Carinthia II

Nature Tech

Part 3

Published since 1811
216th Year of Carinthia

Volume 3

Issue 1

2026 Verlag des Naturwissenschaftlichen
Vereins für Kärnten

Implementing GPS logger data for visitor monitoring in the Karawanken–Karavanke UNESCO Global Geopark

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KEYWORDS

- GPS tracking
- Ecotourism
- Human-Nature Coexistence
- CUAS

ABSTRACT

Human-Nature coexistence is an increasingly important component in the sustainable management of conservation areas. Pioneering conservation approaches are focused on integrating these two aspects rather than creating a strict separation. Disruptions to the balance between humans and nature can affect both natural resource conservation and the tourist experience. To avoid this, resource, infrastructure, and tourism flow management plans are needed. The HUMANITA project aims to develop innovative solutions to monitor tourism and its impact on the environment within selected conservation areas in Central Europe. It includes several methods to estimate tourism numbers, hotspots, and activities. We distributed 69 GPS loggers in the Karawanken–Karavanke UNESCO Global Geopark and created visitor density and intensity maps. This study demonstrates that GPS logger tools can support science-based management in conservation areas by providing quantitative insights for managing tourism flows. However, part of our objective is also to highlight key limitations, including low tourist participation, technical challenges, and concerns related to the high spatial resolution of the data in the UNESCO Global Geopark.

Implementierung von GPS-Logger-Daten zur Besuchermonitoring im Karawanken UNESCO Global Geopark

ZUSAMMENFASSUNG

Die Koexistenz von Mensch und Natur ist ein zunehmend wichtiger Bestandteil der nachhaltigen Bewirtschaftung von Naturschutzgebieten. Wegweisende Naturschutzkonzepte konzentrieren sich darauf, diese beiden Aspekte zu integrieren, anstatt eine strikte Trennung vorzunehmen. Störungen des Gleichgewichts zwischen Mensch und Natur können sich sowohl auf den Schutz der natürlichen Ressourcen als auch auf das touristische Erlebnis auswirken. Um dies zu vermeiden, sind Pläne für das Management von Ressourcen, Infrastruktur und Touristenströmen erforderlich. Das HUMANITA-Projekt zielt darauf ab, innovative Lösungen zur Erfassung der touristischen Aktivitäten und deren Auswirkungen auf die Umwelt in ausgewählten Naturschutzgebieten in Mitteleuropa zu entwickeln. Es umfasst verschiedene Methoden zur Schätzung von Besucherzahlen, Hotspots und Aktivitäten. Wir haben 69 GPS-Logger im UNESCO Global Geopark Karawanken–Karavanke verteilt und Karten zur Besucherdichte und -intensität erstellt. Diese Studie zeigt, dass GPS-Logger-Tools ein wissenschaftlich fundiertes Management in Naturschutzgebieten unterstützen können, indem sie quantitative Erkenntnisse für die Steuerung von Touristenströmen liefern. Ein Teil unseres Ziels besteht jedoch auch darin, wesentliche Einschränkungen aufzuzeigen, darunter die geringe Beteiligung der Touristen, technische Herausforderungen und Bedenken hinsichtlich der hohen räumlichen Auflösung der Daten im UNESCO Global Geopark.

INTRODUCTION

Conservation areas are intended to serve a dual role in protecting biodiversity while also supporting recreational activities [1]. Ecotourism has grown due to cleaner air, reduced water contamination areas, as well as opportunities for enjoyment and inspiration [2], [3]. Two main factors increased the popularity of conservation areas: growing interest in outdoor recreation and the reopening of tourism after the COVID-19 pandemic in 2021 [4]. In recent years, overtourism has become increasingly common including overcrowding, exceeding carrying capacity, anti-tourism movements, touristification, environmental sustainability concerns, and the loss of cultural identity and local traditions [5]. It results not as a singular anomaly, but as the visible expression of a broader system characterized by excess, acceleration, and territorial imbalance [6]. In this context, the main

DOI: 10.71911/cii-p3-nt-2026313

challenge is to balance public access to the conservation areas with the protection of sensitive natural environments. Data on visitor behavior, environmental pressures, and ecological change enable more comprehensive and effective management of the area impacted by overtourism [1], [7]. Indeed, visitor monitoring strategies play a crucial role, capturing data such as the locations people visit, the routes they take, the time spent in each area, and other general information on recreational use [8], [9].

