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To cite this article: Jorge Costa, Alberto Gomes, Martin Stokes & Miguel Saraiva (2024) Recreational use of protected areas: spatiotemporal insights from the Wikiloc mobile app, Current Issues in Tourism, 27:22, 3978-3998, DOI: [10.1080/13683500.2024.2329278](https://doi.org/10.1080/13683500.2024.2329278)

To link to this article: <https://doi.org/10.1080/13683500.2024.2329278>



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Published online: 22 Mar 2024.



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RESEARCH ARTICLE



Recreational use of protected areas: spatiotemporal insights from the Wikiloc mobile app

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ABSTRACT

Managing the rising number of visitors to protected areas (PAs) without compromising their environmental goals is a critical challenge that requires a complete understanding of how and when visitors use these spaces. Georeferenced data from fitness-tracking apps can provide detailed information about the visitor's spatiotemporal behaviour inside PAs, but its potential is still underexplored. This study uses georeferenced data, from Wikiloc, to analyse the visitors' spatiotemporal behaviour in Alvão Natural Park, Portugal. Our findings show that: 52% of the visitors' use is concentrated around the Fígas de Ermelo Waterfall; photos' hotspots coincide with the waterfalls and viewpoints facing them; 2% of the routes crossed a zone where recreational use is illegal; Spring (26%) and April (11%) receive the most visitors; 52% of routes are done on the weekends; 66% of visitors are inside the park during noon; start/end places are located near parking spaces; the most frequent times to start a route are between 08:00-13:00 hrs, ending between 13-18:00 hrs. A new method was developed to calculate daily visitor numbers without photo concentration bias. These results offer valuable insights that can aid in PAs' environmental and recreational use management by quickly providing detailed and low-cost visitor monitoring data.

ARTICLE HISTORY


Received 28 October 2023
Accepted 6 March 2024

KEYWORDS

Visitors' spatiotemporal behaviour; protected areas; visitor monitoring; geotagged data; Alvão natural park

1. Introduction

Protected Areas (PAs), such as national or natural parks, are sites designed to conserve unique landscapes. They ensure environmental protection, provide habitat for endangered species, and bring important socioeconomic and health benefits to local communities and visitors that use them for recreational activities (Beeco & Brown, 2013; Carrus et al., 2015; Stolton & Dudley, 2010; Watson et al., 2014). In many cases, the primary reason for attracting visitors is the distinct features of its physical landscape, including features such as hills, valleys, and bedrock. Managing the human use of these areas without compromising the environment or physical landscape conservation, is a challenging task for park managers (Beeco & Brown, 2013). This is due to the negative effects that human use can have on a PA, like wildlife disruption, waste production, vegetation reduction, or soil degradation and erosion (Marion et al., 2016; Tolvanen & Kangas, 2016). These impacts are especially common and damaging if the number of visitors that an area can take (carrying capacity) is exceeded (Eagles & McCool, 2002; Valentine, 1992). Such impacts are of major concern, as PAs are

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being increasingly pressured by expanding tourism-related recreational use, meaning visitor management is becoming a key sustainability challenge (Eagles, 2014).

Another significant management challenge is the heterogeneity of the environments associated with PAs (Buultjens et al., 2005). These are complex, comprising different sites with distinct characteristics requiring either: (1) bespoke measures to ensure their uniqueness is maintained, or (2) special measures during a particular time of year, for example, during the reproduction season of endangered species (Eagles & McCool, 2002). Similarly, complex spatial and temporal challenges apply to the visitors themselves, regarding their numbers and activities, which can vary considerably in space and time (Eagles & McCool, 2002; Newsome et al., 2012).

Zoning is a widely used strategy to implement different levels of protection inside PAs. This method is important to control and limit the visitors' access to the park core, reducing human-derived impacts (Manning, 2010; Newsome et al., 2012; Veal, 2011). Nevertheless, it is important to consider that areas located in the adjacent transition or buffer zones also have significant environmental value and can be equally or even more susceptible to human pressure. Even when zoning is put in place it isn't necessarily guaranteed or known whether any implemented protected measures will have the desired effect. Thus, addressing management challenges in PAs requires a capable visitor monitoring system. This can be defined as the systematic gathering of data about the number, characteristics, spatial distribution, and outcomes of visitors over time (Griffin et al., 2010; Newsome et al., 2012). There are many techniques to monitor visitors inside PAs, with frequent technological/scientific developments offering new ways to gather data about PA visitor activities (Pickering et al., 2018).

Traditional approaches to studying visitors' spatiotemporal behaviour in PA include field observations, surveys, interviews, automatic sensors, booking registries, or access permits (Cessford & Muhar, 2003). These early methods have advantages and limitations. Whilst providing valuable visitor data, they share a major limitation in that measurements are restricted to either specific park locations, or the larger collective park area (Arnberger et al., 2005; Cessford & Muhar, 2003). A relatively recent technological development for monitoring visitors' spatiotemporal behaviour is the use of GPS devices (e.g. Campelo & Nogueira Mendes, 2016; D'Antonio et al., 2010; Heikinheimo et al., 2017; Orellana et al., 2012). Initially, researchers provided GPS recording devices to willing visitors to accurately record their routes, revealing their spatiotemporal patterns (Brown & Weber, 2011; Hallo et al., 2012; Orellana et al., 2012). However, this data-gathering approach has two major limitations: expensive data-collecting devices and the knowledge bias introduced into the participants' behaviour due to their awareness that their movements were being recorded (Newsome et al., 2012; Norman & Pickering, 2017).

Over the past 15 years, the use of georeferenced data from social media and mobile apps to study visitors' spatiotemporal behaviour in PAs has increased (Barros et al., 2022; Teles da Mota & Pickering, 2020; Wilkins et al., 2021). This can be explained by the growth in mobile device popularity and availability (Barros et al., 2020). Examples of data sources used by researchers to understand where, when, and how many visitors use PAs, include Instagram, Twitter, Flickr, Strava, Wikiloc, and AllTrails (Barros et al., 2022; Ghermandi, 2022; Teles da Mota & Pickering, 2020). Flickr is the most used platform by researchers, this is due to the fact that it has a large dataset of georeferenced photographs and an Application Programming Interface (API) that facilitates data gathering (Barros et al., 2022). While the Flickr dataset is global, most of the geotagged photographs on the platform are concentrated in Europe (40%) and North America (39%) (Wood et al., 2013).

Fitness-tracking apps are particularly interesting for visitors' spatiotemporal behaviour studies because they record the complete visitors' movement during their recreational activities. When analysing large datasets of visitors' activities in PAs, researchers can identify and measure temporal and spatial patterns in the routes undertaken inside PAs. Norman and Pickering (2017) compared the popularity of Strava, MapMyRun, and Wikiloc in different PAs, concluding that Wikiloc was particularly popular for PAs located further away from urban areas. Subsequent studies using sports app-derived data have enabled researchers to explore a range of parameters, for example, to identify and differentiate the intensity of use inside PAs (Barros et al., 2020; Jurado Rota et al., 2019; Norman & Pickering,

2017, 2019), to identify the visitor numbers in the park at different time scales (Jurado Rota et al., 2019; Norman et al., 2019; Schirck-Matthews et al., 2023), or to explore differences in the popularity of PAs or visitor activities (Norman et al., 2019; Norman & Pickering, 2019). For example, Jurado Rota et al. (2019) explored the start location, route and end location of people using the Ebro Delta Natural Park in Spain. They observed that most activities start or end near towns, tourist resorts, tourist attractions and amenities. More recent examples have examined the context of the COVID-19 outbreak, where recreational platform data has been used to study visitors' behaviour differences during the pandemic (Schweizer et al., 2021; Venter et al., 2020; Venter et al., 2021).

