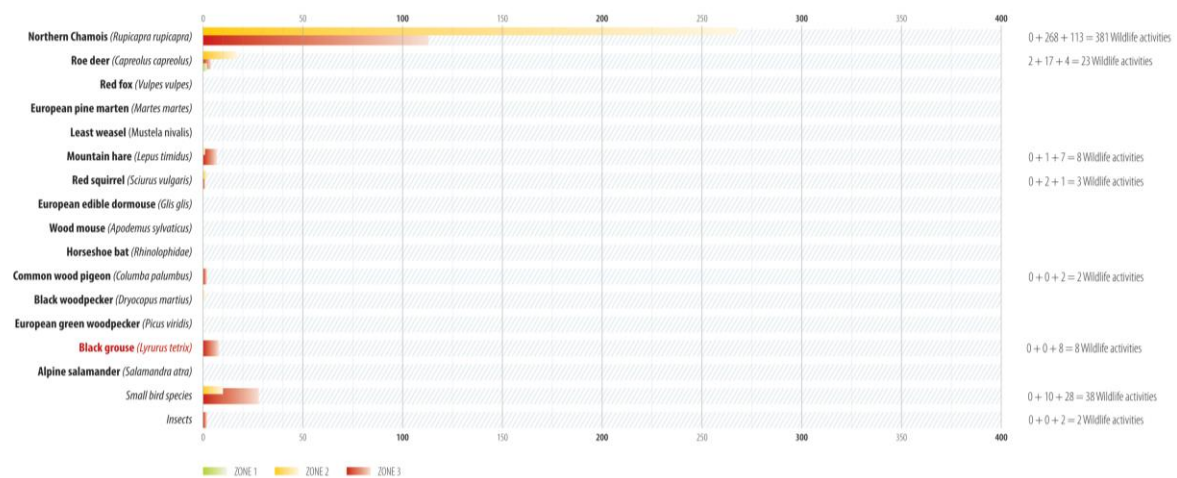


Figure 82. A flat-rate analysis comparing and combining data from three observation zones for the comparison of wildlife activities of species in the same time frame. Late afternoon Wildlife activities (after 5 PM till sunset) – after operating hours and the time



HUMANITA



Pilot site: Petzen/Peca

Flat rate analysis

Period: Summer season 2025 (July – November 2025) – Nighttime Wildlife activities (after sunset till sunrise)

No human presence!

Unidentified: 8 x

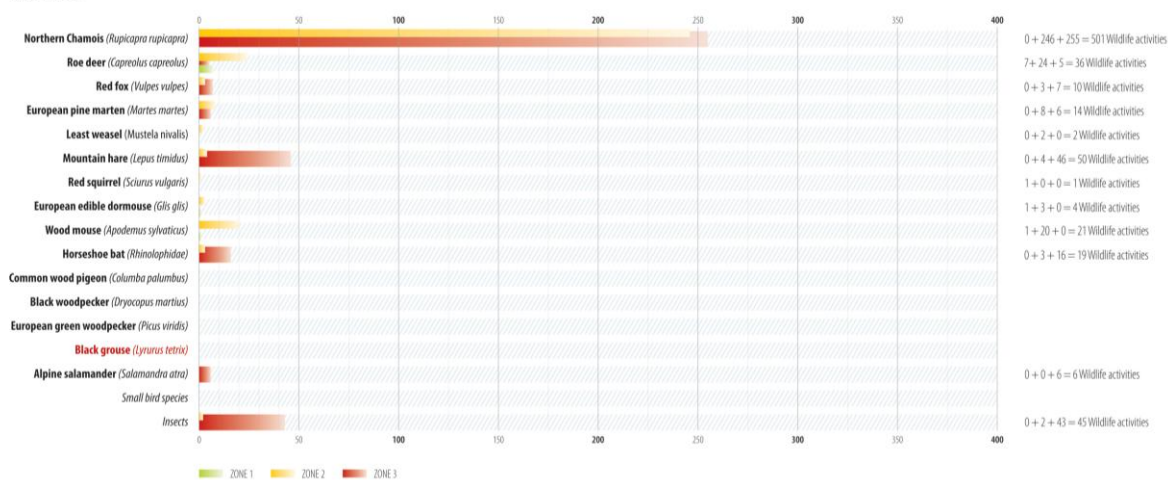


Figure 83. A flat-rate analysis comparing and combining data from three observation zones for the comparison of wildlife activities of species in the same time frame. Nighttime Wildlife activities (after sunset till sunrise).



Pilot site: Petzen/Peca

Flat rate analysis

Period: Summer season 2025 (July – November 2025) – OVERALL 1.767 Wildlife activities

Unidentified: 19 x / Caws: 7 x / Dogs: 10 x

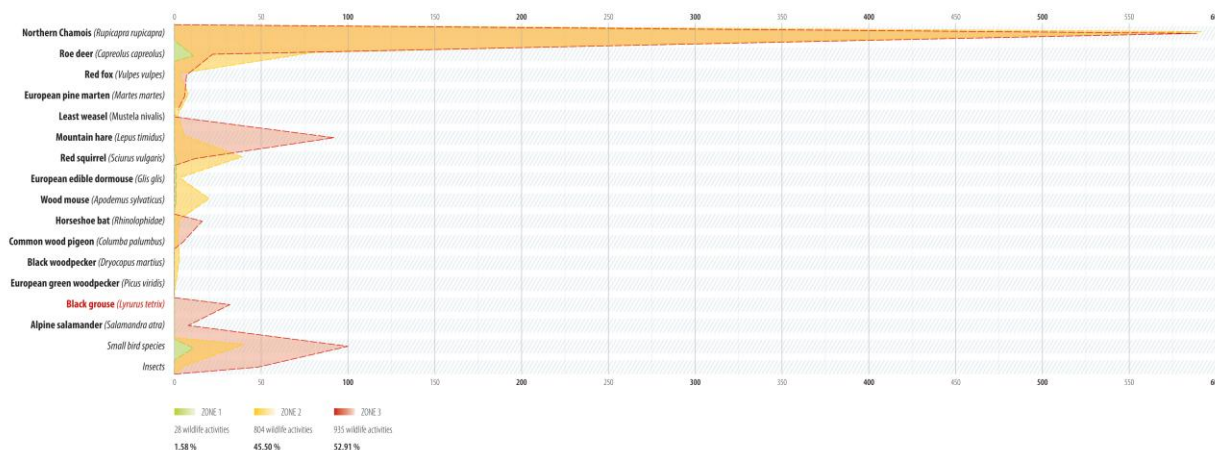


Figure 84. A flat-rate analysis comparing and combining data from all wildlife cameras for a comparison of the overall wildlife activities of species without dividing night and day actions in three observation zones

The wildlife cameras were positioned entirely outside the hiking and biking trails and directed away from areas frequented by visitors. However, they occasionally captured images of people in the observation areas during the 2025 season, primarily in zone 3 and occasionally in zone 2 (Figure 85).

The recorded activity included:

- Hikers: 126 instances (20 of which were completely outside the established trails)



- Dogs: 10 instances (2 of which were untethered)
- Cows: 7 instances
- 1 biker and 1 paraglider in an area where activity is not permitted (heading towards Knieps peak from the upper ski lift station)
- 2 "lost bikers" were also seen on the closed dirt road



Figure 85. Example of caught activities outside legal trails on the Wildlife cameras

5.1.2. Conclusions and Recommendations

This approach not only **confirms existing behavioral patterns in animal habitats** but also provides valuable data for analysis. The information gathered is essential for **conservation efforts**, as it helps identify areas of biodiversity and assess the impact of human activities on wildlife. In addition to photographic evidence of animal presence, the collected data has also **produced educational materials**.

The current indicator suggests that the **greater the distance from constant disturbance of human impact, the greater the diversity and mass of wildlife is**.

To improve the accuracy of our findings, it is **vital to conduct additional observations and increase the density of observation points**.

The camera trigger has a **0.5-second delay when capturing video content**. This delay can limit the ability to **capture fast-moving animals in proximity to the camera** during certain moments. To improve performance, it is advisable to install the camera in a more open area, where you can observe the direction of animal movements (or even use several cameras to cover the area of interest). Additionally, using a dual camera setup for video and photo capture can enhance efficiency, as photos are captured more quickly than videos. **It is not recommended to position the camera facing directly towards the sun (either east or west)**, as this can negatively affect the quality of the capture and may cause unnecessary triggering of the sensor due to high contrast in the environment. Furthermore, due to the **sensitivity of the sensor**, which has three adjustable sensitivity levels, it is important to ensure that there are **no moving elements nearby, such as tall grass or branches**, that may cause the camera to trigger unnecessarily, especially in windy conditions.

The **batteries** are reliable and can power the camera in the field for up to six months when in active standby mode. However, **it is important to ensure that the batteries are installed correctly**. If remote data transmission is not being used, the installation should be turned off, and the battery must be properly seated in the contacts. Failure to do so can lead to unnecessary battery drain and significantly reduce operational lifespan in the field. It is recommended to regularly monitor battery status and replace the battery as needed.

The **256 GB memory card** offers a substantial amount of storage. It can hold approximately **1,000 high-quality 60-second videos**, with an average file size of around 230 MB each. Alternatively, it can store over **2,000 high-quality 30-second videos**, averaging 120 MB each. Additionally, the card can accommodate more than **49,000 high-resolution photos**, with each photo averaging 5.2 MB.

In most cases, this ratio provides adequate data storage for extended periods of field installation. However, **storage capacity can quickly become a limitation**, particularly in areas with high wildlife activity or when



installations are poorly executed. This can lead to the camera capturing a large number of "ghost" images caused by moving branches or other elements that unnecessarily trigger the sensor and fill the memory card. Therefore, it is recommended to connect to the camera and transfer data remotely to prevent the memory card from becoming full (also, you will have better control over the situation - easily recognising bad locations for reinstallation, data storage, battery info, etc.).

Capturing **night footage** presents a significant challenge due to the need for careful adjustment of both camera position and detection settings. This is important to prevent excessive burn-in of the image, particularly in the lower half, where ground reflections can occur. The camera should be installed as horizontally as possible and not primarily directed at the ground. By using a low positioning angle, it's also feasible to capture smaller animals nearby without overexposing the footage. It's advisable to test and fine-tune the camera settings according to its specific positioning. **Most of the time, this could be avoided!**

Bad weather affects the optics, especially if condensation or raindrops accumulate on the lens (as in most cases, since it is a remote device, the lens cannot be wiped and fortunately, due to the coating, it dries/cleans itself with the help of daytime heat and sun).

5.1.2.1. Practical advices

When choosing a location, careful observation of the surroundings is necessary. A **good knowledge of the behaviour of animal species**, knowledge of habitats, recognition of traces such as animal tracks, droppings, bedding or drifting vegetation, helps to determine a good location for better data acquisition results and hunting of various animal species.

When selecting a location, it is necessary to be consistent and **remove obstacles from the viewing angle** that could trigger the sensor (branches should not cover the face of the device, because they will constantly trigger the camera when moving in the wind, and it is also necessary to emphasise avoiding larger grass plants, flowers or small bushes).

Monitor the result if you notice animals moving around the edges of the capture or the camera is triggered without a result (listen to the acoustic capture to see if animals were present or just branches moving due to the wind)... in this case, correct the location for a better capture and result.

The sensor power is not always recommended at the most sensitive setting. In most cases, low sensitivity is more than enough. If you are not sure, monitor the result.

Point the camera to the north or south, exceptionally east or west (only if direct light or the sun is blocked by distant vegetation, otherwise the images will be distorted and burnt due to excessive light contrast).

Place the camera so that it is not noticeable from afar **to avoid theft**.

Do not point the camera directly at the ground (except for daily observations); lower it as much as possible to achieve the desired coverage of the area.

We recommend **settings** in the best possible resolution, as offered by the wildlife camera settings and in our case, due to the shutter delay, a combination of photo/videos (9 consecutive images/60-second videos). The images are of satisfactory quality and can be used for informative and educational material. Also, turn on acoustic recordings.

Always check that the battery is properly inserted and locked into the device (inconsistent insertion can quickly drain the battery).

Turn off all unnecessary settings, such as signal search or remote transmission, frequency, etc., if you are not using these services. They will weaken the battery.

Use a remote connection (even if the signal is poor, you will get a notification about what is happening on the camera; you may not be able to download, but you will have more control over the location and device



itself). You will save yourself from the unnecessary trip of checking the device and data collections, before it is necessary.

Use high-quality and high-capacity SD cards, always reset them before using them again (but first check that you have successfully transferred data from them).

For areas with high wildlife activity, I recommend setting up at least three wildlife cameras in a triangulated arrangement. Position the cameras to cover the center of the area and ensure they overlap at the edges of the zone of interest. This approach will provide comprehensive habitat coverage and allow for multi-angle data collection, which facilitates better comparisons of wildlife presence. With a 99% success rate in triggering the cameras, this setup also helps minimise escape routes for animals.

5.2. Amphibian Monitoring

Protected Area: Bükk National Park Directorate

Project Partner: BNPD

The amphibian monitoring activity investigated the prevalence and spread of infectious diseases across several designated pilot sites in the Mátra Mountains, including Kékes North, Nagy-lápfő, Parádi legelő, Csörgő-valley, Totovics, and Sár-hegy (Figure 86). Swab samples were systematically collected from Yellow-bellied toads to test for the *Batrachochytrium dendrobatidis* (Bd) fungus, and from Common frogs to test for Ranavirus.