Over the years, a range of methods has been developed to measure tourism activity to capture the volume and the characteristics of recreational use [10]. There are two different types of tourism measurement: one based on the monetary value generated by tourism activities, and the other on tourist demand, including the number of visitors compared to social influence and penetration [11]. One example of the latter is the Travel Intensity Index, defined as the ratio between the total number of visitors and the local population [12]. However, the need to incorporate spatial data into planning is evident, as recreational experiences in protected areas are inherently "spatially conditioned" processes [7], [14]. Space provides a platform where social, ecological, infrastructural, and economic factors can be integrated and understood in relation to one another [13]. Understanding the spatial and temporal distribution of tourism helps to assess the extent and impacts on related resources [7], [9], [15]. Several phases have been identified within the last "25 years of tourist tracking," spanning the so-named pre-technology era and the three subsequent technological eras [15]. The earliest method for collecting spatial and temporal data involved asking visitors to record their own travel routes and times on paper maps, a process that often led to errors and imprecision [8]. Then, some technologies were developed for tourism monitoring [10], including Global Positioning System (GPS), Wi-Fi and Bluetooth tracking, Near Field Communication, and social media monitoring [8]. These tools avoid the time-consuming nature of traditional methods based on surveys and drawing trails on maps [16]. The most commonly used technology is GPS tracking [17], as a comparative study reported that GPS data provide more detailed and accurate information than traditional methods [18]. In 2005, response rates for GPS-based methods were already higher than those of traditional approaches, suggesting that they were perceived as less intrusive [19]. In 2012, the use of GPS tracking in the USA was described as an emerging technology, highlighting advantages over traditional methods, including the collection of reliable, accurate, and precise data [8]. Subsequent studies also described the advancement of GPS tracking in different contexts, compared to previous methods [7], [21], [22], [23]. GPS can be intended as a GPS tracking smartphone application, for example TraceMate [23], Catch-my-Day [24], floating smartphone data provided by a third-party company [25], or GPS logger [26]. They have been used in a variety of manners applicable to transportation and mobility [21], [24], [25] including sedentary behavior and health-related issues [27], wildlife ecology [29], [30], [31], and tourism management [32], [33]. GPS tracking has major relevance in the transportation sector, including the use of a variety of advanced data processing methods, machine learning algorithms, and novel semi-supervised deep learning approaches that are being actively developed [26], [27], [36]. Also, some projects have focused on collecting GPS track data and allowing the further use of this data. The "GeoLife" project collected 17,621 trajectories to use in mobility pattern mining, user activity recognition or location recommendation [34]. Some studies were based on the PPGIS tool called "MyDynamicForest" including GPS-tracked and drawn routes [35]. Although GPS tracking is not particularly useful for capturing the total number of visitors entering an area, it can still apply to relatively large and often inaccessible areas that are difficult to study using other methods [9]. Additional advantages include lower staff effort and independence from weather conditions [9]. When GPS tracking is used via tourists’ mobile phones, some issues may arise due to users’ lack of experience with smartphone functions, as they may use their phones mainly for calling and texting. This can lead visitors to leave the mobile phone setup unchanged or improperly configured, thereby preventing the acquisition of data [22]. Other problems can arise from the high cost of distributing a large number of devices, the risk of data loss, and constraints on visitor movement [22]. Dense forest cover, mountainous terrain, and deep canyons can significantly reduce the effectiveness of GPS in these applications [9], [38]. In such environments, spatial data may be lost due to signal obstruction, resulting in poor or incomplete tracking [8].

Specifically, GPS tracking is used in the identification of tourist behavior in conservation areas [10], [39], [40]. GPS tracking was described as a valuable tool for identifying off-piste ski touring ascent and descent routes and for estimating the extent to which users venture outside designated areas [9]. GPS tracking and graph theory were used to evaluate the structure and use of designated skiing zones [39]. GPS logger technology was also implemented to track backcountry recreation use in Denali National Park, Alaska, USA, as the park’s large size and lack of trails make it difficult to identify travel patterns [37]. Within the Interreg Central Europe project HUMANITA, the development of a visitor monitoring strategy led to collection of GPS logger data in the Karawanken-Karavanke UNESCO Global Geopark (UGGp) at the border between Austria and Slovenia. The designation of UGGp is given to a unified geographical area of international geological significance, managed by combining conservation efforts with sustainable development [40]. Geotourism has attracted growing global interest [41], [42], [43] and is defined as a form of nature-based tourism that focuses on geology and the geological environment [44]. The international recognition of their touristic and natural resource values has created opportunities to promote geoconservation while supporting sustainable development [45], [46]. Considering their goals, UGGps require spatial planning for sustainable development within their territorial management plans [47]. A literature review on the application of Geographic Information Systems (GIS) in UNESCO Global Geoparks highlighted their limited use in both territorial characterization and management strategies. Most research focused on GIS-based thematic mapping (16 publications) and remote sensing techniques (7 publications), followed by digital elevation and terrain models, 3D modelling, multicriteria analysis, and related approaches [47]. A significant data gap was identified in the availability of reliable, local, same-day data, which is essential for stakeholders to make informed strategic decisions in tourist destinations [10]. In some UNESCO sites, large-scale questionnaires have been deployed [48], alongside mobile phone data [5], passive GPS data [10], and geotagged photographs [14]. The application of GPS loggers within a UGGp constitutes a gap in the state-of-art-of the research considering the high conservation value of these sites and high degree of tourist involvement.