Ensuring the efficient management of human activities is extremely important to achieve sustainable PAs, but it is very challenging to accomplish. However, detailed visitors' spatiotemporal behaviour studies can uncover important patterns about human activities in PAs and help overcome this challenge. Still, the use of fitness-tracking app data to inform on visitors' spatiotemporal behaviour remains an underutilised resource, despite its considerable potential. For example, only one study exists that analyses the visitors' start and finish locations inside PAs (Jurado Rota et al., 2019), and none that the authors are aware of analyses their temporal patterns (Figure 1). Studying these missing temporal patterns could bring enhanced insights to park managers and contribute to the improvement of visitors' experiences and the park's environmental protection. For example, it could be used to identify the most popular locations and times where visitors start/finish their routes or to investigate if the start/finish locations have the necessary facilities to accommodate certain visitor numbers.

In this study, we evaluate the Wikiloc data contribution to analyse visitors' spatiotemporal behaviour in PAs with distinct physical landscapes, using the Alvão Natural Park as the study area. We



Figure 1. Number of publications that have used route data from fitness-tracking apps to analyse the visitors' spatiotemporal behaviour inside PAs (see supplementary materials for further detail).

extend previous research by presenting a new method to calculate visitor numbers during the day and by exploring the starting and finish times temporal patterns. A methodological approach that, as far as the authors are aware, is still underexplored (Figure 1). Situated in the north of Portugal, the Alvão Natural Park is recognised by its spectacular ‘physical landscape’ landmarks, particularly the ‘Fisgas de Ermelo Waterfalls’. This, combined with the expected popularity difference between ‘physical landscape’ landmarks and the remaining features in the park, makes it the second most visited park in the region (ICNF, 2022) and the ideal case study. Wikiloc was chosen as the data source because it has been validated as an effective proxy for visitation (Barros et al., 2020; Norman et al., 2019; Norman & Pickering, 2017) and due to its popularity in remote areas (Norman & Pickering, 2017). Our objectives are to: 1) measure route intensity and photograph hotspots to differentiate the visitors’ use intensity within the park; 2) measure the visitors’ temporal patterns at different time scales; 3) analyse the spatial and temporal patterns of the visitors’ routes start and end points; and 4) assess Wikiloc data contribution in the improvement of PAs management.

2. Study area

The Alvão Natural Park (Figure 2A), located in the Alvão Mountain (Occidental Mountain Range), was created in 1983. Its highest point (Alto das Caravelas) reaches 1330 m altitude (Figure 2B). The park has a Mediterranean temperate climate, with warm and dry summers and rainy winters, and annual precipitation of 2600 mm in mountaintop areas (Daveau, 1985). It’s located near the city of Vila Real and two major highways that link the main population centres of northern Portugal (Porto and Braga) and to Spain. The park’s main goals are to 1) protect the physical aspects of the landscape, notably its geology and geomorphological features, 2) protect its biology and ecology, including plant and animal species and their habitats, and 3) care for the landscape’s cultural heritage, by collectively promoting its use by sustainable ecotourism (Ministério da Qualidade de Vida, 1983).

The park’s bedrock geology is mostly granite, along with metamorphic rocks, including schists and quartzites in the southern part, and alluvial sediments near Lamas de Olo (Dias et al., 2022). The most important geological features are the rare Andalusite lode mineralisation and the granitic ‘cathedral’ of Arnal (Figure 2G). Geomorphologically, the park comprises steep cliffs, traversed by some of the biggest waterfalls in Portugal, with a combined height drop of 250 metres. These include the Fisgas de Ermelo Waterfalls (Figure 2E), a cascade falling 250 m and one of the most important natural features inside the park. The waterfalls are cited by the Portuguese government as a key reason for creating this PA in 1983 (Ministério da Qualidade de Vida, 1983). Regarding its biodiversity and ecology, the park is the habitat for a vast number of endangered and protected species, including the Iberian Wolf, the Eurasian Bullfinch, and the Heath Spotted Orchid (Lopes et al., 2010). The park’s biological value is further elevated by the presence of native oak woodlands.

The Park also encompasses a rich cultural and architectural heritage, emphasising the local customs and products. These include mountain villages with traditional vernacular architecture, such as Ermelo, Lamas de Olo (Figure 2F), Fervença, Arnal (Figure 2D), and Barreiro. Additionally, the landscape value of cultivated areas and semi-natural meadows, locally known as ‘lameiros’, bring further layers of important features to protect and maintain (Salavessa, 2004).

The Alvão Natural Park is organised into three zones (Figure 2A), each with its own rules and restrictions: 1) total protection; 2) partial protection; 3) complementary protection. The most restrictive zone (total protection) is only applied to the granitic area of Arnal, intending to preserve the natural area in an undisturbed state. Here, human presence is only allowed for scientific or monitoring purposes, in an emergency, or exceptional visitation cases. Partial protection areas are those with natural or scenic value intending to protect and conserve the landscape and ecosystems. Here, visitors are allowed to undertake recreational activities. Economic activities that don’t change the Park’s land use are also permitted. Lastly, areas with a complementary protection status are mainly semi-natural areas (e.g. agriculture areas, and settlements). These zoning seek to maintain the populated areas in the park, promote their social and economic development, and improve the quality of life in



Figure 2. The Alvão Natural Park: A) Protection zoning, hiking routes and main settlements; B) Park's relief and hypsometry; C) Park's location; D) Arnal Settlement; E) Fugas de Ermelo Waterfalls; F) Lamas de Olo Settlement; G) Arnal 'Cathedral' (granitic inselberg).

the local communities, whilst also enhancing traditional activities (Ministério da Qualidade de Vida, 1983).

Human use is another important aspect that must be considered when studying the Alvão Natural Park. The park was created in an inhabited area with an established local community practising economic activities such as agriculture, energy production, and tourism services. The park also possesses wind farms, which impact the landscape, contradicting its goals, but promoting renewable energy and contributing to national sustainability goals. Nowadays, tourism-related activities, including restaurants, accommodation, and organised recreational activities, have increasing economic importance to the park's inhabitants. This is due to the presence of visitors using the park for recreational activities, attracted by the park's natural and cultural value.

There are three official pedestrian routes in the park: the Fiskas de Ermelo route, the Arnal route, and the Lamas de Olo Route (Figure 2A). These routes allow visitors to reach the park's most desired locations and viewpoints. The Fiskas de Ermelo Route is a circular trail that starts in Ermelo town, passing by the Varzigueto settlement and the Fiskas de Ermelo Waterfalls. The trail is long and steep, with a length of 12.4 kilometres and an elevation change of 652 metres; it is estimated that walkers will take 4 h and 30 min to complete this route. The main attractions along this route are the waterfalls and their small lagoons, and the typical mountain landscape scenery. The trail has four viewpoints overlooking the waterfalls that include landscape interpretive panels that allow visitors to understand the landscape. The Arnal Route is a circular trail that starts in the Agarez settlement, located outside of the park, and passes by Galegos da Serra and Arnal settlements. It's 6.5 kilometres long with an elevation change of 300 metres and is expected to take around 3 h to complete. Attractions along this route include the Galegos da Serra waterfalls, the Arnal waterfalls and a view of the wider granitic area of Arnal. Finally, the Lamas de Olo Route (13.5 kilometres) is a circular trail located on the Alvão Mountaintop. It starts near the Cimeira and Fundeira irrigation reservoirs, passes by Lamas de Olo and Barreiro settlements, and takes around 4h30 m to complete. The main attractions are the landscape views, the traditional mountain scenery, and the traditional agricultural areas.