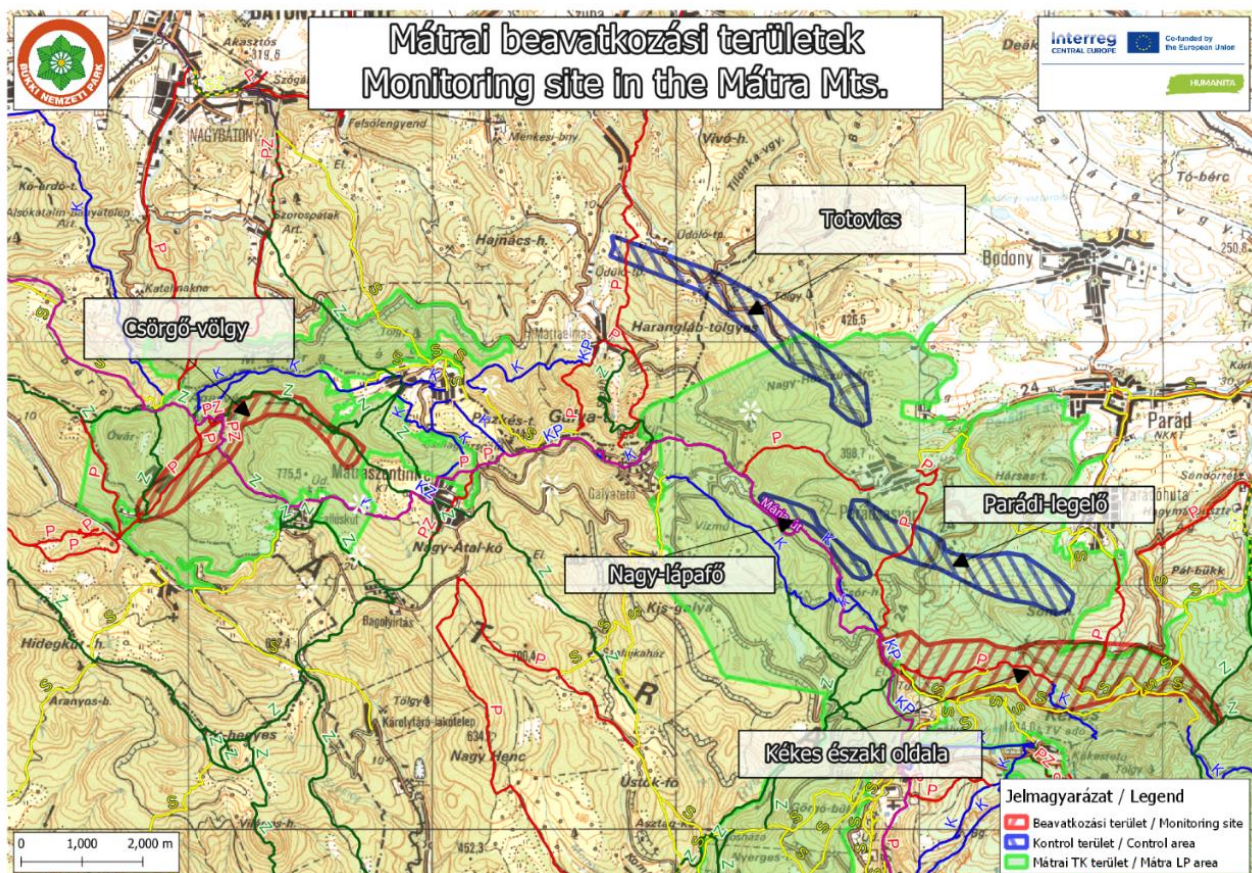


Figure 86. Pilot sites in the Mátra Mts.



5.2.1. Chytrid Fungus Site Analysis

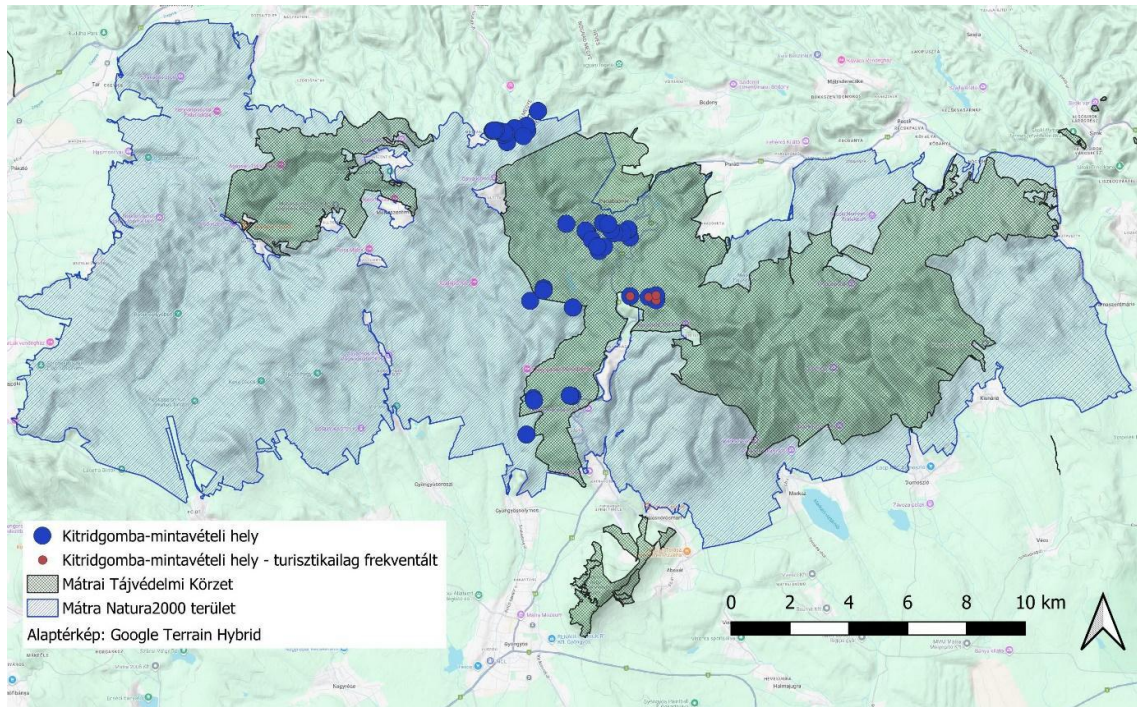


Figure 87. Map of the Kitrid fungus sampling locations

The results obtained from samples collected at sites with low tourist traffic are insightful even when compared with one another. The three locations providing comparable sample sizes were Parádsasvár: Glóbusz út (48 samples); Parádsasvár: Bagolykői út (42 samples); and Gyöngyössolymos: Ilona-kút (42 samples). Kitrid fungus sampling locations are included in Figure 87.

At Glóbusz út, 54.16% of the sampled animals were infected with chytrid fungus, compared to 23.81% at Bagolykői út and 11.90% at Ilona-kút. In our assessment, these differences cannot be explained by tourist pressure. It is evident that within a specific region, the dispersal capacity of large mammals—particularly ungulates that frequently visit water bodies—may reach or exceed the level of direct human-mediated dispersal. Non-tourist vehicle traffic (forestry, hunting) may also play a significant role as a local vector.

At the **Kékes-Észak** sampling sites (Haluskási út, Hidasi út), our investigations revealed high levels of chytrid fungus infection in the local **yellow-bellied toad** (*Bombina variegata*) population. This was unsurprising, as the previously outlined disease and mortality events affected this specific population. Here, the yellow-bellied toad habitats consist of ephemeral puddles forming in roads and roadside ditches. These roads are heavily burdened by both tourist and other traffic (forestry, hunting, off-road, etc.), and big game populations are also highly concentrated in the area. These factors presumably act in concert to maintain high local transmission of the chytrid fungus.

At the **Bagolykői út** sampling site, our studies detected low levels of chytrid infection. While some habitats here are also formed by roadside puddles, individuals are also found in more remote habitats (e.g., Bagolykő Lake). Tourist pressure at this site is low; however, vehicle traffic for forestry and hunting remains significant, and the big game population corresponds to the average values for the **High Mátra** (Magas-Mátra).

At the **Glóbusz út** sampling site, we detected infection levels significantly higher than at Bagolykői út, yet much lower than at Kékes-Észak. Most habitats are provided by roadside puddles. While tourist pressure is low, forestry and hunting traffic is significant, and the big game population is similarly consistent with the High Mátra average.



5.2.2. Chytrid Fungus Site Analysis

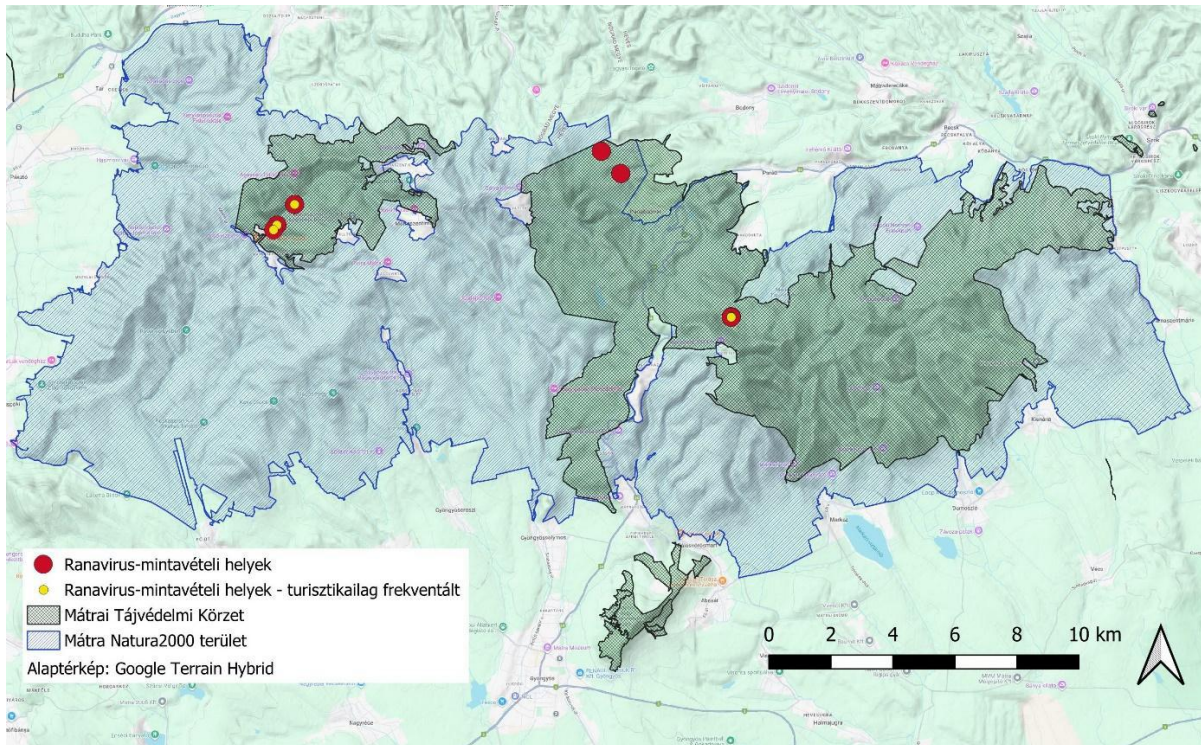


Figure 88. Map of the Ranavirus sampling locations

Surface swabs from amphibians are not suitable for detecting the presence of ranaviruses. Until recently, investigations relied on the internal organs of deceased or euthanized animals, making large-scale sampling problematic from a conservation standpoint. Ford et al. (2022) published a method for successfully collecting ranavirus samples from the oral cavity of live animals⁴. Sampling begins by capturing the frog (using a fresh pair of gloves for each individual); the mouth is carefully opened, and a swab is gently rotated within the oral cavity. As the swab is soft, it causes no injury to the animal.

According to our original plans, we intended to sample adult common frogs (*Rana temporaria*) appearing at breeding sites in the spring of 2024. However, this was unsuccessful due to prolonged cold spring weather and the unpredictability and brevity of the breeding event. Figure 88 shows the map of the Ranavirus sampling locations. We conducted several field visits to two traditionally significant breeding sites: Pisztrángos Lake (Parád) and Békás Lake (Mátrakeresztes). At Pisztrángos Lake, breeding occurred over an extremely short window with much lower numbers than usual; at Békás Lake, breeding did not occur at all in 2024. Despite surveying additional sites, we were unable to find adult common frogs in significant numbers during the spring. Since juveniles were present in terrestrial habitats at both (tourist-frequented) sites, we collected oral samples from them in April-May 2024. During the summer of 2024, field visits to typical terrestrial habitats (cool stream valleys) were unsuccessful, yielding no adult specimens. In September and October 2024, adults were found only sporadically, but juveniles were present in large numbers, allowing us to collect the required sample sizes at both tourist-frequented and non-frequented sites. As a supplement, we also included samples from frogs previously collected in the Mátra that died showing symptoms suspicious of ranavirus infection.

Molecular laboratory tests were conducted for the two ranavirus species causing amphibian die-offs in Europe: Frog Virus 3-like Virus and Common Midwife Toad Virus. Results for all collected samples (including

⁴ Ford C.E., Brookes L.M., Skelly E., Sergeant C., Jordine T., Balloux F., Nichols R.A., Garner T.W.J. (2022). Non-lethal detection of Frog Virus 3-Like (RUK13) and Common Midwife Toad Virus-Like (PDE18) Ranaviruses in two UK-native amphibian species. *Viruses*. 2022;14:2635. doi: 10.3390/v14122635



the deceased individuals) were negative; neither ranavirus species was detectable in any sample. Due to these negative results, the impact of tourism on the spread of ranaviruses in the Mátra could not be demonstrated. We are working to send the samples to a laboratory capable of testing for other ranavirus species not yet known to affect European amphibians. One such potential species is the European Catfish Virus (ECV), which has already caused mortalities in black bullhead populations in Hungary. As black bullhead has been recorded in several waters in the Mátra, this line of research is conservationally relevant. Should these further tests be completed, the results will be provided to the Bükki National Park Directorate.