This article aims to move the application of GPS tracking data in the study of tourist behavior in UGGps one step further by applying GPS logger tools to visitor monitoring. Building on previous studies that applied GPS loggers in different contexts, we aim to evaluate tourist behavior in terms of intensity and spatial density including limitations and concerns within a UGGp. Loggers can facilitate evidence-based decision-making and enable more focused management of visitors, contributing to the promotion of sustainable and efficient tourism practices.

METHODS

1.1 Study Area

The Karawanken-Karavanke UNESCO Global Geopark was established in 2013 as a member of the European Geoparks Network and the Global Geopark Network. In 2015, the geopark became an official UNESCO programme recognized as a UGGp [49]. This geopark covers an area of 1,067 km² and extends across the border between nine municipalities in southern Austria and five municipalities in northern Slovenia. It features remarkable geological diversity between the Alps and the Dinarides that goes back 500 million years [16], [49]. The geopark is within an alpine ecosystem characterized by steep, rocky cliffs on the Austrian side and alpine meadows that descend into the Slovenian valleys [49].

The Mount Petzen/Peca hotspot area is a carbonate mountain range that lies along the border between Austria and Slovenia, with a key crossing at the Kniepssattel/Končnikovo sedlo pass (2,012 m a.s.l.) (Figure 1). Its terrain is shaped by a karst system, where water erosion has created a complex network of cracks, caves, and underground drainage pathways. On the Slovenian side, the southern slopes are part of the Natura 2000 network, designated in 2008 under the Habitats Directive. This area includes the Grintovci Special Protection Area, which safeguards rare bird species under the Birds Directive. The mountain hosts rich biodiversity: springs and wet meadows provide habitat for uncommon plant species such as the common butterwort and several wild orchids. It is also home to sensitive wildlife, including the hazel grouse, Eurasian pygmy owl, and golden eagle.