3. Methodology

3.1. Data retrieving

The data source used for this study was Wikiloc, since it allows to download their users' public routes, is extremely popular in the study area (Table 1) and is frequently used for activities in remote locations (Norman & Pickering, 2019). All pedestrian routes that crossed the Alvão Natural Park (from 2008 to 2022) were downloaded as a GPX file (GPS Exchange Format). This format was chosen to ensure the download of all GPS points recorded. Other file formats, like KML (Keyhole Markup Language), simplify route data to 500 vertices and misrepresent the exact path made by the users. When available, it was transferred any georeferenced photographs to enable the identification of the photographic hotspots. It should be noted that this information isn't always present because some users don't attach photographs alongside their routes. Any routes manually drawn by Wikiloc users were removed, since they didn't correspond to visitor movement.

3.2. Data processing

After downloading all available pedestrian routes, a Python script was used to automate and simplify the conversion of every GPX file located inside a given folder to the Esri feature class format (Figure 3). The data was converted to a feature class and saved inside a geodatabase to correctly preserve the temporal information of the GPX files. Other formats, like shapefiles, automatically truncate the time data and only save the date of when the point was recorded. Initially, all GPX files in the input folder are converted to a point feature and stored in a geodatabase. From this feature, which

Table 1. Factors considered for selecting the data source for this investigation.

| | Available route data | Number of routes (study area) | Route download |
|----------------|----------------------|-------------------------------|----------------|
| Wikiloc | Yes | 1333 | Available |
| AllTrails | Yes | 168 | Available |
| Map My Fitness | Yes | 0 | Available |
| Strava | Yes | High * | Not available |
| Flickr | No | – | – |
| Twitter | No | – | – |
| Instagram | No | – | – |

* The actual number of routes available in Strava couldn't be determined. Nevertheless, based on the number of users and their heatmap (<https://www.strava.com/heatmap#13.05/-7.83639/41.36511/hot/all>), it is predicted that numerous routes were undertaken in the study area using this app.

contains all the points recorded, the track points and Waypoints were exported into separate point features. The Trackpoints were then used to create polyline features containing the routes taken by the visitors. In sequence, the first and last vertices of each trail were extracted to create new point features containing the route start and end points.

Simultaneously, a Pandas data frame was created to store summary information of each processed route. This table contains the route ID and time/date information of the first and last points collected. Using this temporal information, new fields are created containing the year, month, season, day of the week, starting hour, and ending hour, which are used to calculate each route's duration. After processing, the resulting data frame is converted to a CSV file and joined to the route feature, using the route ID to link the files together. The last fields, containing the length and velocity, are calculated using the geometry data from each route.

This process resulted in four features containing s representing the movement of Wikiloc users inside the Alvão Natural Park: one file with the location of the waypoints collected by the visitors; one feature containing the path followed; one feature with the starting location for each route; and a final feature with the ending location of each route.

The next step involved systematically reviewing outputs, to identify and filter out any routes containing spatial or temporal errors. These 'error' routes were removed due to likely interference with the data analysis results. Accordingly, routes were eliminated when 1) contained errors in the location coordinates, which can occur when the GPS signal is 'lost' for a significant portion of the path followed, 2) had errors in the date and time fields (e.g. trails starting 1st January exactly at 00:00:00), and 3) had a route end date earlier than the start date. Trails with unusually high values for length, mean velocity, or duration, were also flagged for further detailed analysis. After verifying the path and attributes for each flagged trail, trails lacking correspondence to pedestrian movement (e.g. trails with a constant high velocity) and trails where the user didn't stop the device after finishing the route were removed. Overall, 188 routes containing spatial errors and 74 with temporal errors were excluded, leaving 1071 routes for further analysis.

Using the filtered data, a multi-faceted approach was applied to analyse the behaviour of Wikiloc users within the park. Firstly, route intensity was determined by counting the number of Wikiloc tracks completed throughout the park. Secondly, the temporal statistics of these tracks were analysed by assessing the visitor numbers by season, month, and day of the week, from which the number of visitors hiking in the park throughout the day was calculated. Thirdly, route intensity by season was examined using a spatial join with a 50 m² fishnet to count the number of Wikiloc tracks that intersect the fishnet polygons.

Fourthly, the Generalised Hot Spot Analysis was used to identify significant photographic hot-spots within the study's area. This process incorporates the Getis-Ord Gi* statistical measure, allowing for the creation of a detailed map that visually indicates statistically significant hot and cold zones. Systematic spatial partitioning is accomplished by grouping data points into a 50-metre fishnet. Following that, hotspots are identified using three different *p*-values (0.01, 0.05, and 0.1), corresponding to Hot and cold spots with confidence levels of 99%, 95%, and 90%.

Lastly, a comprehensive analysis of the start and end points was conducted to identify the most common locations to begin and end the trails, and by performing a statistical analysis of the start and finish times, focusing on the calculation of frequency, average, mode, and standard deviation values during the day.

4. Results

4.1. Visitor use intensity

4.1.1. Route intensity

Figure 4 shows the Wikiloc users' route intensity in Alvão Natural Park. Overall, the area with the highest route intensity is the western side of the park, followed by the centre and the southeastern

sides. On the other hand, the north and north-eastern sectors registered the lowest intensity values.

On the western side, the highest levels of route intensity are found in the Físgas de Ermelo route, which accounts for over 40% of the routes taken by Wikiloc users. The highest value achieved along this route (52%), was recorded near the Físgas de Ermelo waterfalls. Secondary areas with high route intensity were found near the reservoirs and the Lamas de Olo and Barreiro settlements (in the centre of the park), and near the towns of Arnal, Galegos da Serra and Agarez (south-eastern side of the park). These areas have the highest intensity values outside of the Físgas de Ermelo route and correspond to the Lamas de Olo and Arnal routes. Near the reservoirs, they account for 17% of the routes taken in the park. Interestingly, 2% intersected the total protection area, where visitors are only allowed to walk with park management authorisation.

4.1.2. Photograph hotspots

The 3209 photographs taken by the Wikiloc users in the study area, showed a similar pattern to route intensity. Most photographs were taken on the western side of the park, along the Físgas de Ermelo route, and at the Físgas de Ermelo waterfalls (Figure 5). Only in this area of the park were identified