5.2.3. Conclusions and Recommendations

Our results appear to support our preliminary hypothesis that higher chytrid infection rates can be expected at popular tourist sites compared to less-frequented areas. However, the comparison between Bagolykői út and Glóbusz út highlights that significant variations can exist even among low-traffic sites. The aforementioned secondary dispersal factors undoubtedly exert a strong influence on the presence of the fungus. In summary, tourism should be viewed as a significant but by no means exclusive (and perhaps not even primary) factor in the local spread of the fungus. However, it may play an outstanding role in inter-regional dispersal, which we will detail further.

The key outcome of the laboratory analyses was the confirmation of zero positive cases for Ranavirus across all sampled locations, indicating that this specific pathogen is currently not posing a detectable threat linked to tourism in these areas. However, testing for the Bd fungus revealed a concerning trend, as significantly high infection rates were found in heavily trafficked zones such as Kékes North, particularly along the popular Haluskási and Hidasi roads.

A major limitation of this monitoring is that swabbing provides only a temporal snapshot of infection rates, making it difficult to trace the exact origin of the pathogens. The subsequent analysis strongly suggests that while hikers are not the originators of the disease, human activity and the movement of contaminated footwear along established trails act as a highly effective vector for spreading the Chytrid fungus between previously isolated amphibian habitats.

Since the Ranavirus tests returned entirely negative results for the currently tested strains, future analytical approaches should be enhanced by sending the collected samples to specialized laboratories capable of testing for different viral species. Specifically, testing for the European Catfish Virus (ECV) is highly recommended, as this virus is known to exist in the Mátra region and could potentially cross-infect amphibian populations. Finally, to combat the spread of the Bd fungus, it is highly recommended to integrate biological security measures into tourist information channels. Promoting the disinfection of hiking boots and equipment, for example by using a 1% Virkon S solution or other universal disinfectants, is a vital step to prevent the inter-regional spread of these devastating pathogens.

5.3. Soil mites presence

Protected Area: Malá Fatra National Park

Project Partner: UNIZA

Soil mites are various species of mites that live in soil. Their presence is usually beneficial because they help to decompose organic matter, form humus, improve soil structure, and support the cycling of nutrients. They are often considered an indicator of healthy and biologically active soil.

We use them as the indicator to observe the degree of erosion on hiking trails. When a trail becomes heavily used, the soil is compacted, the upper organic layer is damaged or removed, and erosion increases, especially on slopes. These changes affect soil mites. During monitoring we compared soil samples from the hiking trail and from nearby less or undisturbed areas. Lower abundance and diversity of mites usually indicate disturbed or eroded soil. Higher abundance and diversity suggest a stable soil with intact organic layers. When erosion removes these layers, their populations decline. Because of this sensitivity, they can help scientists monitor the ecological impact of tourism and trail use.



Four pilot sites were selected in the Malá Fatra National Park, and one additional site in the TANAP was chosen for a blind experiment. Samples were collected twice a year manually (6/2023, 6/2024, 9/2024, 6/2025, and 9/2025) before and after the main tourist season. Three samples were collected at each pilot site, directly on the trail, at the ecotone, and near the trail at the unaffected place. We extract mites using a Berlese-Tullgren funnel). This device uses light and heat to drive small organisms out of the soil into a collecting container, where they can be observed under a microscope.

5.3.1. Results, Assessment, and Interpretation

The Simpson's Index (D) is one of the most widely used measures of biodiversity in ecology. It expresses the probability that two randomly selected individuals from a given sample will belong to the same species. All data were normalized using min-max scaling (0-1), which allowed for direct comparison of variables across years (2023 vs. 2024), seasons (before and after the tourist season), and sampling site types. The results were visualized using boxplots and interpreted for those three categories.

Figure 89 shows results of non-parametric tests for seasons - Simpson's index: M-W U (1;30) = 69.50, p = 0.16; density and number of individuals: M-W U (1;30) = 90.00, p = 0.84; results are not significant.

Interpretation of values: The index ranges from 0 to 1.

- 0 - 0.2 → very low diversity
- 0.2 - 0.4 → low diversity
- 0.4 - 0.6 → moderate diversity
- 0.6 - 0.8 → high diversity
- 0.8 - 1.0 → very high diversity

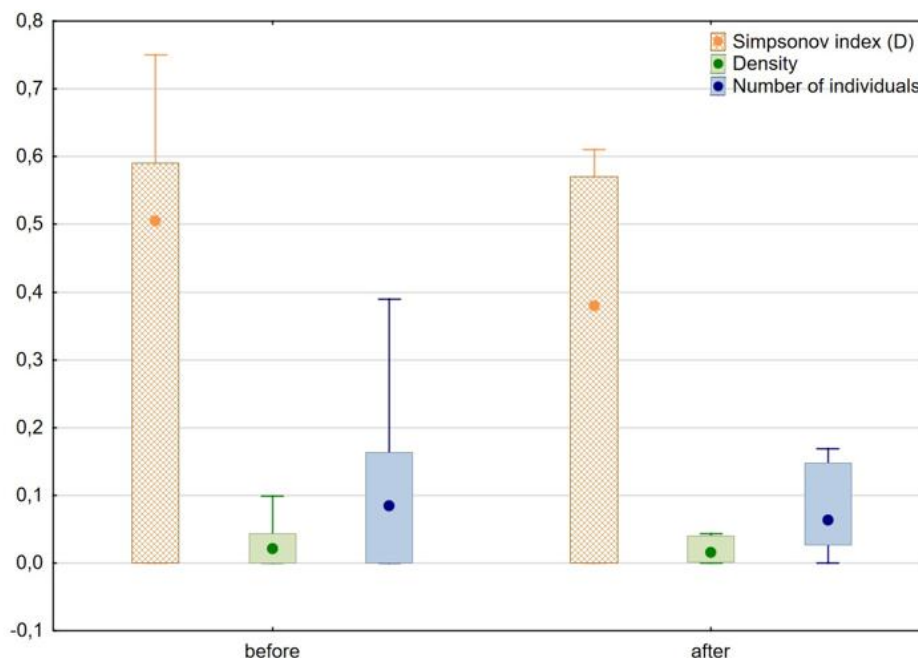


Figure 89. Comparison between seasons

Higher value means more species and a more even distribution. Lower value means dominance of one or a few species. If Simpson's index decreased from about 0.5 to 0.38, it means that after the season the community became less diverse and some species likely became dominant while others declined.



Figure 90 shows results of non-parametric tests for sampling site types - Simpson's index: K-W H (2;36) = 23.109, $p = 0.0001$; density: K-W H (2;36) = 24.55, $p < 0.0001$; number of individuals: K-W H (2;36) = 24.07, $p < 0.00001$; results significant.

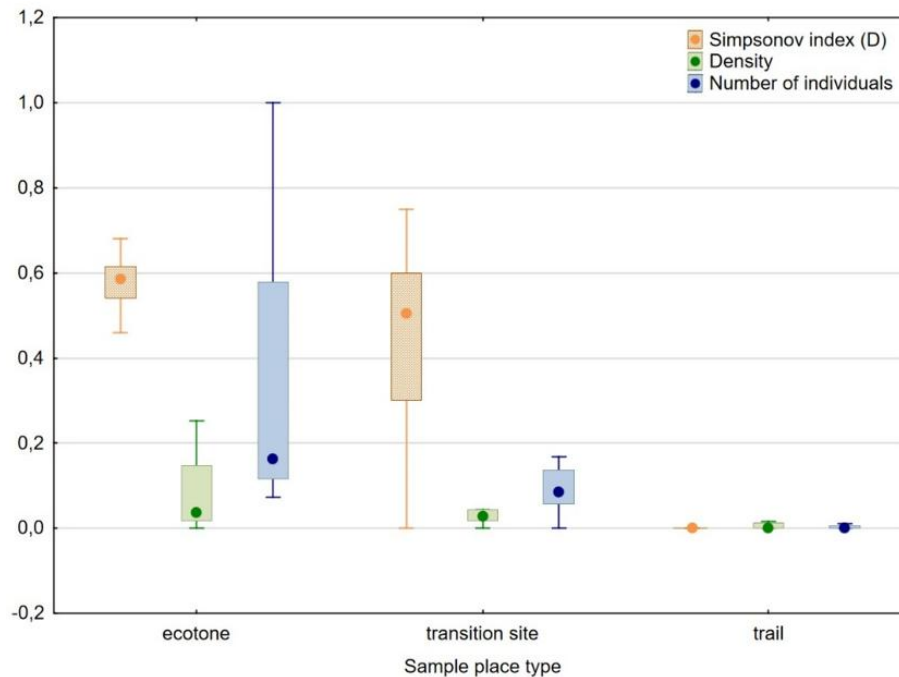


Figure 90. Sampling site types

The results show a clear gradient of ecological disturbance: Ecotone → Transition site → Trail. Biodiversity, density, and abundance decrease toward the trail. Areas with less disturbance support more diverse and abundant soil communities. The trail environment appears strongly degraded, likely due to tourism-related pressure.

5.3.2. Conclusions and Recommendations

The data indicate that human activity on the trail significantly reduces soil biodiversity and organism abundance, while nearby natural habitats (especially the ecotone) maintain healthier and more diverse soil communities. Several factors can influence the variability of results between different seasons, years, or sampling periods. These factors may affect species diversity, density, and the number of individuals in soil samples. Many soil organisms show seasonal life cycles, meaning their populations increase or decrease at specific times of the year. Different seasons strongly affect soil communities. Temperature influences the activity, reproduction, and survival of soil organisms. Soil moisture varies throughout the year. Availability of organic matter (e.g., fallen leaves in autumn) provides food and habitat. Because of these factors, abundance and diversity may be higher in some seasons (often spring or autumn) and lower in others (summer drought or winter cold). Environmental conditions can vary significantly from one year to another (wet vs. dry years). Extreme weather events (storms, droughts, heat waves) are also important. These conditions can influence soil moisture, vegetation growth, and decomposition rates, which in turn affect soil organisms. However, our results clearly indicate a strong influence of tourist activity on the soil community. On the trail, all measured indicators were significantly lower compared to less disturbed habitats. The most probable explanation for these differences is soil disturbance caused by tourism, including soil compaction from repeated trampling, removal or damage of the litter layer, increased soil erosion, reduced moisture retention, and habitat availability. These changes negatively affect soil microfauna, leading to lower abundance and reduced biodiversity.



Therefore, the results clearly demonstrate that tourist activity has a significant negative impact on soil biodiversity, particularly in the most heavily used parts of the trail. Soil organisms such as mites can serve as bioindicators because they react sensitively to environmental changes. By repeatedly measuring indicators such as Simpson's diversity index, density, and number of individuals, we can track how soil communities change over time at specific places. Variability in ecological results across seasons and years is influenced by a combination of environmental conditions, biological cycles, human disturbance, and methodological factors. For this reason, long-term and repeated sampling is important to obtain reliable conclusions about soil biodiversity and ecosystem changes.

5.4. Acoustic monitoring focused on bat populations

Protected Area: Bükk National Park Directorate

Project Partner: BNPD

Acoustic monitoring was deployed in the **Forrás-valley**, specifically targeting the **Kecske-lyuk cave** to evaluate the impact of human disturbance on protected bat populations. From the beginning of 2025, scheduled samplings have been regularly conducted, with sound recorders capable of saving approximately 24 hours of daily audio material. These devices monitor both human and bat activity from sixty minutes before sunrise to sixty minutes after sunset. The monitoring specifically targets several protected species, including hibernating populations of the lesser horseshoe bat (*Rhinolopus hipposideros*) and the greater horseshoe bat (*Rhinolophus ferrumequinum*). Additionally, the cave serves as a summer roost and breeding site for Schreiber's bat (*Miniopterus schreibersii*) and the Mediterranean horseshoe bat (*Rhinolophus euryale*).