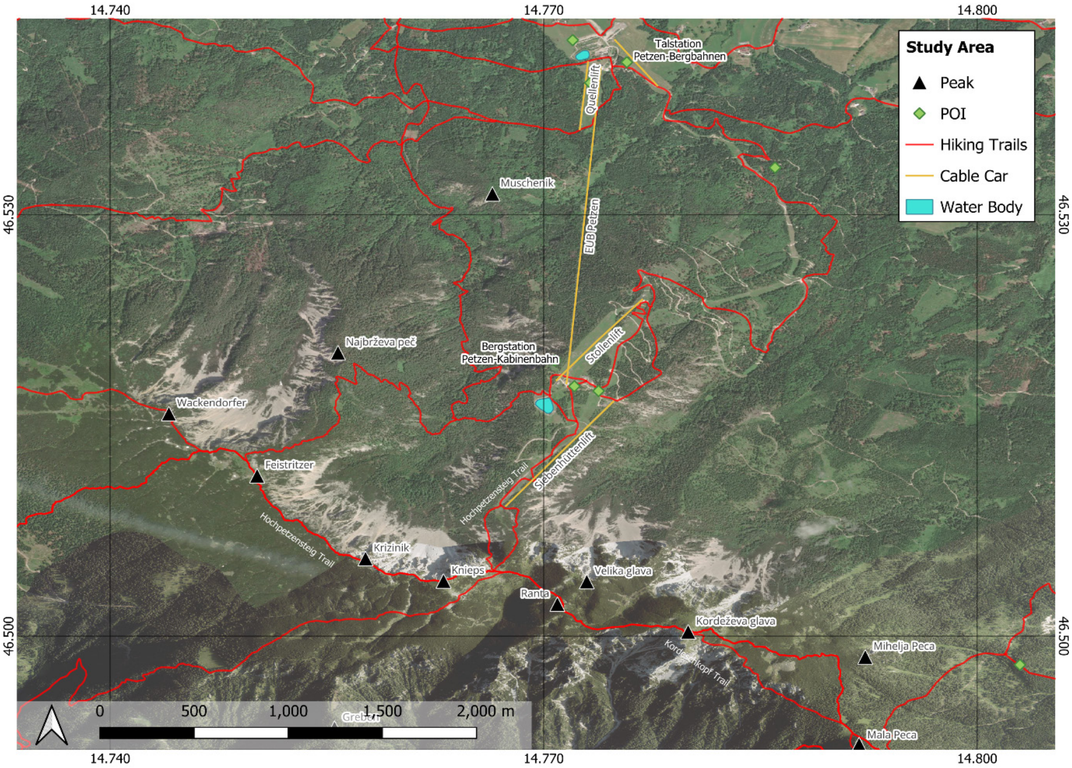

Fig. 1

Figure 1:
Study area in Mount Petzen/Peca area.

Abbildung 1:
Untersuchungsgebiet auf der Petzen/Peca

The proximity of major airports in Klagenfurt and Ljubljana allows easy access via the public transport network. Due to this accessibility, the Geopark is widely used for outdoor recreation, including hiking, cycling, paragliding, and rock climbing in summer, as well as winter tourism, with around 15 km of ski slopes served by the Petzen cable car [49]. These activities are supported by various tourist facilities, such as chalets, guesthouses, and hotels [16]. In 2022 the Austrian side recorded over 3 million visitors, while the Slovenian side accounted for approximately 55,000 tourists [50], [51]. Between 2005 and 2015, Austria attracted around 70% of park visitors; however, Slovenia experienced a notable increase in tourism, rising by about 37% in 2022. Domestic visitors make up roughly 65% of the total. Seasonally, summer has the highest numbers, with peak months in July and August averaging about 7,400 and 8,800 arrivals per month respectively. In contrast, during the winter season (November to April), the geopark hosts a total of around 13,100 visitors.

1.2 Data Collection

Forty Renkforce GT-730FL-S GPS loggers were provided to the ticket office at the cable car valley station (Talstation Petzen Bergbahnen). The data collection initiative was promoted by the employers and posters around the area. Tourists passing through the ticket office for the cable car during working hours were asked over four specific days whether they would like to participate in the data collection. To encourage greater participation, a free ski pass was offered as a prize in a random drawing. Those who agreed were asked to record metadata for each deployed GPS logger, including age, gender, and group size.

For calibration and acquisition of a GPS signal, the devices were switched on in advance of tourist departures. In total, 69 GPS loggers were distributed among pedestrians and hikers at the cable car station. Some GPS loggers were switched on and off during use, resulting in 75 tracks being downloaded: 15 on 7/19/2024, 28 on 8/26/2025 representing 56 people in total, and 32 on 9/19/2025 representing 53 people. For 7/19/2024, the group size data was not collected. Another data collection session was conducted, but no data were collected, likely due both to limited staff engagement and to tourists’ concerns about carrying GPS loggers. The devices were set to record the GPS location at 5-second intervals, not only to record the spatial movement, but also to represent higher concentrations of points if visitors stayed at a location for a longer period of time.

1.3 Data Cleaning and Analyses

The literature reports several manual data-cleaning procedures for GPS logger data [7], [10]. In this study, our aim was to develop an automated tool to support the independent management of the geopark. Therefore, we implemented data-cleaning in Python [18] to enable a more efficient and streamlined processing workflow.

We applied four spatial filters in Python, iteratively, three times. The distance and speed filters were partly based on the methodology of [17], while the other parameters were determined through iterative testing and adjustments. First, a minimum distance filter of 2 m was applied between two consecutive points. Since the GPS loggers recorded data every 5 seconds, this allows for high-resolution data but can also introduce potential inaccuracies during short breaks. A short recording interval may lead to an overestimation of stay time, particularly in cases of slow walking speeds or in steeper trail sections. Second, a maximum distance of 50 m between two consecutive points was set, as pedestrians would not normally cover more than this distance in 5 seconds, and points exceeding this threshold were considered indicative of signal distortion. Third, a maximum speed filter of 6 km/h was applied, as higher speeds were considered signal errors, since they would exceed the typical walking speed of a person. Fourth, isolated points were identified using a spatial filter: any cluster of fewer than five points within a 50-m radius was removed. This threshold was chosen based on a visual inspection of the raw data and was considered appropriate for our data distribution. Finally, the tracks were subjected to a final quality check in QGIS [52]. Three GPS tracks were manually adjusted through the Move Feature tool in QGIS, since they were displaced by several meters from the only plausible trail, and seven tracks were manually removed due to irregular GPS points that the Python cleaning procedure could not detect. These anomalies were likely caused by signal interference from the cable car, as the issue mainly occurred on trails nearby.