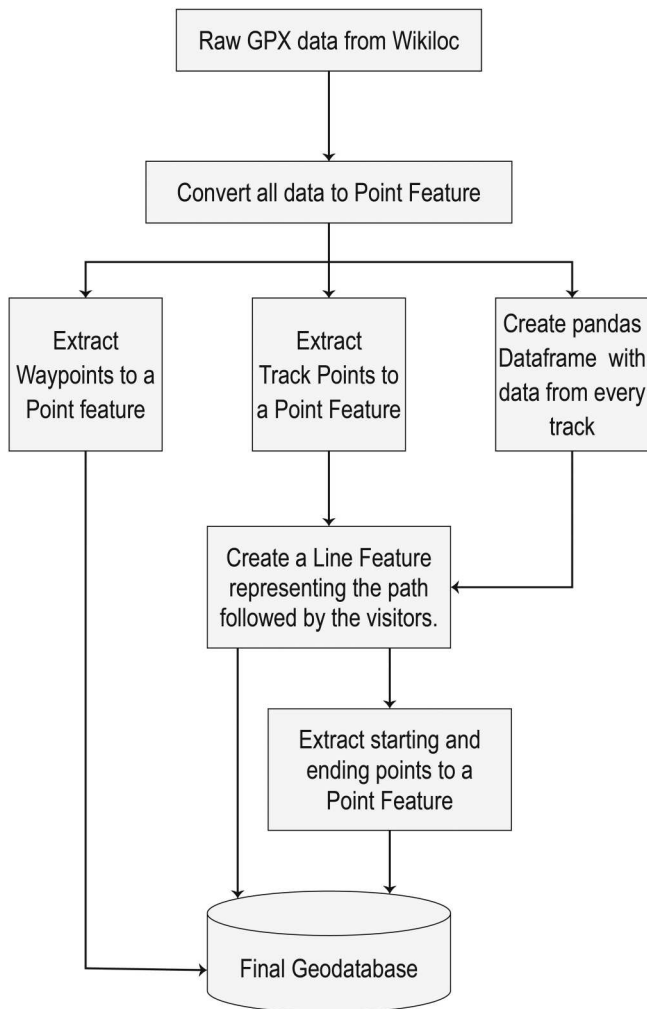


Figure 3. Data processing diagram.

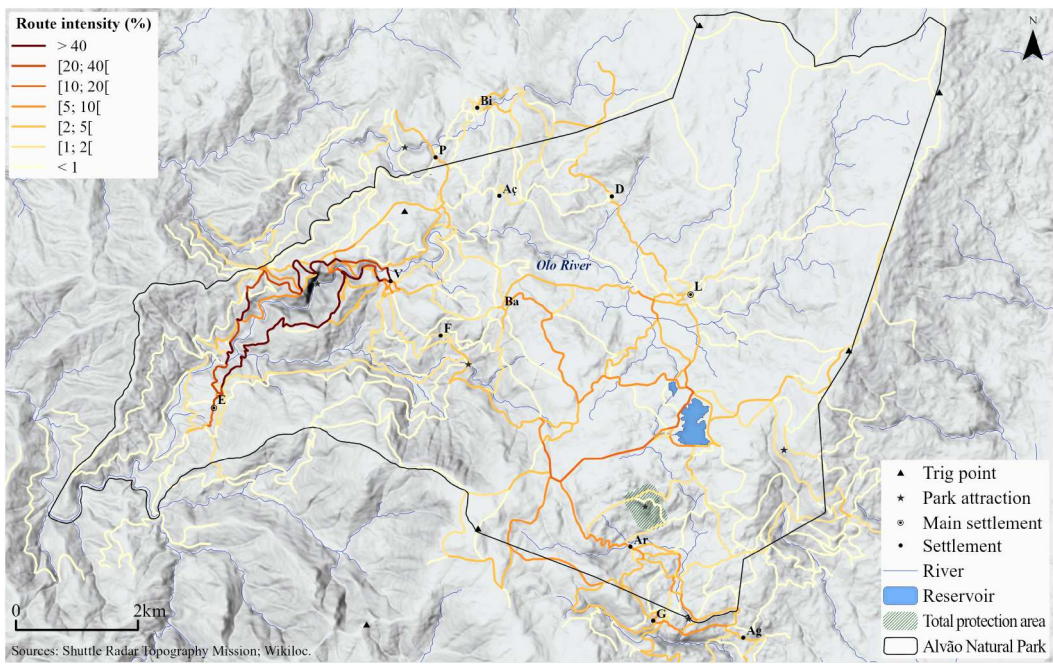


Figure 4. Number of Wikiloc routes in each trail of Alvão Natural Park (2008–2022).

significant Hotspots. Most of the hotspots are located on the Fiskas de Ermelo route and they correspond to areas with an open view towards the waterfalls (Figure 5A and C). Other areas with significant hotspots correspond to the Fiskas de Ermelo lagoons (Figure 5A and B), and the Ermelo (Figure 5D) and Varzigueto (Figure 5A) settlements.

Other areas in the park had a much lower number of photographs, with most places having less than 1%. The Galegos da Serra waterfalls and Bobal Waterfalls also had an important number of photographs taken (78 and 39, respectively), though not as many as at the Fiskas de Ermelo Waterfalls (228). The remaining settlements within the Alvão Natural Park also registered small

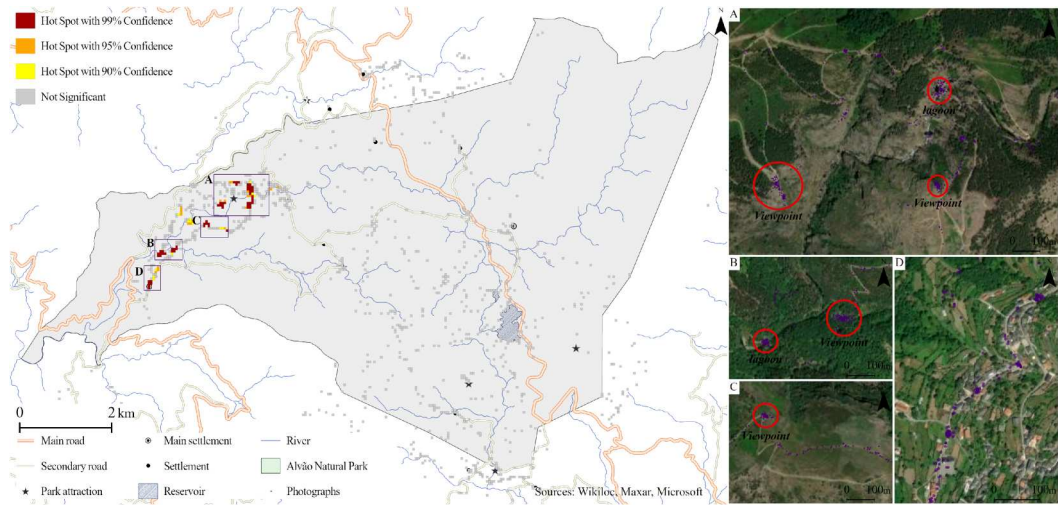


Figure 5. Wikiloc users' photograph hotspots inside the Alvão Natural Park.

concentrations of photos taken by the visitors: Lamas de Olo (90 photos), Arnal (46), Fervença (35), and Barreiro (25).

4.2. Route temporal analysis

Seasonally, spring is busiest (31%), followed by summer (26%), autumn (23%), and winter (20%). On a monthly scale (Figure 6A), May and April have the highest number of routes undertaken by users, each accounting for 11% of the dataset. August and June, each with 10%, are the other months that also register high route numbers. Conversely, February (5%) and March (7%) have the lowest visitor numbers. Half of the routes (51%) are done during the weekend (Figure 6B). The remaining days receive fewer users, with percentages varying between 7% (Thursday) and 12% (Wednesday). Additionally, routes taken during the weekend are longer, in length and duration, than the ones made during the weekdays.

Figure 6C shows the distribution of routes made in the park during the day in hourly intervals. Most visitors use the hiking trails between 11:00 and 14:00 hrs, with more than 60% of visitors being inside the park during this time, reaching a maximum of 68% at 12:30 hrs. There are almost no visitors in the park at night, with less than 1% of routes being taken during this time. During the morning, the visitor numbers undertaking routes in the park increase rapidly, while during the afternoon, they slowly decrease until 16:00 hrs, after which the decrease is rapid.