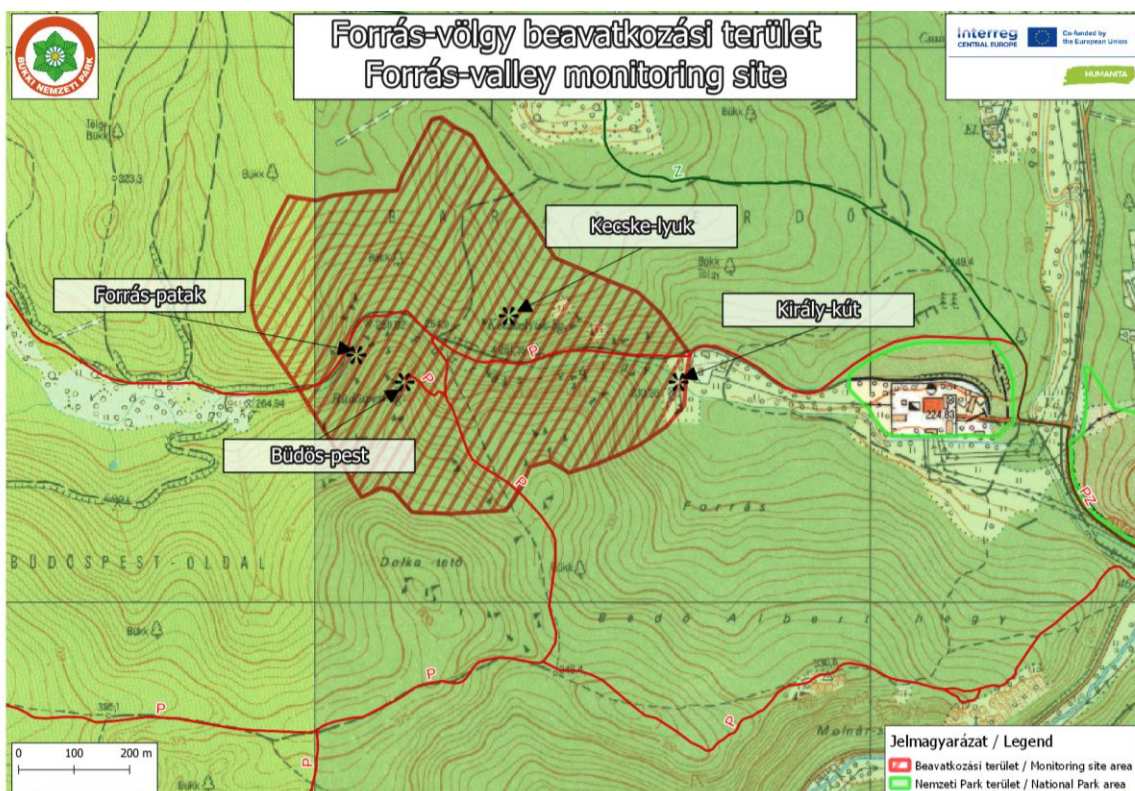


Figure 91. Forrás-valley pilot site

The Kecske-lyuk cave is a high-priority conservation site, playing a vital role as a marker species habitat for the Natura 2000 network within the regional populations of Hungary and the Carpathians. However, its proximity to the city of Miskolc and its large, accessible opening make it a popular destination for tourists despite being located directly next to a designated hiking trail. Although the bat colony has learned to



tolerate human disturbance to some extent, they occasionally relocate to the Herman Ottó rock cavity a few kilometers away when pressured. Typical forms of human interference include walking through cave passages, making fires at the entrance or inside the cave, littering, using the area as a toilet, and damaging cave surfaces with graffiti. Most alarmingly, direct harassment and destruction of bats have been observed, with dead or injured individuals suffering from bone fractures found on the cave floor.

Several practical limitations have been identified during this activity, such as the late seasonal arrival of target bat populations and rapid battery depletion of sensors triggered by high volumes of human and wildlife traffic. To support ongoing data collection, the purchase of at least 48 AA 2500mAh Eneloop batteries, 4 high-capacity memory cards, and 4Tb of external storage is justified. Once the raw audio files complete complex processing, the analysis is expected to definitively correlate the frequency and acoustic intensity of human disturbances with disruptions in the emergence and roosting behaviors of these protected colonies.

5.5. Biodiversity of earthworm population

Protected Area: Lower Kamenjak

Project Partner: PIK

The aim of the monitoring was to assess the biodiversity of earthworm population in the area of Lower Kamenjak, and the relation of microplastic pollution to the health of the habitats and the effect on earthworm population. The monitoring utilized a combination of soil sampling tools and molecular identification methods.

5.5.1. Results, assessment, and interpretation

Initial results have confirmed the presence of five species of earthworms with the most represented species being *Octodrilus bretscheri* and *Octodrilus istrianus* (Table 4). A single species has dominated most samples, which is consistent with ecological expectations for the habitat. Furthermore, the diversity of earthworm species reflects the rich biodiversity of the area, however, vegetation succession due to changes in land usage threatens the habitats. Tables and images included in this section come from the work carried out by Hackenberger Kutuzović and Hackenberger Kutuzović (2024)⁵.

Table 4. Frequency of earthworms from 50 sites on Lower Kamenjak⁵

SPECIES	FREQUENCY IN SAMPLES(%)
<i>Octodrilus kvarnerus</i>	73.91
<i>Octodrilus istrianus</i>	19.57
<i>Murchieona minuscula</i>	2.17
<i>Aporrectodea trapezoides</i>	2.17
<i>Aporrectodea rosea</i>	2.17

Using QGIS software, detailed maps were created to show the spatial distribution of earthworms and microplastic particles in the pilot area (Figure 92, Figure 93, Figure 94). Multiple spatial layers, including CORINE Land Cover, were used to deepen the analysis and improve the understanding of how earthworm communities relate to microplastic distribution across the different habitat types of Lower Kamenjak (Figure 95). Also, the trends in habitat quality reduction due to succession were identified.

⁵ Hackenberger Kutuzović, D., Hackenberger Kutuzović, B. (2024) Istraživanje koncentracije mikroplastike u tlu i monitoring distribucije gujavica (Oligochaeta: Crassicitellata) s posebnim osvrtom na endemsku vrstu *Octodrilus istrianus* na području značajnog krajobraza Donji Kamenjak: Završno izvješće o provedenoj usluzi.



Figure 92. *Octodrilus bretscheri* species distribution⁵



Figure 93. *Octodrilus istrianus* species distribution⁵



Figure 94. Species findings of: *Aporrectodea rosea* (green circle), *Murchieona minuscula* (red circle) and *A. trapezoids* (blue circle)⁵

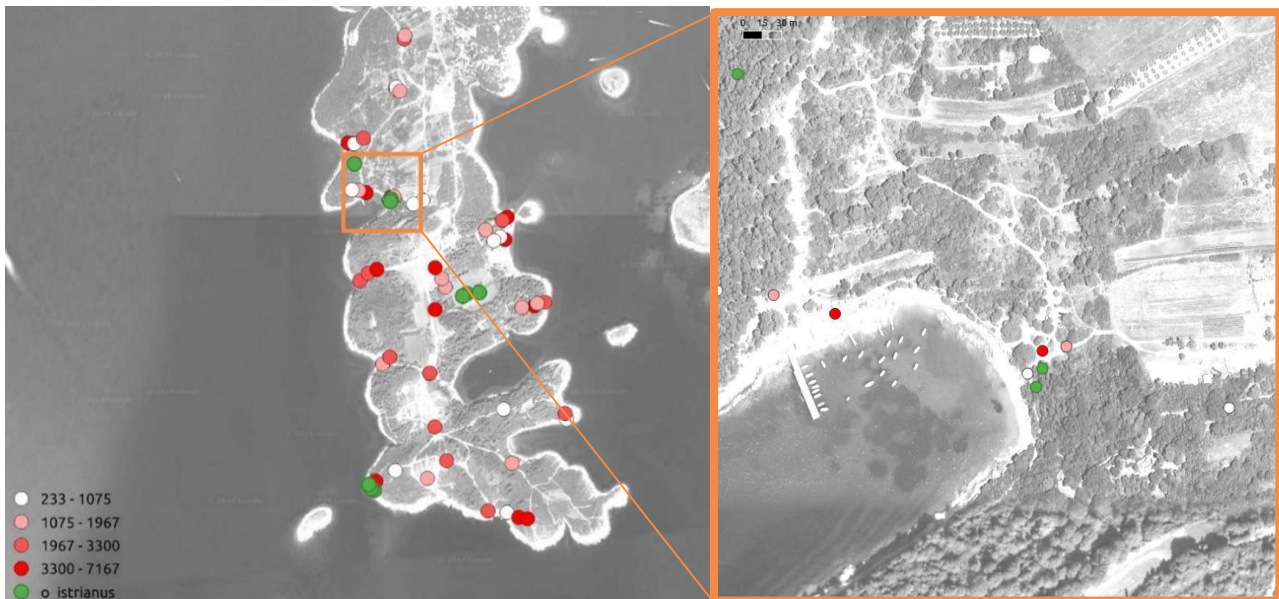


Figure 95. Overlapping between the distribution of microplastic particles (N/kg) and *Octodrilus istrianus* species distribution in the entire Lower Kamenjak (left), and in a specific section (right)

5.5.2. Conclusions and observations

Challenges encountered included difficult terrain outside of established paths, leading to access issues, as well as the impact of increased tourism and vegetation changes on sampling locations. The monitoring has to be continuous to assess changes in species diversity over time, especially when taking into account environmental pressures such as tourism and land usage changes. Also, it is crucial to establish a systematic monitoring program for earthworms and other soil organisms for tracking their status and assessing the effectiveness of conservation measures. Although preliminary, these findings highlight the potential of earthworms as bioindicators of soil quality and human disturbance/influence.

5.6. Bioacoustic monitoring of bird communities

Protected Areas: Tuscan-Emilian Apennine National Park

Project Partner: PNATE

In Val Parma Forest, four **bioacoustic sensors** were installed to investigate potential anthropogenic disturbance affecting bird communities in two locations selected for this purpose. Two main areas were identified, both originating from the location known as “I Cancelli”: one route leading to Rifugio Lagdei and the other to Rifugio Lagoni, both following unpaved roads accessible to vehicles (Figure 96). These routes are highly comparable in terms of environmental characteristics, as they are both surrounded by beech and fir forests.

Within each of these areas, suitable points were selected for the installation of paired bioacoustic sensors. In each pair, one sensor was placed in close proximity to the road, while the second was positioned further into the forest, at a greater distance from the vehicle-accessible track, identified as the main source of anthropogenic disturbance. This setup was designed to allow the comparison of bird vocal activity under different levels of disturbance, with the expectation of detecting variations in singing activity between the two conditions.

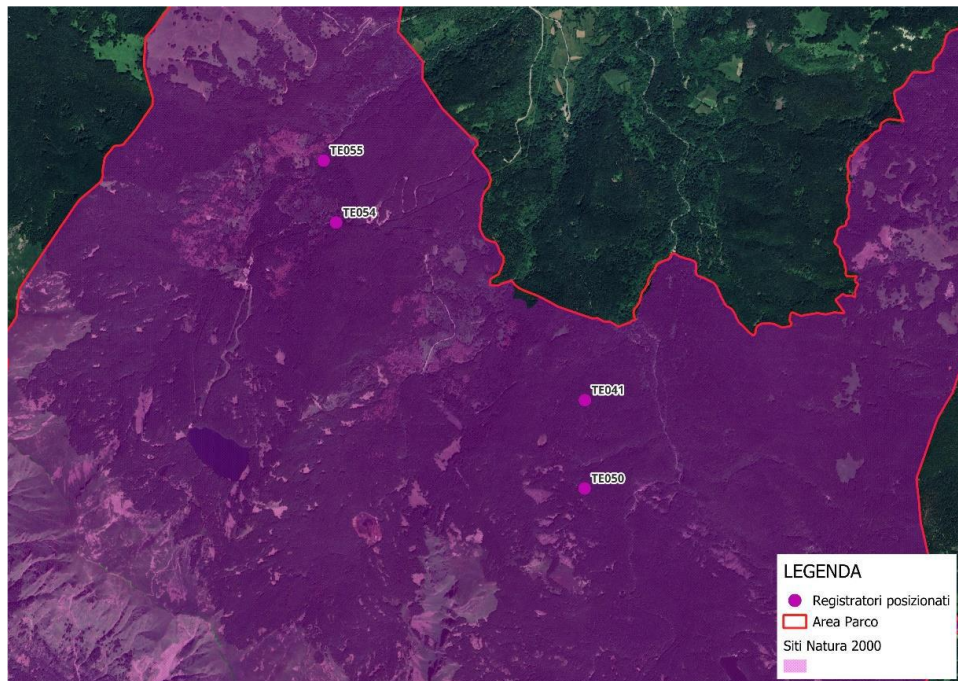


Figure 96. Location of recorders within the National Park borders

5.6.1. Data Handling and Analytical Methods

All data were collected through automated sensors, which were configured according to a standardized protocol developed in collaboration with expert ornithologists, and subsequently analysed using specialized software for species identification. The resulting data were organized in the form of bird species checklists. These checklists, initially generated by the software, were later validated by an expert ornithologist, ensuring the reliability of the final dataset and enabling comparisons across sites and sampling periods.

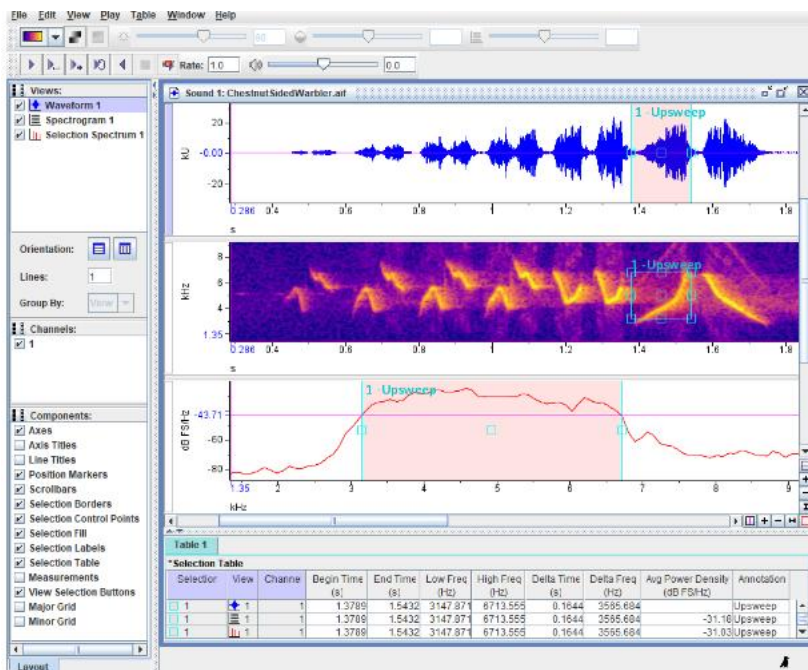


Figure 97. Kaleidoscope Pro sonogram visualization

In particular, to optimize recognition accuracy, the “species by location” function was applied by setting the specific geographic coordinates of each recording device. Recordings were processed in batch analysis mode with a 1-second overlap. The outputs were divided into 6-second audio segments and, for each species identified by the model, the 30 segments with the highest confidence scores were selected for verification. This validation was supported by additional software tools, such as Raven Lite 2 and Kaleidoscope Pro, which allowed a more detailed visualization of the sonogram (Figure 97).