A descriptive analysis was carried out in R, including a statistical summary of distance of trips and travel time for each track [53]. To examine the spatial distribution of tourists, the density of recorded GPS track points and their stay times were analyzed using QGIS. The density map shows the areas with the highest tourist presence and the intensity map indicates the locations with the longest duration of stay. The results are expressed as tourist stay per cell and the number of visitors per cell, following a workflow also adopted by [11], offering an improved understanding of touristic hotspots. The density map was generated using the Heatmap tool, applying a Kernel Density Estimation approach [54], as also implemented in previous studies [10], [15], [35], [39]. A search radius of 10 m was applied, with an output raster resolution of 0.10 and meters used as the unit to estimate the spatial density of point data. The intensity map was generated by calculating the mean stay time in Python, resulting in a raster heatmap with a spatial resolution of 30 m. Each track was analyzed individually, and each point was assigned to a grid cell. For each cell, all points from the track falling within that cell were considered, and the stay time was computed as the difference between the maximum and minimum timestamps of those points.

RESULTS

The analyses were conducted on 68 GPS tracks collected in the geopark. On average, a distance of 6.5 km was covered (min = 0.11 km, max = 15 km, SD = 4.32 km), and the tracks lasted an average of 197 minutes (min = 3 min, max = 421 min, SD = 112 min). Short distances and durations were observed near restaurants, where tourists likely switched off the devices during break times. These tracks were retained, as they were not considered a source of bias for the analysis.

The density map represents a heatmap of the GPS logger data (Figure 2). The scale is standardized, ranging from 0 (low intensity) to 100 (high intensity). To facilitate interpretation, the map is displayed together with viewpoints, points of interest, the cable car route, and hiking trails. We highlight four points of interest including two viewpoints, the Panoramarestaurant and the Alte Zollhütte. The latter is a historic alpine hut that has been converted into a restaurant and mountain refuge on Mount Petzen, offering panoramic views and a strategic location along hiking and tourism routes. The Panoramarestaurant is a modern summit restaurant focused on views and tourism services at the top of the area. The highest-intensity hotspot is located around the cable car valley station. During peak hours, this area becomes particularly dense, likely due to its role as the primary starting point of the cable car and the presence of a bike rental shop and restaurant. Consequently, the cable car mountain station (Bergstation Petzen-Kabinenbahn) experiences high visitor concentration; however, density decreases more rapidly there, as visitors spread out along different routes to engage in various activities. The results obtained at the cable car valley station are not shown on the map, as they were considered prone to error. This is because the GPS loggers were switched on before participants began their trip, and some devices were found to still be running afterward. At the summit station, an artificial lake for snow production in the winter season is surrounded by several resting areas, where many visitors enjoy the lake's summer recreational facilities. The Hochpetzensteig circular route is frequently used in two variants: from the lake along the ski slope or a forest road towards a resting area at the top station of the Siebenhütten T-bar lift. Most visitors turn back at the Knieps Saddle, representing an easy turning point to the lake without reaching one of the peaks. Other visitors either complete the circular trail, passing the Knieps towards the Petzen summit (Feistritzer), and descending along the Hochpetzensteig back to the lake or they turn left at the Knieps saddle towards Kordeschkopf, a very popular destination also from the Slovenian side of Mt. Petzen/Peca. Visitor density remains low in the upper sections of the mountain massif compared to the lower sections closer to the infrastructure facilities. The map highlights some instances where GPS points deviate slightly from the trail network, likely due to signal-related inaccuracies.