Table 2 shows the summary statistics for all the 1071 routes done by the Wikiloc users inside the park, both globally and by different periods. On average, these routes are longer during spring and autumn (13 km) and are particularly shorter in duration during summer (4 h). Overall, on average, the routes taken in the park have a length of 13 km, a duration of 5 h, and a speed of 3 km/h. Routes undertaken during the weekend have average higher values in length and duration (14 km and 5 hrs) when compared to those made during the weekdays (12 km and 4 hrs). The route velocity values didn't show any notable differences.

4.3. Route intensity per season

The route intensity in the Alvão Natural Park has differences throughout the seasons (Figure 7). During the hot seasons (spring and summer), visitors' routes are more concentrated on the western side of the park, along the Fiskas de Ermelo route. In contrast, during the cold seasons, they are more dispersed in the park, with visitors choosing the Lamas de Olo and Arnal reservoirs, as well as the Galegos da Serra areas to do their activities. Among these areas, the reservoirs show the highest intensity values outside of the Fiskas de Ermelo area. Furthermore, during winter and autumn, the route intensity along the Fiskas de Ermelo trail only reaches its highest

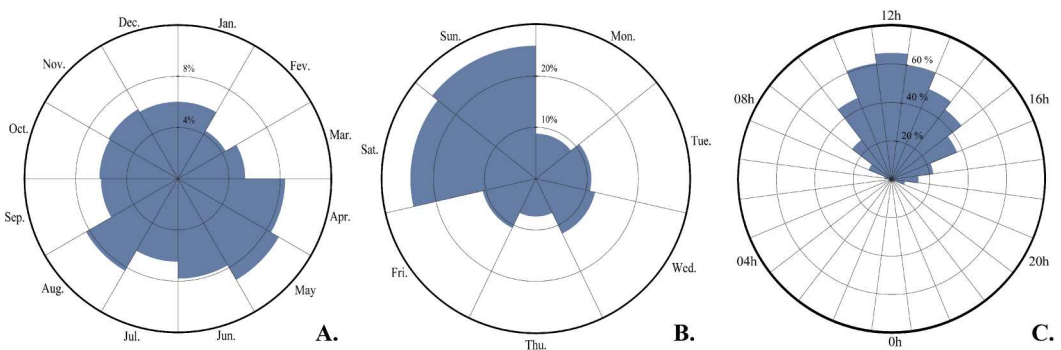


Figure 6. Temporal patterns: A) Monthly; B) Daily; and C) Hourly.

Table 2. Summary statistics (mean [\bar{x}] and standard deviation [s]) and temporal distribution of all collected Wikiloc user routes inside the Alvão Natural Park.

| | Length (km) | | Duration (hrs) | | Velocity (km/h) | |
|----------|-------------|-----|----------------|-----|-----------------|-----|
| | \bar{x} | s | \bar{x} | s | \bar{x} | s |
| Total | 12.9 | 6.8 | 4.6 | 2.3 | 3.1 | 1.6 |
| Season | | | | | | |
| Winter | 12.5 | 6.1 | 4.3 | 2.0 | 3.2 | 1.5 |
| Spring | 13.7 | 7.1 | 4.7 | 2.5 | 3.3 | 1.8 |
| Summer | 12.1 | 7.2 | 4.6 | 2.3 | 3.0 | 1.6 |
| Autumn | 13.2 | 6.2 | 4.8 | 2.3 | 3.0 | 1.6 |
| Week | | | | | | |
| Weekdays | 12.4 | 6.3 | 4.4 | 2.7 | 3.2 | 1.8 |
| Weekend | 13.5 | 7.1 | 4.7 | 2.9 | 3.1 | 1.5 |

intensity value (>40%) near the waterfalls and the main viewpoints, suggesting that fewer visitors choose to take the whole route during winter. The park's northern area has the fewest routes. However, even with such low use, the route intensities also increase during the winter and autumn.

4.4. Start/end points analysis

The highest number of start and finish points are in Ermelo, where the Fiskas de Ermelo route begins (Figure 8A). A total of 438 starting points and 419 ending points were recorded in this area, corresponding to approximately one-third of all recorded points. Along this route, there were other locations with significant concentrations of start and finish points. The Municipal Road 1200 (Figure 8C) was the second-most popular location where visitors started (134) or finished (118) their routes. Along this road, most of the points are located near the Fojo Chapel and at the Fiskas Ermelo Waterfalls Viewpoint. The town of Varzigueto is another important starting and finish location near the Fiskas de Ermelo route, with 94 starting points and 95 finishing points.

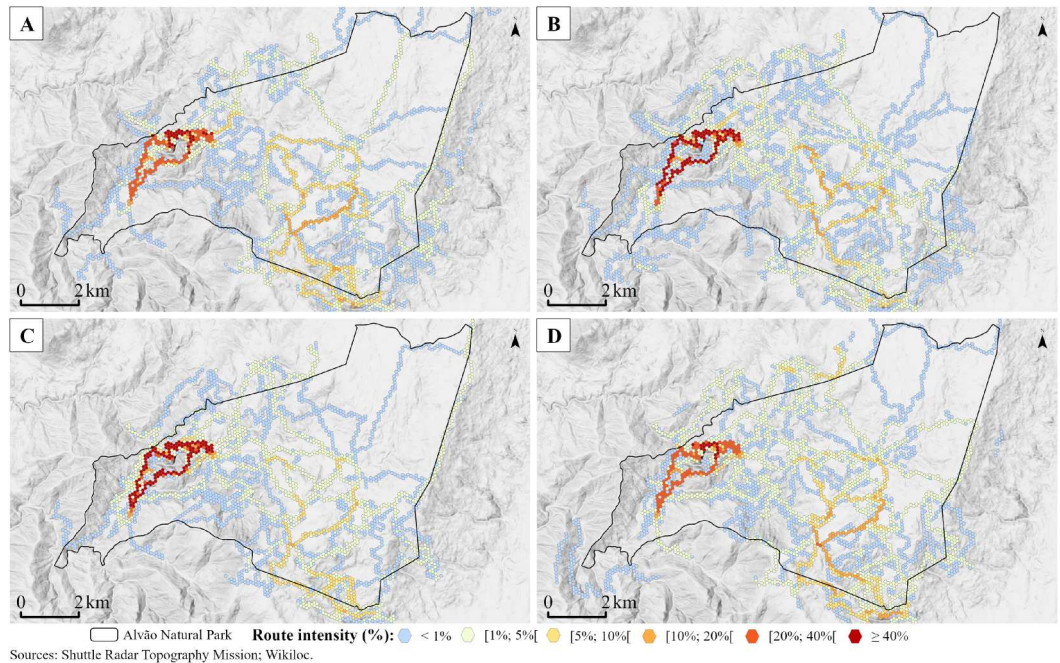


Figure 7. Percentage of Wikiloc users in the Alvão Natural Park per season: A) Winter; B) Spring; C) Summer; and D) Autumn.

Outside of the Físgas de Ermelo area, there are other locations with considerable start and finish points. Among them, the reservoirs where the Lamas de Olo route begins are the most significant, with 114 start points and 107 finish points. Nearby, in Lamas de Olo was the starting place for 75 routes, and the finish place for 52 visitors. On the south-eastern side of the park, the town of Arnal had 31 starting points and 25 finishing points. However, the highest number in this area is in Agarez, with 71 starting points and 69 finishing points, this settlement is the Arnal route starting location. Additionally, another popular spot located outside of the park's boundaries to start and finish activities is the Bilhó settlement, containing 33 starting points and 39 finishing points.