This manual validation procedure was essential to confirm the software identifications and to correct potential false positives. Finally, the validated data on species detected at each recording station were organized and stored in a Microsoft Excel spreadsheet, with taxonomy and nomenclature following Baccetti et al. (2021)⁶.

5.6.2. Results, Assessment, and Interpretation

Bioacoustic monitoring provides a preliminary assessment of avian communities within the study areas, based on recordings collected through automated sensors and subsequently processed into structured species checklists. These outputs, generated by dedicated identification software and organized in Excel format, report the number and identity of detected species for each recording session and monitoring location. The results were then validated by expert ornithologists, ensuring a higher level of reliability and allowing for a more robust ecological interpretation of the data.

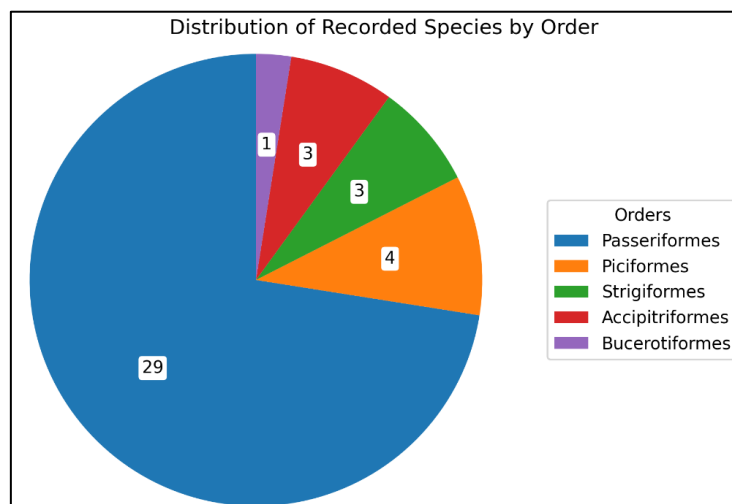


Figure 98. Taxonomic orders identified during the bioacoustic monitoring campaign

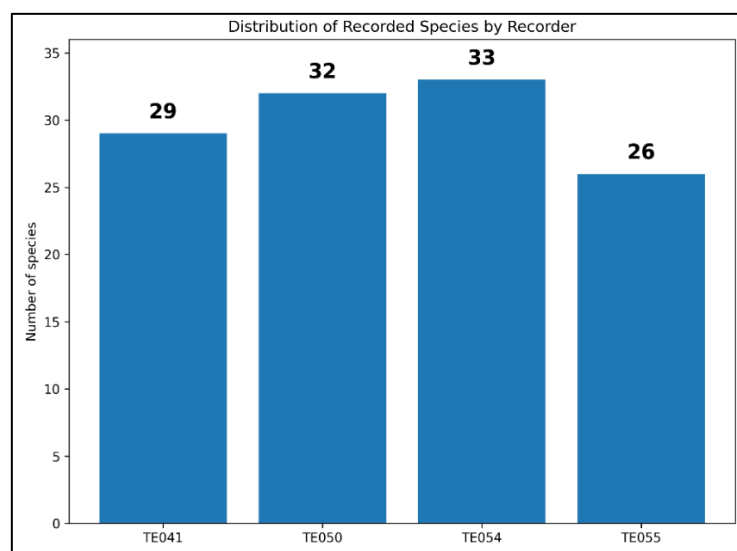


Figure 99. Species richness for each sensor

Overall, a total of 40 bird species were detected (Figure 98), of which only the Black Woodpecker (*Dryocopus martius*) is included in Annex I of the Birds Directive (2009/147/EC). The most represented order was

⁶ Baccetti, N., Fracasso, G., Commissione Ornitologica Italiana (COI) (2021). Lista CISO-COI 2020 degli uccelli italiani. AVOCETTA, 45: 1-64.



Passeriformes (N=29; 73% of the total), followed by Piciformes (N=4), Accipitriformes (N=3), Strigiformes (N=3) and Bucerotiformes (N=1). Among the recording units, TE054 showed the highest species richness (N=33), as illustrated in Figure 99.

Given the checklist-based structure of the dataset, the analysis primarily focuses on species presence and richness rather than on detailed abundance or activity patterns. Nevertheless, the monitoring design, which includes sensors placed both near areas of higher human activity (e.g. roads) and in more undisturbed forest environments, allows for a qualitative assessment of potential differences in species occurrence along disturbance gradients. In this context, differences in species composition or richness between recording units may reflect variations in habitat conditions or levels of anthropogenic pressure.

Although the dataset does not support detailed quantitative analyses or robust assessments of temporal trends, the validation and interpretation carried out by ornithologists enable the data to be meaningfully related to environmental factors and potential tourism-related disturbance. This approach provides a useful baseline for understanding how human presence may influence avian communities, while acknowledging the limitations linked to the structure of the data, the need for expert validation, and the relatively short monitoring period.

All collected data were compiled in a comprehensive database (provided in Excel format, see Figure 100 as an example), including species occurrence per recorder, regional phenology (Bagni et al., 2003)⁷, SPEC conservation categories (BirdLife, 2017)⁸, and threat status according to the Italian Red List of breeding birds (Gustin et al., 2021)⁹, supporting future monitoring and more detailed analyses.

	A	B	C	D	E	F
1	Registratore	Periodo	Specie	Ordine	Contatti ≥ 10	Contatti < 10
2	TE041	01/08/2025-10/10/2025	<i>Fringilla coelebs</i>	Passeriformi	TRUE	FALSE
3	TE041	01/08/2025-10/10/2025	<i>Garrulus glandarius</i>	Passeriformi	TRUE	FALSE
4	TE041	01/08/2025-10/10/2025	<i>Phylloscopus collybita</i>	Passeriformi	TRUE	FALSE
5	TE041	01/08/2025-10/10/2025	<i>Turdus merula</i>	Passeriformi	TRUE	FALSE
6	TE041	01/08/2025-10/10/2025	<i>Erithacus rubecula</i>	Passeriformi	TRUE	FALSE
7	TE041	01/08/2025-10/10/2025	<i>Sitta europaea</i>	Passeriformi	TRUE	FALSE
8	TE041	01/08/2025-10/10/2025	<i>Dendrocopos major</i>	Piciformi	TRUE	FALSE
9	TE041	01/08/2025-10/10/2025	<i>Dryobates minor</i>	Piciformi	FALSE	TRUE
10	TE041	01/08/2025-10/10/2025	<i>Picus viridis</i>	Piciformi	TRUE	FALSE
11	TE041	01/08/2025-10/10/2025	<i>Buteo buteo</i>	Accipitriformi	TRUE	FALSE
12	TE041	01/08/2025-10/10/2025	<i>Certhia sp.</i>	Passeriformi	TRUE	FALSE
13	TE041	01/08/2025-10/10/2025	<i>Troglodytes troglodytes</i>	Passeriformi	TRUE	FALSE
14	TE041	01/08/2025-10/10/2025	<i>Turdus viscivorus</i>	Passeriformi	TRUE	FALSE
15	TE041	01/08/2025-10/10/2025	<i>Turdus philomelos</i>	Passeriformi	TRUE	FALSE
16	TE041	01/08/2025-10/10/2025	<i>Periparus ater</i>	Passeriformi	TRUE	FALSE
17	TE041	01/08/2025-10/10/2025	<i>Parus major</i>	Passeriformi	TRUE	FALSE
18	TE041	01/08/2025-10/10/2025	<i>Cyanistes caeruleus</i>	Passeriformi	TRUE	FALSE
19	TE041	01/08/2025-10/10/2025	<i>Pyrrhula pyrrhula</i>	Passeriformi	TRUE	FALSE
20	TE041	01/08/2025-10/10/2025	<i>Ardea cinerea</i>	Ardeidi	FALSE	TRUE
21	TE041	01/08/2025-10/10/2025	<i>Strix aluco</i>	Strigiformi	TRUE	FALSE

Figure 100. Excel file summarizing the collected data

5.6.3. Conclusions and observations

Bioacoustic monitoring provides a valuable, non-invasive tool for assessing avian communities and establishing a baseline of species presence.

⁷ Bagni, L., Sighele, M., Passarella, M., Premuda, G., Tinarelli, R., Cocchi, L., Leoni, G. (2003) Check-list degli uccelli dell'Emilia-Romagna dal 1900 al giugno 2003. PICUS, 29 (2): 85-107

⁸ BirdLife International. (2017). European birds of conservation concern: populations, trends and national responsibilities. BirdLife International, Cambridge, UK

⁹ Gustin, M., Nardelli, R., Bricchetti, P., Battistoni, A., Rondinini, C., & Teofili, C. (2021). Lista Rossa degli uccelli nidificanti in Italia 2021. Comitato Italiano IUCN e Ministero della Transizione Ecologica, Roma



The detection of 40 species, validated by expert ornithologists, confirms the ecological relevance of the monitored areas. The monitoring design, based on sensors placed along a disturbance gradient, enables a preliminary qualitative assessment of potential effects of human presence on bird communities; however, the current dataset—structured as species checklists—limits the possibility of conducting detailed quantitative analyses, such as examining activity patterns or estimating abundance. The relatively short monitoring period further constrains the interpretation of temporal dynamics.

Future developments should aim to extend monitoring over longer time periods to capture seasonal and interannual variability, to collect more detailed metrics such as acoustic activity indices and detection frequency instead of relying solely on species presence, and to standardize recording protocols to improve comparability across sites and periods. Strengthening the integration between bioacoustic data and environmental variables—including visitor pressure—would allow a more robust understanding of disturbance effects, while the exploration of advanced analytical approaches could improve assessments of how wildlife responds to human activities. Overall, bioacoustic monitoring should continue to be developed as a complementary tool within an integrated ecological monitoring framework.



6. Pollution monitoring

6.1. Surface Water Quality

Protected Area: Malá Fatra National Park

Project Partner: UNIZA

Tourists can cause or increase surface water pollution in several ways:

- Littering: Plastic bottles, wrappers, and other trash can end up in rivers and lakes.
- Sewage from accommodation: Hotels, lodges, and other tourist facilities may release wastewater into nearby water.
- Soaps and cosmetics: Sunscreens, detergents, and other chemicals wash into the water.
- Ski resorts: Artificial snowmaking, chemicals, and increased runoff can pollute streams.
- Boat and fuel pollution: Oil or fuel leaks from boats and jet skis contaminate water.

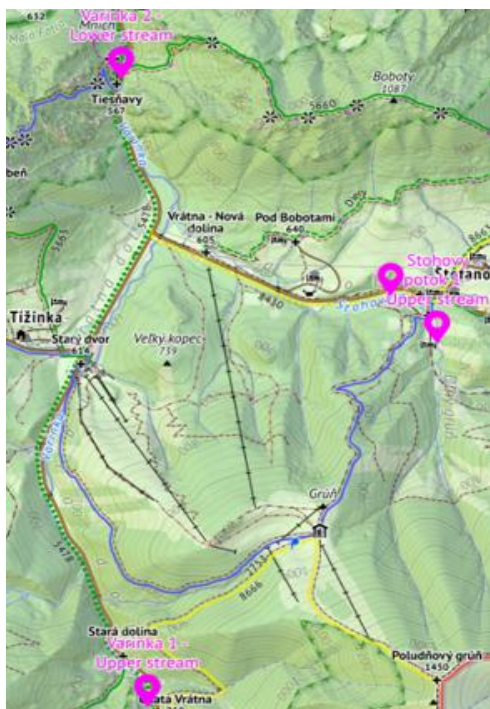


Figure 101. Sampling point in Vrátna Valley

In Malá Fatra National Park, the cumulative effects of various human activities may contribute to the deterioration of river water quality. Tourism contribute to direct water pollution through the improper disposal of solid waste. Accommodation facilities may also represent a potential source of pollution if adequate waste and wastewater management systems are not implemented. A ski resort is also located in the studied area. For this reason, the sampling locations were selected to capture possible impacts of these sources on surface water quality. The objective of this monitoring was to confirm or exclude the potential influence of recreational human activities on water quality in the Varínka River (Vrátna Valley) and in the Stohový Stream, which flow through the ski resort Vrátna and settlement of Štefanová, an important tourist centres in Malá Fatra National Park. We placed the monitoring points in such a way that they help us clarify the impact of tourist infrastructure (cable car, accommodation and dining facilities, ski resort) associated with intensive human activity. Four sampling points were selected to represent different levels of potential human impact within the Vrátna Valley catchment (Figure 101).

They included reference sites with minimal anthropogenic influence, locations potentially affected by tourism and settlement activities, and a downstream site representing the overall water quality leaving the valley. The Varínka 1 site (below Chata Vrátna) represents baseline water quality of the main stream in the upper part of the valley. Stohový potok 1 (near Chata Vyhnaná) serves as a reference point for the Stohový stream catchment upstream of the Štefanová settlement. Stohový potok 2 (below the Štefanová settlement) was selected to assess the potential impact of the settlement and tourism infrastructure on water quality. The final point, Varínka 2 (Tiesňavy), represents the cumulative water quality of the Varínka River after the confluence of tributaries from the Vrátna Valley.

Water samples were collected at bi-weekly intervals from all four sampling points in period 8/2024-8/2025. During the laboratory analysis, several quality indicators were determined, including chemical oxygen demand (COD), physical parameters, pH, and basic chemical indicators (nitrates, ammonium nitrogen, total hardness, phosphates, chlorides, and sulfates). COD was analysed using a standardized manganometry



titration method. Chemical analysis was performed by spectrophotometry using the Novel Palintest method with a YSI 9500 Photometer. Physical parameters and pH were measured with a WTW Multi 3430 multimeter. Turbidity was determined using the nephelometric method, which compares absorbed and transmitted light through the liquid, using a YSI Turb® 430 T device. After the data collection and validation period, the results were evaluated using statistical methods while also considering seasonal visitor numbers and weather conditions.