The intensity map (Figure 3) shows the visitor stay time in 30-m resolution pixels. Stationary visitor stays ranged from less than 2 minutes to 50-120 minutes. It is developed using the same legend elements as the density map to facilitate comparison and the scale is standardized. Visitors spent between 60 and 170 minutes at the cable car valley station, likely due to the presence of facilities such as service areas (ticket office, bike rental, bike wash) and a restaurant, or possibly as a result of the previously mentioned GPS-related issues. At the cable car mountain station, visitors mainly rested around the lake area, with stay times ranging from 2-10 minutes up to 25-50 minutes. Visitors tended to move to the eastern side of the cable car area, where longer stay times are associated with the presence of restaurants, huts (Panoramarestaurant and Alte Zollhütte) and the Geopark visitor center (Geo.Dom). Many times, the GPS signal was lost around this area, likely when visitors entered the buildings. Notably, on the western side of the cable car mountain station, a viewpoint was associated with an average stay time of approximately 10-25 minutes. At the trail bifurcation from the Siebenhütten rest area towards the Knieps Saddle, visitors tended to spend more time on the left-side trail with various stops until they reach the Knieps, probably due to an easier and better trail view. Along the trail

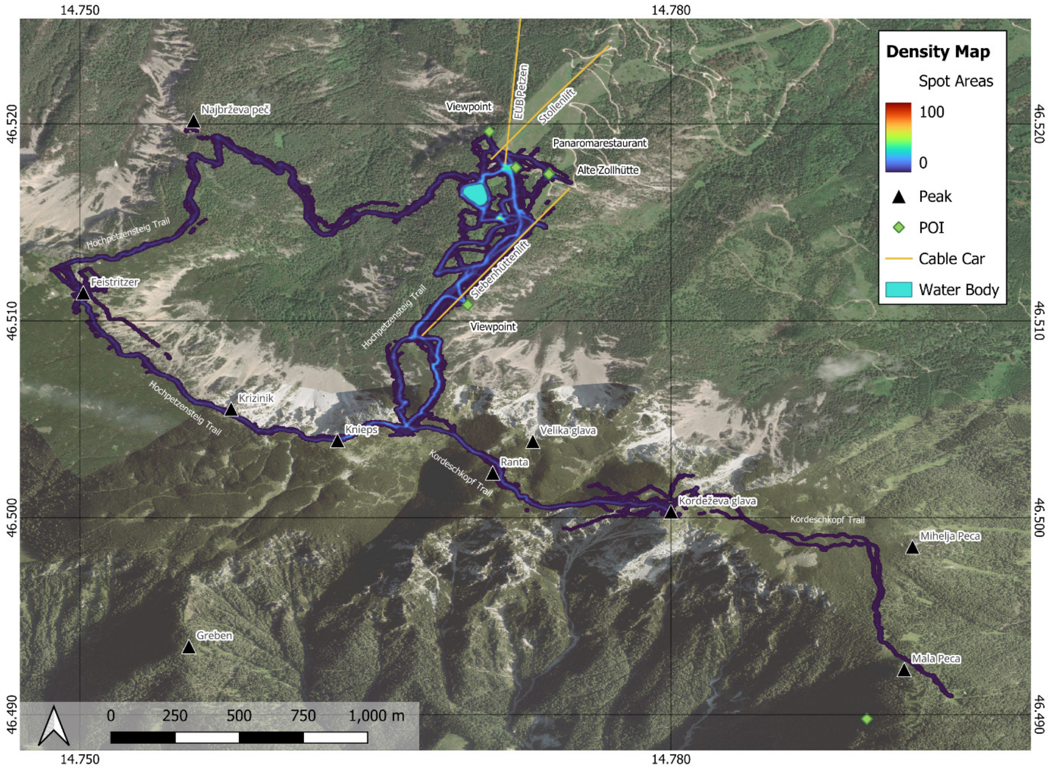

Fig. 2

Figure 2:
Density map of visitors in the Mount Petzen site.

Abbildung 2:
Besucherdichtekarte des Gebiets am Berg Petzen.