Figure 9 displays the starting and ending times of Wikiloc users' trails during the day. On average, users begin their routes at 11:39 hrs, with a mode of 11:00. And a standard deviation of 2 h and 45 min. As for the ending times, the average is 16:02 hrs, with a mode of 17:00 and a standard deviation of 2 h and 52 min. As depicted in Figure 9A, Wikiloc users generally prefer to commence their trails late in the morning or around noon, with the majority concluding their activities during the afternoon. It is worth noting that the end times exhibit slightly more dispersion compared to the start times.

The main peak of start times occurs between 08:00 and 13:00, but with a considerable amount of visitors starting their activity after lunch (from 15:00–17:00). After 17:00 the number of visitors starting a route steadily decreases until 20:00, with only a few visitors who start an activity between 20:00 and 06:00. Regarding the finish time, there is a significant number of visitors who finish their activity from 12:00–20:30, with two periods having a higher number of visitors finishing: the first from 13:00–14:00 and the second from 16:00–18:00. In contrast, only a small number of visitors finishes their activity between 22:00 and 10:00. Visitors' start and finish times during winter and autumn and during spring and summer are shown respectively in Figure 9B and C. During autumn and winter, users tend to start their activities later in the morning, with the most frequent starting time being between 10:00 and 13:00. It's also noticeable that users finish their activities earlier in the day. In contrast, during spring and summer, users start their activities earlier (from 08:30–13:00). The finish time is more scattered, ranging from 12:00–20:00, with the most common time to finish a route being at 17:00 and gradually reducing thereafter.

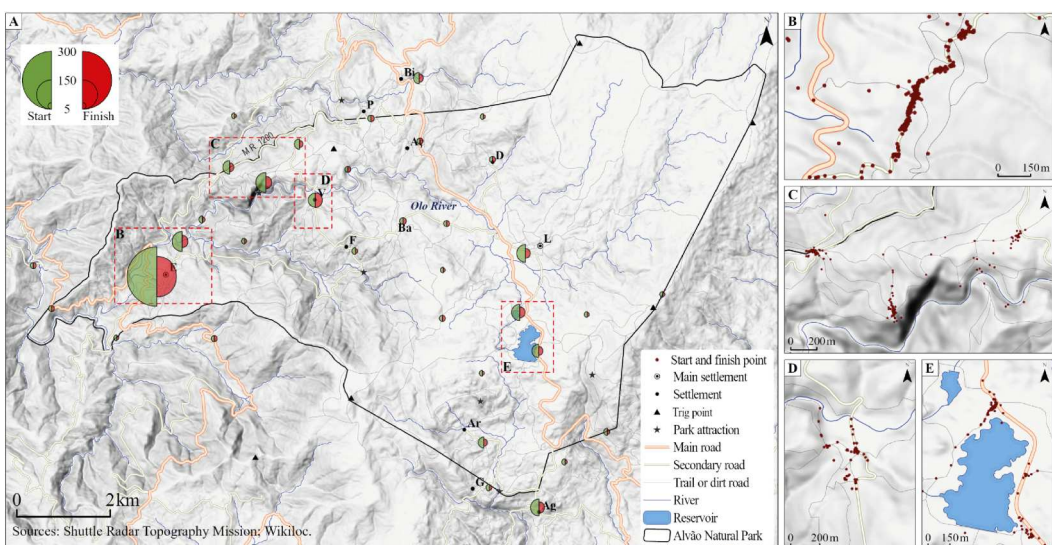


Figure 8. Location of the route's start and end points: a) global, b) Ermelo settlement, c) Municipal Road 1200, d) Varzigueto settlement, e) Reservoirs.

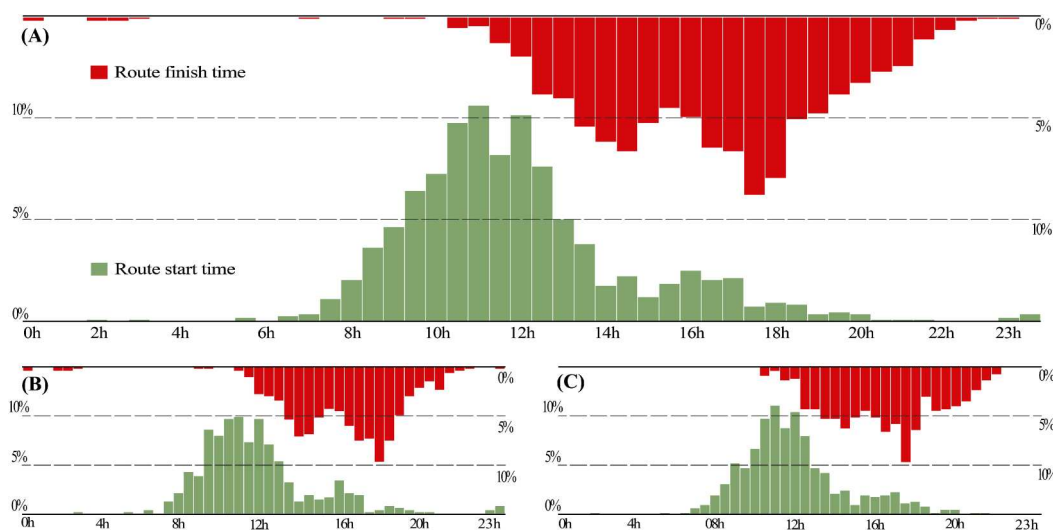


Figure 9. Route start and finish temporal patterns: a) All dataset b) winter and autumn, and c) spring and summer.

5. Discussion

5.1. Spatial patterns

Considering the spatial patterns, it was observed that Fiskas de Ermelo Waterfalls was the area with the most intensive use and that visitors crossed prohibited areas. Since the waterfalls are the most outstanding feature of the park and are widely known and advertised, their intensive use is no surprise. This pattern may also be explained by the Fiskas de Ermelo route, which makes this area more accessible to visitors when compared to other points of interest.

Jurado Rota et al. (2019) emphasised the importance of outstanding sites, amenities, and the trail network in determining use intensity inside PAs. In the Alvão Natural Park, the presence of outstanding sites is the key factor. This was shown in the photographs' hotspots analysis since they were located near the waterfalls or the viewpoints facing them. However, this interpretation differs from Callau et al. (2019), who suggest photograph locations are influenced by the presence of official trails. While most photographs are taken along the trails, they aren't evenly distributed, suggesting other reasons for the observed pattern. The same pattern was observed at other waterfalls within the park, suggesting that geomorphological features are the main factor influencing use intensity in the Alvão Natural Park. However, our approach doesn't consider the content of the photographs.

Regarding visitors trespassing in prohibited areas, this only occurred when visitors walked between the reservoirs and the Arnal settlement, indicating a need for a planned path connecting both places without crossing prohibited areas. Previous studies have found similar behaviours, such as the identification of illegal activities and informal/off-trail use (Campelo & Nogueira Mendes, 2016; Norman & Pickering, 2017). Our finding, alongside those of others, suggests that the Wikiloc app provides a useful tool to detect visitor behaviours capable of damaging PAs. The occurrence of these behaviours exemplifies the conflict between nature conservation objectives and recreational use, highlighting the importance of identifying spatial patterns in PA management.

5.2. Temporal patterns

5.2.1. Seasonal, monthly, and daily usage patterns

Regarding the temporal patterns, it was found that: 1) the season receiving most park visitors is spring, with April recording the highest visitor numbers in a single month; 2) half of visitors go to the park during the weekend; and 3) the time of day with most visitors in the park is noon (12:00hrs).