6.1.1. Processing and preliminary examination of the water quality dataset

The primary objective was to understand the trends and variability of key water quality parameters at the four designated sampling points. The procedure was executed as follows:

1. Data loading and validation: The raw dataset was loaded and systematically inspected for completeness, format consistency, and potential outliers. All numerical values were standardized to a consistent data type to ensure computational accuracy.
2. Selection of key indicators widely recognized as indicators of municipal wastewater and human-induced pollution:
 - Chemical Oxygen Demand (COD): An aggregate measure of organic pollution.
 - Conductivity: A proxy for the total dissolved solids, indicative of inorganic and ionic pollutants.
 - Ammonium ions (NH_4^+): A primary indicator of recent sewage or wastewater contamination.
 - Nitrates (NO_3^-): An indicator of older, more oxidized organic pollution or septic system leachate.
 - Phosphates (PO_4^{3-}): A critical indicator of contamination from detergents and domestic wastewater.
 - Turbidity: A measure of water clarity affected by suspended solids, which can be linked to runoff and pollution events.
3. Calculation of descriptive statistics: For each key indicator at every sampling point a comprehensive set of descriptive statistics was computed. This included the number of observations (n), mean, median, standard deviation, minimum, and maximum values.

6.1.2. Results, Assessment, and Interpretation

6.1.2.1. Comparative Analysis and Testing of Hypothesis H1 (Impact of the Štefanová Settlement)

This analysis focused on a statistical comparison of the water quality of the Stohový potok stream, specifically contrasting the reference site located upstream of the Štefanová settlement (Stohový potok 1) with the impacted site located downstream (Stohový potok 2). The primary objective was to statistically test Hypothesis H1: that recreational and residential activities within the settlement exert a significant, measurable impact on water quality.

To visually assess the differences in data distribution between the two sites, box plot diagrams were generated (Figure 102) for the key pollution indicators (phosphates, ammonium ions, and COD) This graphical method is highly effective for comparing distributions, as it illustrates the median, interquartile range (IQR), and the full range of the data, thereby highlighting systematic shifts in concentration and variability.



Comparison of Ammonium Ion (NH₄⁺) Concentrations

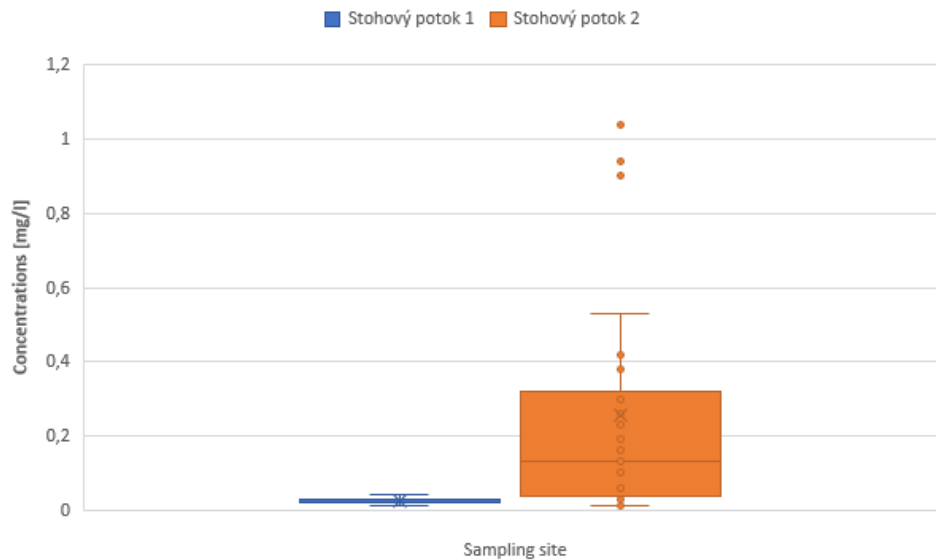


Figure 102. Comparison of ammonium Ion (NH₄⁺) concentrations

The magnitude of the impact was quantified by calculating the percentage increase in the mean concentration of each indicator between the reference and impacted sites (Table 5)

Table 5. Summary of mean concentration increases and statistical significance testing between Stohový potok 1 and Stohový potok 2

Parameter	Mean: Stohový potok 1 [mg/l]	Mean: Stohový potok 2 [mg/l]	Mean Increase	p-value	Statistical Significance
PO ₄ ³⁻	0.04	0.20	+400 %	< 0,001	Highly Significant
NH ₄ ⁺	0.02	0.28	+1300 %	< 0,001	Highly Significant
COD	1.26	2.01	+60 %	< 0,001	Highly Significant

To formally test the hypothesis, the Mann-Whitney U test, a non-parametric statistical test, was employed. This test was selected due to its robustness and suitability for environmental datasets, which often do not conform to a normal distribution. The test evaluates the null hypothesis (H0): There is no statistically significant difference in the median concentrations of the indicator between Stohový potok 1 and Stohový potok 2. against the alternative hypothesis (H1).

The results obtained in this step strongly support Hypothesis H1.

- Confirmation of anthropogenic impact:** The visual and statistical analyses converge to demonstrate that the Štefanová settlement is a significant source of water pollution. The observed increases in pollutant concentrations are not attributable to random chance ($p < 0.001$).
- Nature of pollution:** The specific chemical signature of the pollution characterized by a dramatic rise in both phosphates and ammonium ions is a classic indicator of contamination from municipal wastewater. This strongly points towards sources such as malfunctioning small-scale wastewater treatment facilities, septic tank leakages, or direct discharge of sewage and detergent-rich greywater.
- Statistical certainty:** The extremely low p-values indicate that there is less than a 0.1% probability that the observed differences are coincidental. Therefore, we can conclude with a high degree of confidence that the source of contamination is located within the stream segment between the two sampling points.



Conclusion: Hypothesis H1, stating that pollutant concentrations are significantly higher at the Stohový potok 2 site compared to the Stohový potok 1 site, is **confirmed**.

The objective was also to test **Hypothesis H2**, which posits that the **pollution signature from the impacted tributary would be detectable in the main river channel post-confluence, but that its magnitude would be attenuated due to dilution**. This was confirmed.

Hypothesis H3 investigates the temporal dynamics of the pollution load, which posits that pollutant concentrations will correlate with periods of high tourist activity. Line graphs were created for the primary pollution indicators (phosphates and ammonium ions), plotting their concentrations against the sampling date (Figure 103). Each of the four sampling sites was represented by a distinct colored line, facilitating direct comparison of their temporal behavior throughout the monitoring period (August 2024 - August 2025).

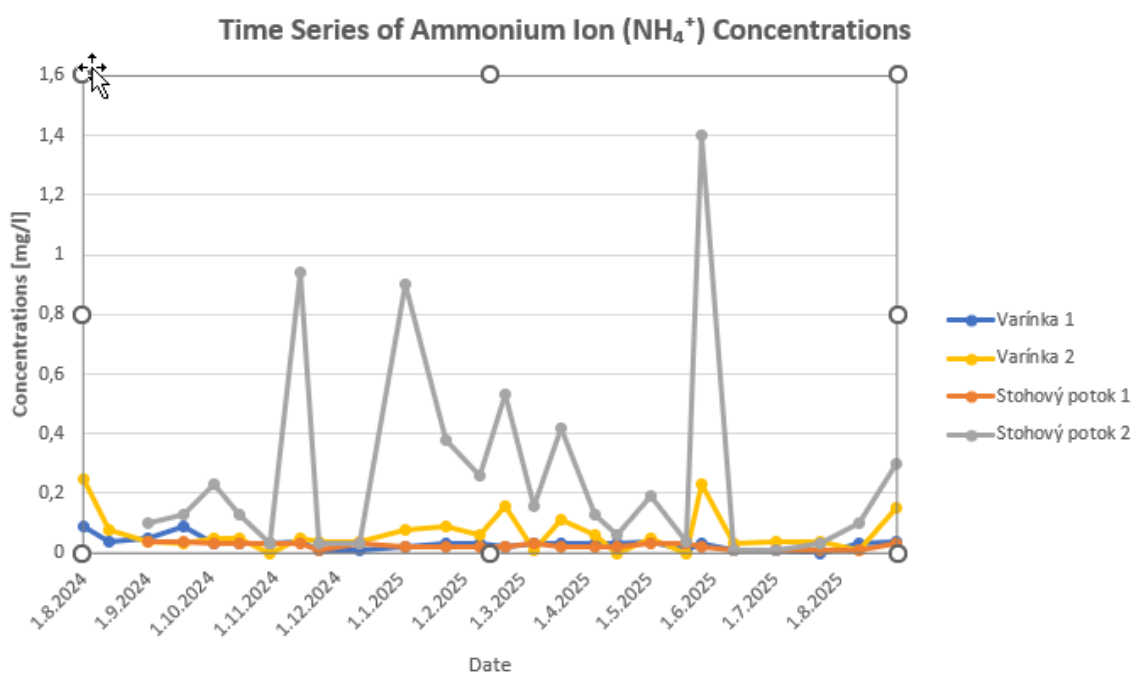


Figure 103 Ammonium ion concentrations

The time series for ammonium ions reveals a more episodic pollution pattern, characterized by sharp, intermittent concentration peaks. The reference sites remain near the detection limit. The Stohový potok 2 site exhibits several extreme concentration peaks, most notably in November 2024, during the January-February 2025 period, and again in May-June 2025. These sharp peaks are indicative of acute, high-intensity discharge events. The data clearly indicates that the pollution at Stohový potok 2 is a chronic, year-round issue. Superimposed upon this baseline level of contamination are acute, high-magnitude events. A plausible correlation with tourism activity can be inferred. The pronounced ammonium peaks during January and February 2025 align well with the high winter tourist season. The elevated levels of both indicators in May and June 2025 coincide with the onset of the summer season, a period of increased visitor traffic.

The data, however, also presents complexities. The relatively lower concentrations during the main summer holiday month of August 2025 and the high phosphate peak in the off-season month of October 2024 suggest that other variables are also influencing the results. These could include specific discharge events from accommodation facilities or meteorological factors, such as heavy rainfall which may cause septic system overflows.

6.1.3. Conclusions and Recommendations

The monitoring has yielded clear and actionable results: this statistical evaluation of the monitoring data provides conclusive evidence that the recreational settlement of Štefanová acts as a significant point source



of pollution, severely degrading the water quality of Stohový potok and measurably impacting the main Varínka river within the Malá Fatra National Park. The problem is chronic and is further exacerbated during peak tourist seasons. These results also align with data from a 2022-2023 bachelor's thesis study, confirming identical pollution patterns.

The results of this study provide a robust, evidence-based foundation for environmental protection and water management authorities to conduct targeted inspections of wastewater management practices at all commercial and residential properties within the Štefanová settlement. To further resolve the relationship between tourism intensity and pollution events, the monitoring program could be enhanced by integrating it with data on tourist numbers and accommodation occupancy rates. The findings clearly indicate that the current wastewater infrastructure is inadequate. A long-term, systemic solution is required to mitigate the ongoing pollution and protect the sensitive aquatic ecosystem of the national park.

6.2. Hulladékradar – citizen science approach

Protected Area: Bükk National Park Directorate

Project Partners: BNPD, CEEweb

Monitoring of illegal waste dumping was conducted across the entire Bükk National Park Directorate operational area using the Hulladékradar citizen science application in collaboration with the Hungarian Ministry of Energy.

The key outcome of this activity was the successful mapping of distinct clusters of illegal dumpsites within protected boundaries (Figure 104). A prominent trend identified during the analysis was that nearly a quarter of all reported dumpsites were located within ten meters of an established road, and the significant volumes of these piles indicate organized, local fly-tipping rather than incidental littering by passing hikers.