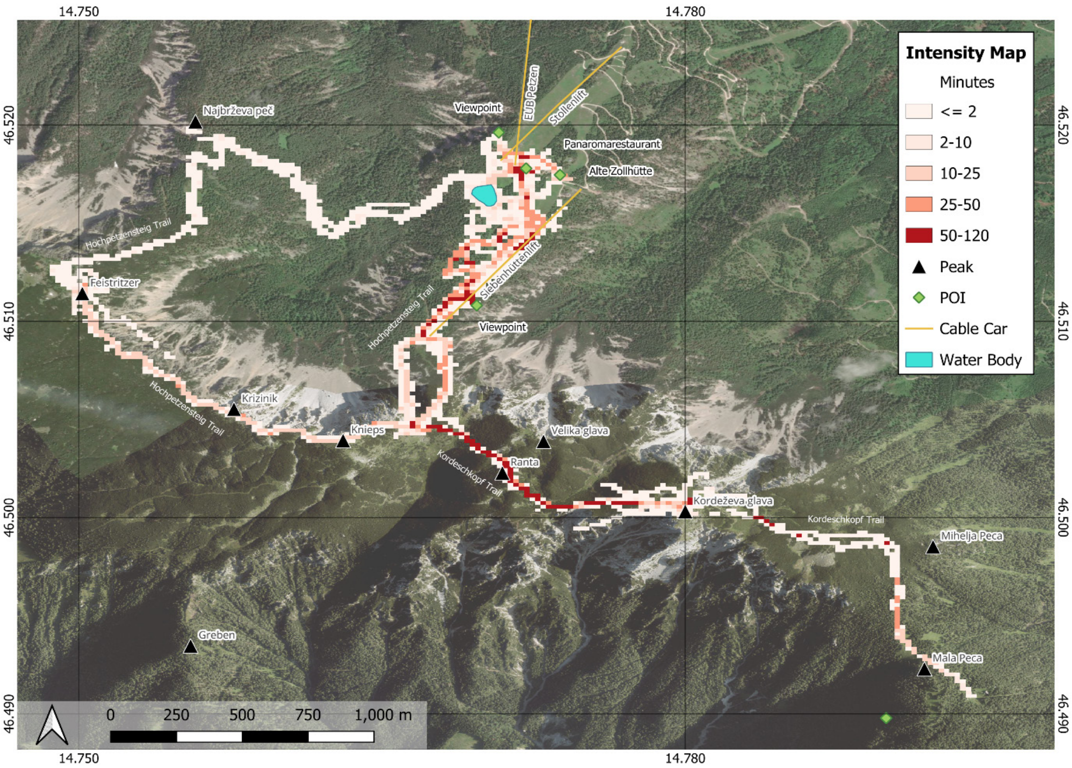

Fig. 3

Figure 3:
Intensity map of visitors in the Mount Petzen site.

Abbildung 3:
– Intensitätskarte der Besucher im Gebiet des Berges Petzen.

leading to the summit, several viewpoints overlapped with areas of longer stay times. Also, visitors appeared to spend more time along the trail leading to the summit, likely because they took breaks to rest or stop at viewpoints. The Mt. Petzen/Peca summit (Feistritzer) itself showed a 30-m pixel corresponding to an average stay time of around 25-50 minutes. Finally, the Kordeschkopf trails showed high stay times across the entire network, which may be explained by some GPS tracks that were not entirely accurate in that area.

DISCUSSION

In the tourism industry, understanding where and when tourists visit provides valuable insights for selecting the most suitable locations to develop new activities [32]. Managers can define visitor groups and design more targeted, diverse offerings that better align with the needs and interests of different audiences [13]. To address these interests, we aimed to study recreational use patterns by investigating movements within a UGGp rather than simply reporting them [8]. Given the global importance of these areas, more targeted research using GPS tracking should be conducted through multiple case studies, as the variability among sites is considerable. The results of this analysis demonstrate how GPS logger technology can provide high-resolution data with a wide range of potential applications. The density and intensity maps help in better understanding visitor behavior and trail preferences, including their temporal patterns. Indeed, they give insights into the most frequented trails and the hotspot areas for tourists. The former helps to identify where human–nature interactions are more concentrated and where greater attention is needed to monitor and manage the potential impact of tourists on these areas. The latter is also important for this purpose, but it additionally helps to better understand the type of tourism that characterizes the area. Visitors may seek solitude and relaxation, or more social experiences such as playing and picnicking [37]. Indeed, understanding human movement and behavior in parks is embedded within a social-ecological systems framework [37]. Our study area points to a predominantly family-oriented tourism pattern, concentrated in lower-elevation areas, with higher visitor density and intensity around shared facilities such as restaurants, huts, and picnic sites. This information supports informed conservation area management, improving the coexistence between tourism activities and conservation of natural resources.

In the Mount Petzen area of the UGGp, it is evident that the highest visitor densities occur in zones with the greatest concentration of services and infrastructure, such as the cable car stations, gear rental points and washing facilities, as well as restaurants and huts. Most tourists remain near the cable car mountain station and do not move far along the trails. Consequently, picnic areas, lake surroundings, and huts frequently experience high visitor density. Higher-elevation areas, such as those near the summit, are locations where visitors tend to stop briefly at viewpoints or to rest. These areas do not experience the same levels of crowding as the lower, more accessible zones.