When considering the seasonal (spring) and monthly (April) patterns are uncommon when compared to the results of other cited studies. These conclude that the most common time to visit PAs is during the summer, especially August (northern hemisphere) or December (southern hemisphere) and that this tendency can be explained by the warmer climate and by the summer holidays (Barros et al., 2019; Sessions et al., 2016; Sinclair et al., 2020; Tenkanen et al., 2017). Additionally, previous studies have also noted that natural features, climate, and geographical location influence temporal visitation patterns (Barros et al., 2019; Hadwen et al., 2011). In Australia, the presence of SKI resorts resulted in high visitor numbers during winter months (Walden-Schreiner et al., 2018). For the Alvão Natural Park, the preference for springtime visiting is likely due to the favourable climatic conditions. During spring, the Ólo River catchment has a higher river flow when compared to summer, meaning the waterfalls are more active and visually appealing. Additionally, spring is the main bird breeding season, thus attracting birdwatchers (Barros et al., 2019). Furthermore, in Portugal is culturally common to spend summer vacations in coastal areas (Moreira, 2018). Also, inland mountains are sweltering during summer and have higher solar exposure, which, combined with the lack of amenities in the park, can limit the number of visitors.

The tendency to visit PAs during the weekend was commonly observed worldwide (Barros et al., 2019; Sinclair et al., 2020). Considering that the Alvão Natural Park is located at a significant distance (~100 km) from population centres, this distance requires spending more time travelling to and from the park; therefore, the weekend is likely to be more convenient for users. Additionally, the park's features and topography make it ideal for hiking activities which require more time to undertake, and that are more common during the weekend (Norman et al., 2019).

For the hourly visitation pattern, the park location (distance from population centres) and type of visitor activities (hiking) can explain the observed patterns. Identification of detailed temporal visitation patterns is important because it informs when overcrowding occurs and the PA carry capacity is more likely to be surpassed (Barros et al., 2019). Additionally, temporal patterns, if known, can be used to adapt staff levels and service availability (accommodation) in a PA (Norman et al., 2019).

5.2.2. Methods for spatiotemporal insight and comparisons

Considering the method used to analyse temporal patterns on a daily scale, a different approach was used in comparison with existing studies (Barros et al., 2019; 2020; Do & Kim, 2020; Retka et al., 2019) by calculating the visitor numbers in the park using route data. This approach avoids any potential bias related to the photographs' spatial distribution. The photographs of visitors in our study area are concentrated in a few specific areas of the park, implying that the results obtained using this data may overestimate the visitor numbers only when they are in these specific locations. On the other hand, given that most route start/end times are located near car parking places, it's possible to suppose that most visitors begin recording their activities as soon as they enter the park and stop before leaving. To calculate the daily temporal patterns, the following equation was devised and a graphical summary (Figure 10):

$$Rn = \sum_{i=1}^n I((a_{i1} \geq t \cup a_{i1} - a_{i2} < 0) \cap t < \text{mod}(a_{i1} - a_{i2} - \Delta t, 24)) \quad (1)$$

Rn represents the number of routes being analysed. The variable a is a matrix with 2 columns and n rows, where n is the number of routes being analysed, the first column (ai1) represents the route finish time, whilst the second (ai2) corresponds to the route duration. The variable t represents the time interval, and Δt denotes the length of the time interval being analysed. This equation

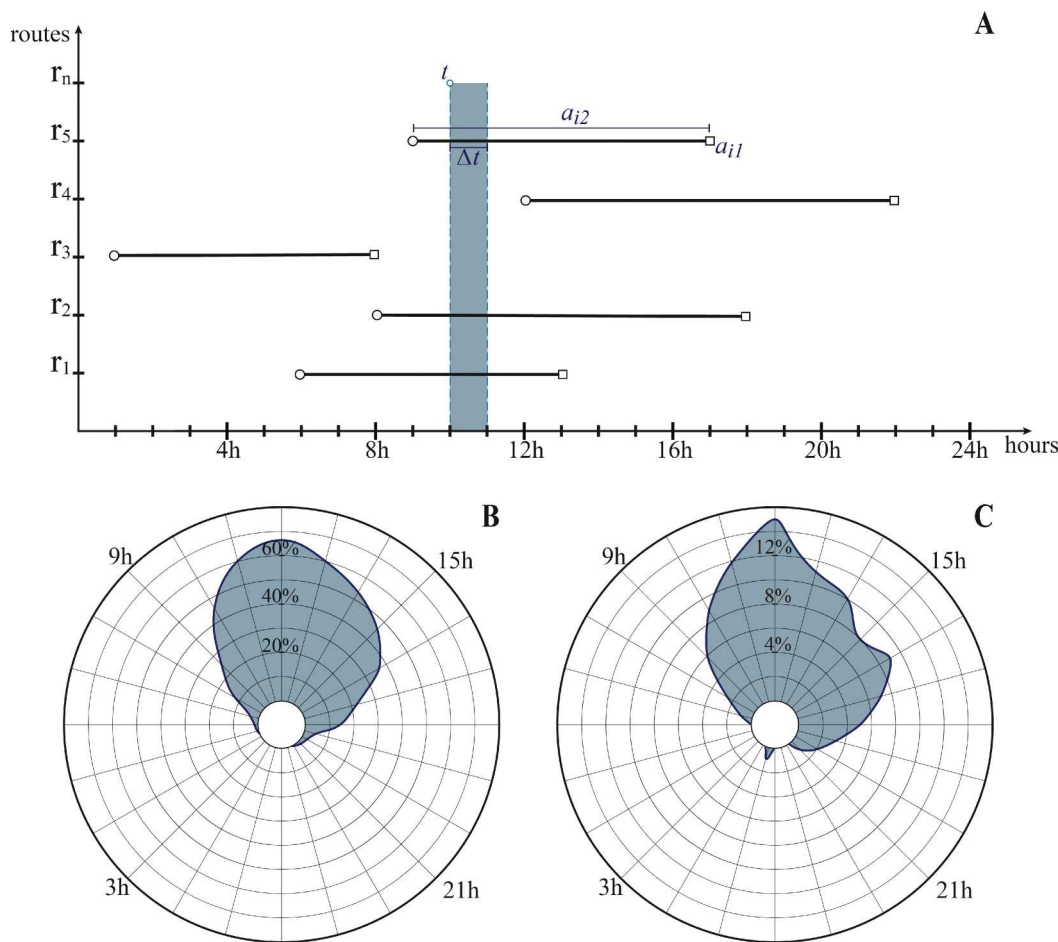


Figure 10. Visitation patterns during the day. A) Illustration of the equation variables. B) Percentage of routes during the day. C) Percentage of visitor photographs during the day.

can be conveniently implemented in Excel or Python. The Python code necessary to implement this function is available at <https://github.com/jorgecosta97/RouteFunctions>.

Figure 10B shows the difference between the visitor numbers during the day using photograph time stamps and the route data. Both methods displayed similar patterns. However, the data derived from the photos (Figure 10C) indicates that the number of visitors inside the park starts to increase later in the day and decreases earlier. Additionally, for the photo data, there is an increase in the number of visitors during the afternoon from 13:00–14:00 hrs, whereas the route data shows a slight decrease in the number of visitors from noon onward until the end of the day. Concerning these differences, using route data appears to be a more accurate method for calculating the visitor numbers within the park throughout the day given that: 1) photo data doesn't reflect the amount of time people are in the park walking to the location where they take the photos; 2) the photos are focused on specific locations within the park; and 3) most visitors start and end their journey recording near parking spaces.