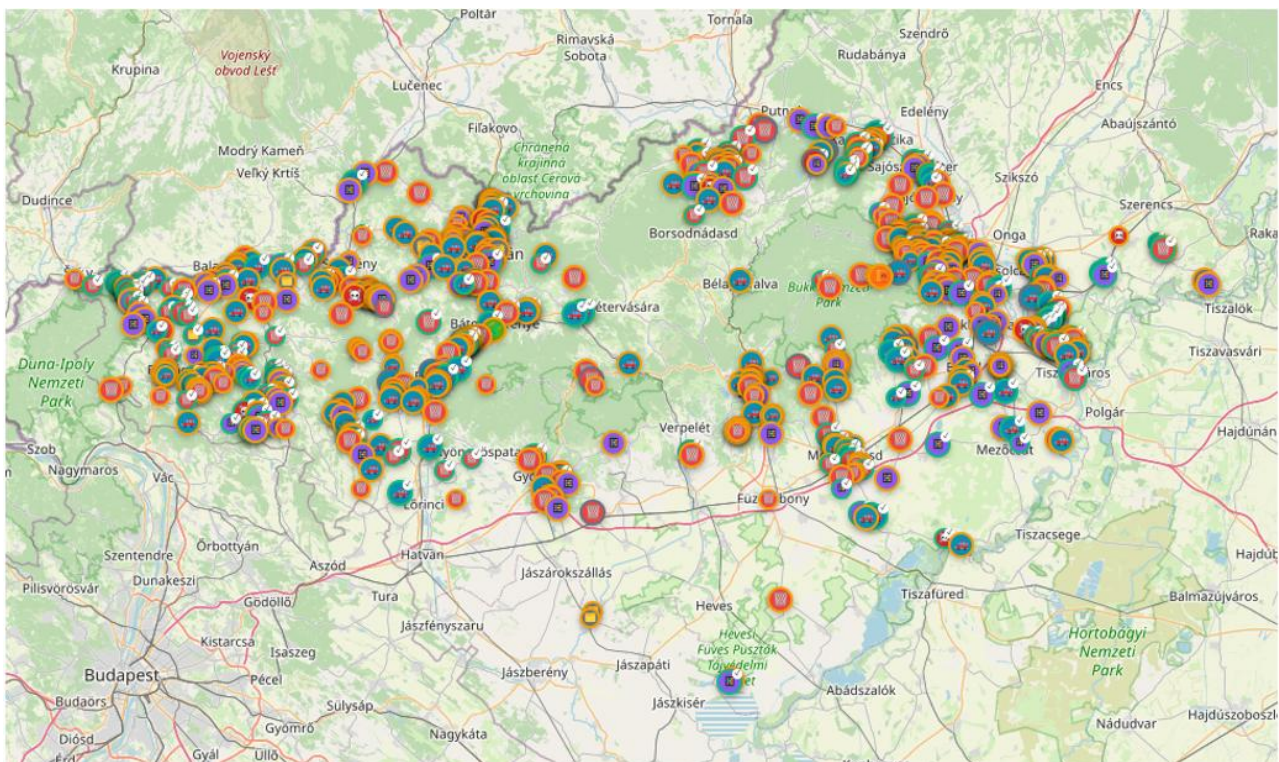


Figure 104. Waste dumping locations recorded with the Hulladékradar app, visualized on the HUMANITA dashboard

Based on the available indicators within the reporting system, the most prevalent form of illegal dumping in the region is mixed municipal and household waste, which was identified in 3414 distinct reports. The second most frequent category encompasses packaging materials and plastics, recorded at 2634 sites.



Furthermore, heavy pollutants such as construction and demolition debris are a major concern, having been flagged at 1248 locations. Other notable forms of pollution include green waste and glass, which were present in approximately 918 reports, alongside hundreds of instances involving hazardous materials like discarded tires and electronic appliances.

In terms of remediation and the resolution of these reports, the data indicates a relatively active response from regional authorities. Out of the total recorded sites, 1368 locations, representing approximately 35.6% of the dataset, have been successfully cleared and marked as removed. Conversely, 1050 reports were classified as requiring no task or the waste could not be found, which typically points to false alarms, duplicate reports, or instances where the waste was cleared prior to an official inspection. At the time of this analysis, 477 reports are actively being processed by the regional government offices in Heves, Borsod-Abaúj-Zemplén, and Nógrád counties, while 439 newly logged sites remain in the reported status and are awaiting their initial inspection.

The volume of illegal waste is primarily categorized by estimated cubic meters, highlighting a widespread issue of medium-scale dumping. The most common occurrence is medium-sized dumps ranging from one to five cubic meters, which accounts for 1719 reports and typically represents the capacity of a small truck or trailer. Smaller accumulations of less than one cubic meter were reported 1350 times. More severe, large-scale dumping involving volumes greater than five cubic meters was recorded at 767 distinct sites. When aggregating the specific numerical quantities provided for cleared sites, the region has seen the removal or reporting of nearly two million units of waste, which likely translates to roughly 1973 metric tons of environmental pollution.

Finally, a spatial analysis was conducted to determine how close these reported dumping sites are to the core protected areas within the BNPD's jurisdiction, including the Bükk National Park and the surrounding Landscape Protection Areas of Mátra, Lázberc, Hollókő, and Tarnavidék. The average distance from an illegal dump to the geographic center of the nearest protected area is 22.3 kilometers. This suggests that the vast majority of illegal dumping takes place in peripheral buffer zones, agricultural lands, and the outskirts of settlements, rather than deep within the protected forests. However, twenty-five percent of all recorded sites are located within 15.3 kilometers of a protected area center, indicating a significant and consistent environmental pressure on the borders of these nature reserves. Most alarmingly, the closest reported illegal dumps are situated a mere 660 meters from the core of a protected zone, meaning these specific pollution events occurred directly inside the legally protected boundaries, posing a direct threat to the local flora and fauna.

6.2.1. Improvements for future data collection

The primary limitation of this activity is the severe reporting gap caused by public perception, as most visitors assume national park staff are already aware of and responsible for waste removal, resulting in very low user engagement within the deep protected zones.

Consequently, the analysis highlights that while the application is excellent for identifying large-scale peripheral pollution, it is currently insufficient for accurately capturing the micro-littering footprint directly caused by standard pedestrian tourism, and cannot be considered as a valid substitute for structured, professional environmental monitoring in isolated protected areas.

In this context, the continuous promotion of the Hulladékradar app within the actual boundaries of the national park is necessary to increase reporting coverage and overcome the public misconception regarding waste management responsibilities.



6.3. Microplastic and macroplastic identification

Protected Area: Lower Kamenjak and Medulin Archipelago

Project Partner: PIK

Pollution monitoring was performed by analysing micro and macroplastic pollution in the area of Lower Kamenjak and Medulin Archipelago:

- Microplastic pollution - the aim of the monitoring was to analyze the microplastic pollution near the 10 parking zones, and to analyze the impact of microplastics on the distribution of earthworms, which was done by experts from the University of J.J. Strossmayer from Osijek. Samples were collected in triplicate from 50 different locations to ensure data representativeness and precision in analyzing the spatial distribution of microplastics across the area.
- Macroplastic pollution - PIK has engaged experts from the Center for Marine Research Rovinj to collect macroplastics on selected pilot beaches of Školjić, Polje, and the island of Ceja. The methodology was aligned with the standards set by the Interreg Med Plastic Busters MPAs project, which measured litter density as the number of items per 100-meter stretch.

6.3.1. Results - Microplastic pollution

The results indicated a wide variability in microplastic concentrations, ranging from 0 to as high as 14800 particles per kg of dry soil, with an average of 2460 particles. The distribution of microplastic particles shows that areas near popular trails, main roads, and tourist zones have higher concentration values (Figure 105). However, there are some inconsistencies, which suggest the effect of wind, rain, waterways, erosion, and seasonal human activities on microplastic spread through the area.

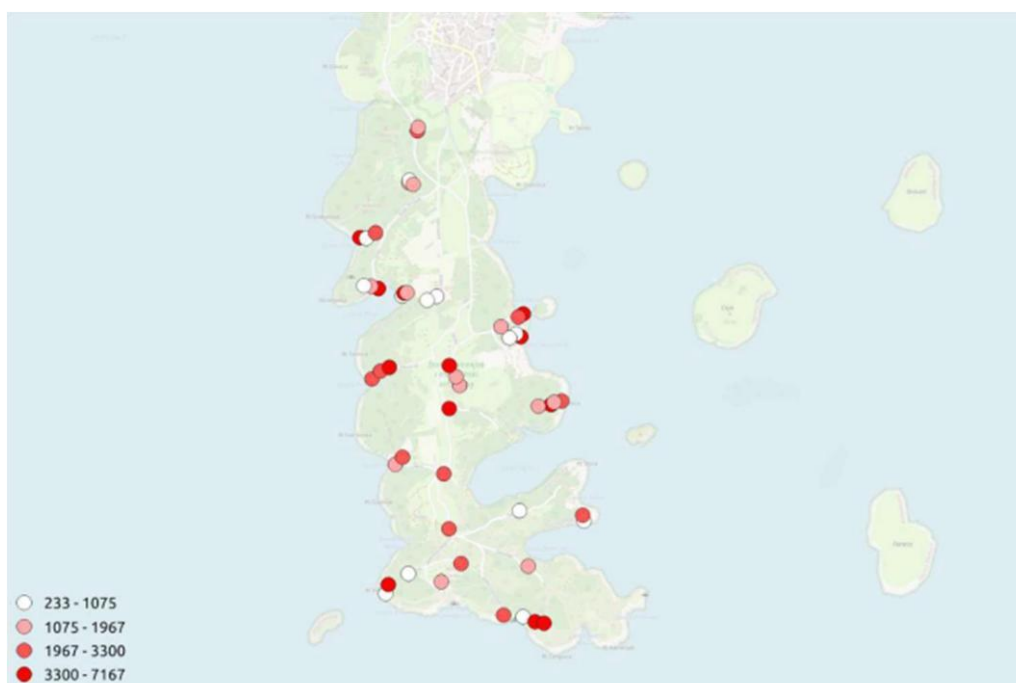


Figure 105. Distribution of microplastic particles (N/kg) across Lower Kamenjak (The number of particles is divided into quartiles)

6.3.2. Results - Macroplastic pollution

Stranded litter on three pilot beaches was collected through all seasons (Summer, Fall, Winter, Spring) by external experts from the Center for Marine Research Rovinj. The litter was categorized into eight groups, namely plastic, rubber, cloth, paper, processed wood, metal, glass, other (Table 6).



Table 6. Waste categories found on pilot sites¹⁰

WASTE CATEGORY	SHARE(%)
Plastic	85
Rubber	1
Textile	2
Paper	2
Wood	4
Metal	3
Glass	2
Other	1

Selected groups with more than 20 items per sampling were further analyzed for material composition using an Agilent 4500 Series Portable FTIR Spectrometer. Material analysis was conducted on a total of 690 items from the study, divided into individual groups (Table 7). The most common was xylon and olefin fibers, which are commonly used in textile and other industries.

Table 7. Material analysis of litter found on the three pilot beaches in the Lower Kamenjak and Medulin archipelago area¹⁰

MATERIAL	Percentage %
Xylon, Olefin fiber	17.10
Amaco Olefin, Olefin fiber	7.10
Styreneethylene/Butylenestyrene block copolymer used for roller skate break	5.80
Polyethylene plasticized #2	4.93
Polypropylene	4.78
Polypropylene, Olefin fiber	3.77
Linear low density polyethylene film	3.33
Polyolefin foam	2.32
MS2A-Resin	2.32
CP 310 W(Dried)	2.03
Highly filled and softened copolymer used for beach shoe	2.03

6.3.3. Conclusions

Comparing microplastic levels in Lower Kamenjak to other European regions is challenging since there are no standardized techniques for extraction and quantification, and thus, various extraction methods can significantly affect results. Also, with macro and microplastic pollution monitoring, other forms of pollution, like heavy metal pollution have to be monitored to get a clearer picture about overall pollution of the area and thus the effect of human impact on the area. It is also important to highlight the dependence on seasonal tourism when there are extreme pressures in a short period, as the dominance of recreational activities also reduces the attention to the rules of conservation.

¹⁰ Smodlaka Tanković, M. (2025) *Analiza otpada makroplastike naplavljenog na plažama Polje, Školjić i na otoku Ceja: Izvješće*. Rovinj: Institut Ruđer Bošković, Centar za istraživanja mora.



7. Other monitoring

7.1. Water consumption due to tourists presence

Protected Areas: Tuscan-Emilian Apennine National Park

Project Partner: PNATE

In the Monte Cusna area, **water use** was **analysed** by a methodology that was designed to assess the impact of seasonal tourism on groundwater resources within the Appennino Tosco-Emiliano National Park, focusing on the aqueduct system of the Municipality of Toano, which captures water from a group of springs located on the north-eastern slopes of Mt. Cusna (Figure 106). This case study was selected due to the availability of detailed spring discharge data, making it possible to evaluate variations in groundwater availability in relation to tourist flows, particularly during peak periods and low aquifer recharge conditions.

The approach integrated multiple datasets, including the geological and geomorphological framework, hydrogeological setting, aqueduct system characteristics, and historical time series (2018-2022) covering spring discharge, water quality, climatic variables, water use, and seasonal variations in users, with specific attention to tourism-related demand. These data were complemented by information provided by the local water management authority.

In addition, field surveys were conducted to assess spring capture systems, their state of conservation, and the presence and management of overflow, as well as to identify springs still in natural conditions through a citizen science initiative. Data collection activities continued over time, with ongoing updates and validation, and all datasets were organized in a georeferenced digital format (QGIS). This integrated methodology allowed for the reconstruction of the hydrogeological framework of the area and the evaluation of water resource capacity, vulnerability, and potential impacts related to tourism pressure.

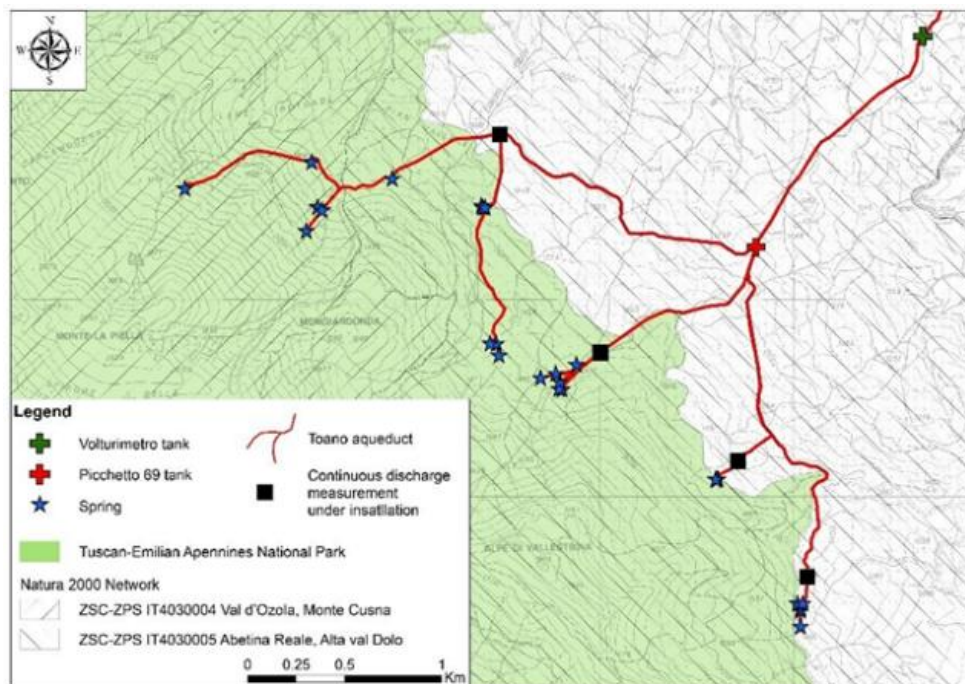


Figure 106. Location of springs and accessory infrastructures connected to the Toano aqueduct

The collected data—including hydrogeological, climatic, and water use parameters—were integrated with available historical time series and organized into structured datasets. Within the platform, these data were further processed and converted into graphical outputs, allowing the analysis of water demand trends in relation to seasonal variability and tourism pressure.