Despite these findings, some limitations were encountered during data collection, including low tourist participation. Considering the large number of annual visitors to the UGGp, the low number of 69 devices distributed may limit the representativeness of the data. For this reason, we limited the extent of generalizations drawn from the study, focusing instead on identifying key issues and potential areas for future improvement. Our limitations may be related both to tourist reluctance to participate in the study and to insufficient collaboration with the third-party partner responsible for distributing the GPS loggers. Other studies encountered related problems describing that some visitors declined to participate due to privacy concerns or unfamiliarity with tracking technologies [7], [22], [55]. A possible solution includes strengthening communication activities that incorporate education and awareness-raising, which would benefit both park staff and visitors and contribute to more efficient data collection. Developing simple materials such as step-by-step instructional flyers, short videos, or QR codes explaining how to use the device, as well as checklists for staff outlining what to communicate to visitors, could support more efficient data collection. These measures would also help stakeholders better understand the innovation and practical benefits of the tool. These types of activities are particularly important given that GPS loggers are managed directly by tourists, which can introduce certain biases in data collection. For instance, awareness of being tracked may influence visitor behavior [9]. In our study, we also observed that devices were often switched on and off during use, which can lead to tracking biases that are difficult to identify and correct. This may occur because visitors, when stopping at areas such as picnic sites or restaurants, choose to pause the tracking without being aware that the time spent at these locations is also important for identifying recreational patterns. This highlights another example of how the purpose of the technology and the objectives of the study need to be clearly and effectively communicated.

Another limitation of this study was the incomplete acquisition of metadata, resulting from insufficient collaboration and active involvement of park staff. Indeed, not all GPS loggers were properly registered, even when the tracking data were recorded. This highlights an additional challenge when relying on third parties for data collection. GPS logger data should be analyzed in combination with questionnaire surveys that provide a socio-demographic profile of the population and visitors who decline to participate, in order to assess the representativeness of the dataset [21], [22]. Participants may be biased, as they tend to be younger, more technology-oriented, stay longer, or travel from greater distances [22]. Again, this highlights an issue that can arise when data collection is delegated to third parties, particularly when the importance and relevance of the study is not particularly clear to them.

Finally, signal deviation was a challenge. The automatic cleaning in Python only addressed point-level errors and did not account for the spatial context of the tracks. As a result, certain anomalies—such as GPS tracks deviating from plausible trails—cannot be resolved automatically and require manual intervention. One of the primary objectives was to make data processing as automated as possible, so that this approach can be accessible to a broader range of users. However, this is not always guaranteed with this type of data, especially in natural environments and in areas with cable car infrastructure, where signal distortions are more likely to occur. An initial data cleaning and preprocessing phase is necessary to reduce potential bias and improve the reliability of the results. Even so, the Kordeschkopf trails illustrate that, despite preprocessing and filtering, misleading data can still persist when using high-resolution technologies.

CONCLUSION

Analyzing the data quantitatively (numerical estimates) and qualitatively (mapping) offers a clearer understanding of tourist flows and behavior. Using GPS technologies offers a concrete approach to managing conservation areas, making observations possible at high-resolution. However, several challenges can arise in the deployment of GPS loggers. These include tourists' reluctance to carry the devices, limited involvement of park staff, signal reception issues, and the time and staff skills required for data cleaning. These factors represent important limitations of using this tool in the context of a UGGp. UGGps are often characterized by large areas and high-variability landscapes. Here, GPS loggers can provide valuable information for management purposes. However, their level of resolution may sometimes be too high to represent the diversity of the park. Within this framework, we encourage implementing an approach that integrates multiple technologies to manage visitor flows in UGGps. GPS loggers make it possible to identify the most likely movement patterns, stopping areas, and hotspot locations. However, they do not provide information on the number of tourists experiencing specific areas, as automatic counters do. Similarly, they do not offer insights into tourists' environmental sensitivity or attitudes toward nature, which can instead be captured through surveys. Finally, the limitations mentioned above should be considered alongside those of other tools, with the aim of identifying cross-method solutions. Therefore, combining different tools allows for a more holistic view of visitors within the area than single approaches [10], [56]. This knowledge can support the planning of new infrastructure or recreational facilities in order to address a sustainable form of tourism.

ACKNOWLEDGMENT

Funding for the GPS logger data collection was provided through the Interreg Central Europe project HUMANITA, Project Number Interreg CE-100-248.

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