5.3. Start/end points: spatiotemporal insights

For the analysis of the start/end points, it was found that: 1) the most used start/end points are located in places where it is possible to park the car; 2) the most common times to start a route

is during the morning and 12:00hrs (noon); and 3) that visitors' route ending time also follows a bimodal distribution, with the most common times to end routes being in the mid and late afternoon.

Considering that the park is located far away from larger population centres and that the park doesn't have public transportation connections, it is expected that visitors use their vehicles to get to the park. These characteristics explain the first pattern. For the temporal patterns identified, it was expected that visitors started their routes during the morning. Despite different people planning their days in different ways, considering that the routes available in the park require time to undertake and that visitors must expend time to get to the park, it is expected that they would need to arrive early to ensure they can finish their route. The end time patterns suggest that some visitors aim to end their routes at lunchtime. This indicates that some may intend to have lunch in the park restaurants because many start/end points coincide with restaurant car parks. However, the ability of route data to fully explain this pattern is limited, and traditional methods, such as surveys, are required to answer this question.

Nevertheless, it's essential to recognise that knowing where and when visitors begin and conclude their routes is useful for managing PAs. This is justified because, in addition to the environmental damage caused along the routes, the location and intensity of visitor start/end points introduce additional impacts (Jurado Rota et al., 2019). The temporal patterns of start/end times provide unique insights that can influence the administration of PAs and enhance the visitor experience. These insights could be used, for instance: to establish litter-removal programmes, identify unmonitored parking lots, improve safety measures during peak hours, optimise personnel levels and resource allocation throughout the day, or identify areas of significant noise perturbation (Jurado Rota et al., 2019).

5.4. Route data from fitness-tracking apps: benefits and limitations

Using route data from fitness-tracking apps to support visitors' spatiotemporal behaviour studies offers notable benefits but also comes with limitations. The first benefits are cost and data availability. At the time of this study, the data used was cost-free, and the time required to collect this data was significantly reduced compared to traditional methods (Barros et al., 2022; Ghermandi & Sinclair, 2019). This is of key importance for researchers and park managers, especially in places with limited resources. A further benefit is the absence of 'knowledge bias' as stated by Newsome et al. (2012). This bias occurs in datasets where visitors are aware that their movements are being recorded, and in consequence, they carry out behaviours that they wouldn't naturally undertake. However, limitations are inherent in the use of route data. Firstly, there is a potential sampling bias where the use of fitness-tracking apps might not be representative across the population, with specific groups (e.g. younger people, sports enthusiasts) possibly being more represented than others (Barros et al., 2020; Heikinheimo et al., 2017; Norman et al., 2019; Norman & Pickering, 2019). Other limitations include user privacy concerns and potential future changes in how mobile apps share data with researchers (Barros et al., 2022). For privacy concerns, noting that PAs often have financial resource limitations, it is recommended the development of an infrastructure capable of storing and supplying mobile app data to researchers and park managers. A system like GBIF (www.gbif.org) would be ideal, as it could facilitate data access and ensure the protection of the user's personal information.

6. Conclusion

This study has evaluated the application of route data from the Wikiloc mobile walking app to analyse visitors' spatiotemporal behaviour within PAs and its contribution to the management of these areas. It was found that visitor use intensity is concentrated near the park's biggest attraction (waterfalls). Park visitation numbers vary significantly during the year, week, and day. Visitors most

commonly start/end their walks at car parks, starting in the morning, peaking at 12:00 hrs (midday) and ending their routes in the early or late afternoon. Combined, insights from this study contribute to understanding visitor behaviour in PAs. Specifically, they contribute to detecting crowding and identifying places/times where the carrying capacity is exceeded. The study also identifies behaviours that could damage a park's environment, such as walking along unofficial routes that disregard restrictive zoning regulations. Given that zoning is a common management strategy (Newsome et al., 2012), this approach can be easily implemented in other PAs. Consequently, they can help park managers reduce human pressure on the PA's ecosystems and natural features. Additionally, the insights provided can also assist staff management and the allocation/maintenance of essential park services and facilities. Therefore, this could help make parks more economically viable and improve visitors' experiences and satisfaction.

Overall, our study highlights the importance of conducting a detailed visitors' spatiotemporal behaviour analysis using mobile app route data. This approach offers a novel method that could help reduce the negative impacts of visitor activities and support the development of long-term management strategies in PAs. A better understanding of the visitor's spatiotemporal patterns enables park managers to design and implement policies and infrastructure that meet the needs of visitors without compromising the environment. This is especially beneficial in PAs where there are no consistent visitor datasets, for example as obtained through official surveys. In summary, the use of mobile app route data for analysing visitors' spatiotemporal behaviour patterns presents a promising avenue for balancing recreational use and conservation in natural areas while also improving the efficiency and effectiveness of park management strategies and laying a foundation for sustainable tourism that not only protects and preserves natural environments but also enhances the PA's economic viability.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This work was supported by the Foundation for Science and Technology (FCT) [grant number 2021.05304.BD]; and the Foundation for Science and Technology by FEDER funding through the COMPETE 2020 programme and framed within the activities of UIDB/04084/2020 – CEGOT financed through the European Regional Development Fund (COMPETE 2020), with ref. POCI-01-0145-FEDER-006891.

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Appendix

Table A1. Papers using route data from fitness-tracking apps to analyse visitor behaviour. Bibliographic analysis made of the articles identified by Barros et al., 2022 and Teles da Mota & Pickering, 2020 and complemented with a systematic search on WOS and SCOPUS.

| Papers | Number of visitors going to PAs | | | Route intensity | Photo's location | Start and end point analysis | | Summary statistics |
|-----------------------------|---------------------------------|-----|------|-----------------|------------------|------------------------------|-------------------|--------------------|
| | Month | day | hour | | | Spatial Analysis | Temporal Analysis | |
| Barros et al. (2015) | | | | | | | | X |
| Barros et al. (2019) | X | X | | | X | | | |
| Barros et al. (2020) | X | X | | X | | | | |
| Bhatt and Pickering (2022) | | | | | X | | | |
| Brovelli et al. (2016) | | X | | | | | | |
| Callau et al. (2019) | | | | | X | | | |
| Gea García et al. (2021) | X | X | | | | | | |
| Horst et al. (2023) | | | | X | | | | X |
| Jurado Rota et al. (2019) | X | | | X | | X | | |
| Norman and Pickering (2017) | | | | X | | | | X |
| Norman et al. (2019) | | X | | X | | | | |
| Orsi and Geneletti (2013) | | | | X | | | | |
| Pickering et al. (2020) | X | X | | | X | | | |
| Sessions et al. (2016) | X | | | | | | | |
| Sinclair et al. (2020) | X | X | | X | | | | |
| Smith et al. (2021) | X | | | | | | | |

(Continued)

Table A1. Continued.

| Papers | Number of visitors going to PAs | | | Route intensity | Photo's location | Start and end point analysis | | Summary statistics |
|-----------------------------------|------------------------------------|-----|------|--------------------|---------------------|------------------------------|----------------------|-----------------------|
| | Month | day | hour | | | Spatial Analysis | Temporal Analysis | |
| Taczanowska et al. (2014) | | | | X | | | | |
| Tenkanen et al. (2017) | X | | | | | | | |
| Walden-Schreiner et al. (2018) | X | | | | X | | | |