Overall, the adoption of a single platform enabled the standardization of the data management workflow and the integration of multiple data sources within a coherent system. The analyses were conducted through a combined approach based on graphical visualization, temporal analysis, and expert validation, while addressing the challenges associated with managing large volumes of heterogeneous data.

7.1.1. Quantitative and qualitative findings

The collected data include historical time series of spring discharge, hydrochemical parameters, climatic variables (e.g., temperature and precipitation), and information on water supply systems and user demand (Figure 107, Figure 108, and Figure 109). These datasets provide a framework for evaluating seasonal variability in water availability and consumption.

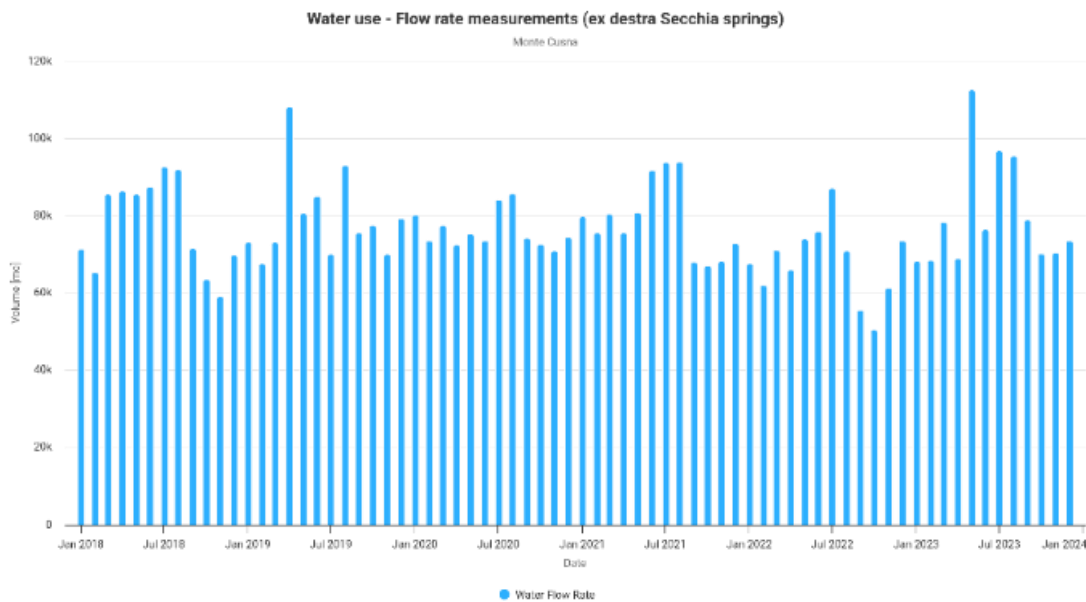


Figure 107. Water flow rate measurements

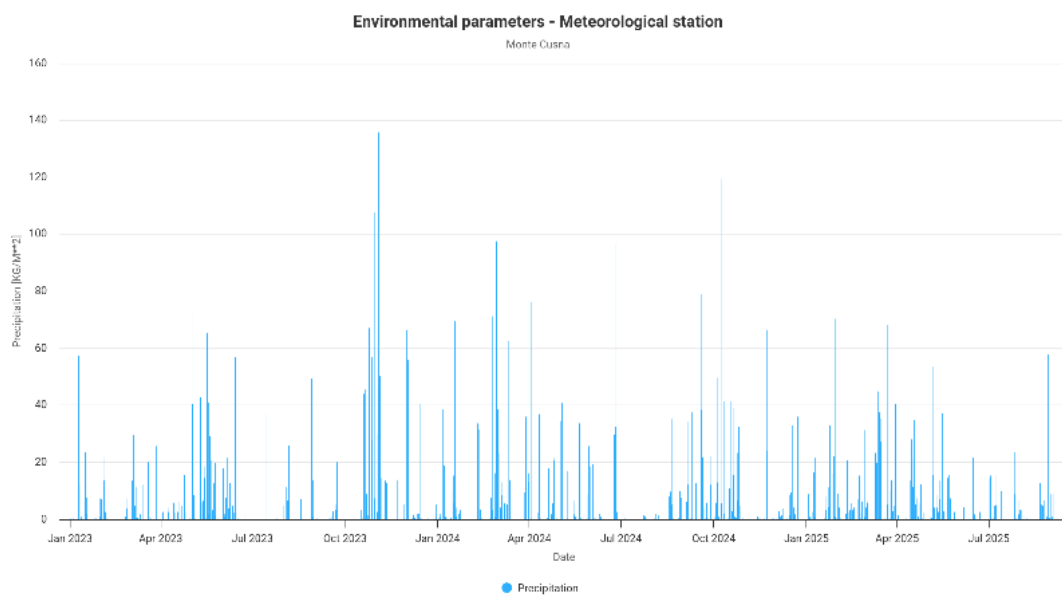


Figure 108. Rainfall data collected by the weather station

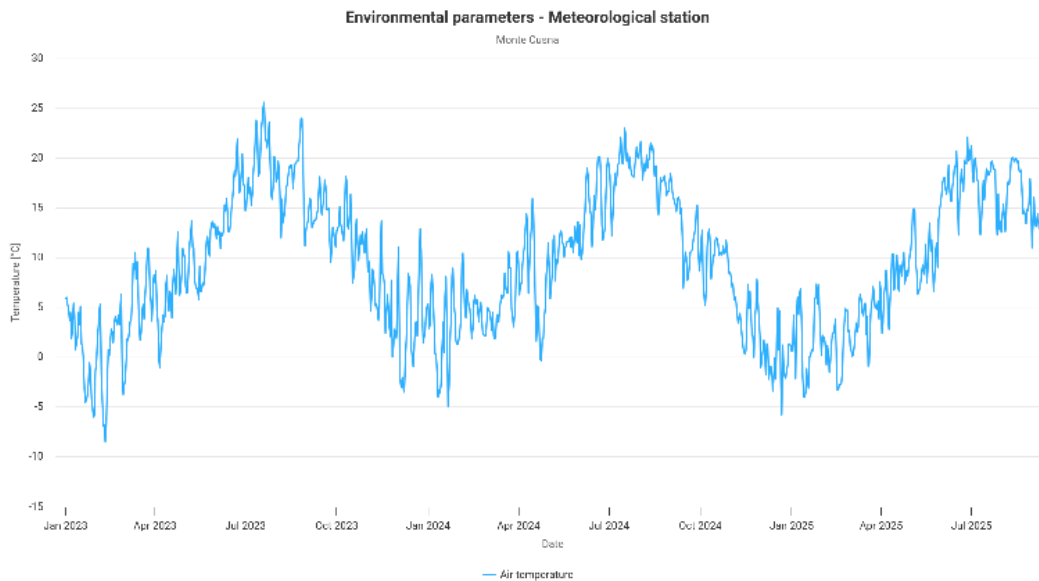


Figure 109. Temperature data collected by the weather station

7.1.1.1. Interpretation of patterns

The observed patterns highlight the combined influence of anthropogenic and environmental factors on water resource dynamics. While increased tourist presence likely contributes to higher water demand during summer months, climatic conditions—such as reduced precipitation and increased frequency of drought periods—also play a significant role in shaping water availability.

The interaction between these factors suggests that groundwater systems in mountain environments may be particularly vulnerable during periods of peak demand, when reduced recharge coincides with increased consumption.

7.1.1.2. Implications for monitored phenomena

From a management perspective, the results underline the importance of monitoring both water availability and demand in order to assess the sustainability of current usage patterns. The increasing tourist flow, combined with climate-related stressors, may require the identification of additional water sources or the implementation of more efficient management strategies.

Moreover, the condition and design of water capture systems emerge as critical elements, as inadequate infrastructure or poor maintenance may exacerbate water loss and reduce overall system efficiency.

7.1.1.3. Limitations and uncertainties

The interpretation of the relationship between tourism and water demand is subject to several limitations. The available data do not allow for a direct attribution of increased consumption exclusively to tourist presence, as local usage patterns and other socio-economic factors may also contribute.

In addition, variability in data availability and quality across different parameters and time periods introduces uncertainty in the analysis. Climatic variability further complicates the interpretation, as changes in water availability may result from natural fluctuations rather than anthropogenic pressure alone.

7.1.1.4. Added value of the approach

The integration of multiple data sources—including hydrogeological, climatic, and infrastructural information—represents a key strength of the analysis. This multi-dimensional approach allows for a more comprehensive understanding of water resource dynamics and supports the identification of potential vulnerabilities within the system.



Overall, water resource monitoring provides essential information for assessing the sustainability of tourism in mountain environments and highlights the need for adaptive management strategies in the context of increasing demand and climate change.

7.1.2. Conclusions and observations

Water monitoring indicates a clear seasonal increase in demand during the summer period, coinciding with peak tourist presence. This suggests that tourism contributes to additional pressure on groundwater resources, particularly in systems with limited recharge capacity.

However, water availability is also strongly influenced by climatic factors, such as precipitation and drought conditions. The interaction between increased demand and reduced recharge highlights the vulnerability of mountain aquifer systems.

Field observations further show that the condition and efficiency of water capture infrastructure play a crucial role in determining overall system performance.

Future monitoring and management should focus on:

- Improving the temporal continuity and completeness of hydrogeological and consumption datasets
- Enhancing the integration between climatic, hydrological, and tourism data
- Assessing the efficiency and maintenance status of water capture systems to reduce losses
- Developing strategies to optimize water use during peak demand periods
- Evaluating the sustainability of current water supply systems under increasing tourism and climate stress

Moreover, where necessary, the identification of alternative water sources or adaptive management strategies should be considered.



8. Final remarks

The analyses presented in Deliverable D2.1.2 offer a broad and integrated perspective on how tourism influences the environmental conditions of the HUMANITA pilot areas. The combined evidence shows that a wide range of monitoring methods is necessary to understand the full spectrum of pressures that arise in protected landscapes. **Visitor** numbers, their movement patterns, and the intensity of use vary across seasons and locations, yet they consistently concentrate along specific corridors and around key access points. This concentration helps explain many of the impacts observed across the various thematic domains and highlights the importance of continuous and diversified observation systems.

The **vegetation**-related results indicate that tourist presence often produces effects that remain spatially confined but still relevant for ecological stability. Trampling tends to modify plant cover and create small openings in the habitat, which can become favourable points for the establishment of disturbance-tolerant or non-native species. At the same time, natural fluctuations - such as yearly climatic variability or extreme weather events - can interact with visitor pressure and influence vegetation dynamics in ways that are not immediately attributable to tourism alone. This interaction highlights the need for interpretations that incorporate both human influence and natural environmental cycles.

The investigations related to **erosion** and geomorphological change show that trail degradation emerges gradually and depends on a combination of visitor activity, terrain characteristics, and weather conditions. Changes in terrain shape or soil stability rarely result from a single factor, and their detection requires observations collected at multiple moments and spatial scales. These findings confirm that erosion processes cannot be understood solely through short-term measurements and instead require long-term datasets that reveal how physical transformations accumulate over time.

Wildlife-related monitoring, including soil organisms, amphibians, and other faunal groups, demonstrates that many species respond quickly to changes in habitat conditions. Areas subjected to intense passage or persistent disturbance tend to support less diverse and less stable communities. In some cases, the movement of visitors can also facilitate the transfer of biological material or pathogens across different parts of the landscape. This tendency underlines the importance of wildlife as a sensitive indicator of broader environmental stress and reinforces the need to maintain conditions that minimize unnecessary disturbance.

The work devoted to **pollution** and waste highlights how the effects of tourism extend beyond the immediate vicinity of trails and viewpoints. Water quality, soil contamination, and waste accumulation reflect not only visitor behaviour but also the role of infrastructure, settlement patterns, and episodic events such as peak tourist periods or heavy rainfall. These pressures often act together and produce cumulative effects that are not always visible in the short term. As a result, monitoring strategies must consider both localized impacts and diffuse forms of pollution that can influence entire catchments or coastal zones.

Taken as a whole, the results reveal that **tourism does not operate as an isolated driver of change**. Environmental conditions evolve under the combined influence of geomorphological processes, climate, land-use practices, visitor presence, and ecosystem dynamics. Tourism can amplify existing vulnerabilities or accelerate ongoing trends, but its effects may also remain hidden when natural variability dominates. This complexity reinforces the **need for long-term data series, multi-indicator approaches, and analytical frameworks that distinguish structural patterns from temporary fluctuations**.

The HUMANITA project has also demonstrated the **importance of collaborative work, capacity building, and technological innovation**. The exchange of expertise among partners and the adoption of advanced tools have strengthened the ability of the involved institutions to observe environmental change in a consistent and comparable manner. These improvements contribute to the development of management approaches that rely more strongly on evidence, anticipate emerging pressures, and support the long-term protection of natural areas.