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Behavior Analysis of Rhinoceroses and their Monitoring using a 3D Geovisualization Prototype

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Abstract. Black and white rhinoceroses are emblematic large mammals of the African wilderness, yet poaching and habitat disturbance are critically endangering their survival. To ensure the conservation of the species, the population needs to be closely monitored. This paper presents a prototype of an integrated system designed to support rhino monitoring by providing a complete data pipeline, from data collection and visualization, to behavioral analysis. As part of a conservation program, more than 200 rhinos across seven nature reserves in South Africa and Mozambique have been fitted with GPS horn pods. The transmitted data is then displayed in real-time on *Rhinos3D*, a web-based 3D visualization which allows the rhinos to be visualized in their 3D environment alongside their pre-calculated home ranges. The scientific value of this infrastructure is demonstrated by an exploratory analysis of a small data sample which highlights differences in activity patterns and home range size across species, sex, season, and time of day. The long-term aim of the *Rhinos3D* platform is to function as a digital twin of a game reserve by integrating additional variables (e.g., vegetation, weather), enriching individual rhino profiles with movement and activity metrics, and developing automated anomaly detection to identify deviations from normal behavior, thus becoming a key asset for field rangers and researchers in rhino conservation.

Submission Type. Infrastructure, Analysis, Project

BoK Concepts. EO for biodiversity & ecosystems (TA12-2), Use of geospatial information in environmental issues (GS3-4)

Keywords. Rhinoceros, GPS tracking, Animal Movement Analysis, 3D Web Application

1 Introduction

The population of Black Rhinoceros (*Diceros bicornis*) and White Rhinoceros (*Ceratotherium simum*) remain endangered, requiring close and continuous monitoring to support conservation and species recovery efforts (IUCN, 2025). Given that rhinos are highly threatened by poaching, GPS tracking has become a crucial tool in anti-poaching efforts (Lynam et al., 2025). Accordingly, as part of a conservation plan, rhinos in South African game reserves have been fitted with GPS trackers that record their position hourly. These devices enable near real-time remote monitoring, helping rangers quickly assess populations and detect irregularities more efficiently than through field patrols alone.

In this paper, we present a prototype of an integrated system designed to support rhino monitoring through a complete data pipeline: from data collection and visualization to behavioral analysis. The prototype combines GPS tracking data with a 3D representation of the reserve's terrain and vegetation, improving the understanding of animal movements. Beyond visualizations, the prototype includes exploratory analyses based on GPS records to highlight species-specific movement characteristics. These analytical outputs are aimed to be accessible directly within the visualization platform. The ultimate objective of this prototype is to explore the feasibility of creating a digital twin of a game reserve, providing conservation teams with a unified platform to access, explore, and interpret animal data.

The remainder of this paper is structured as follows. We present the state of the art of technologies for animal movement analysis to support conservation efforts. We then describe the infrastructure deployed for data collection, followed by the architecture of the 3D visualization component. Next, using a sample dataset, we illustrate the analytical opportunities enabled by the prototype.

1.1 Animal movement analysis studies

Conservation scientists have been using a wide range of technologies to monitor wildlife, including fixed sensors such as optical or thermal camera traps, radars, and acoustic sensors, as well as mobile platforms like drones or manned vehicles. In parallel, the growing use of biologging technologies, sensors attached directly to animals, such as GPS devices sometimes coupled with inertial measurement units (IMUs), has considerably expanded monitoring capabilities (Lahoz-Monfort and Magrath, 2021).

An increasing number of animals are now being equipped with GPS devices (Beltran et al., 2025), and technological advances allow tracking large numbers of individuals at high spatio-temporal resolutions and reduced costs (Nathan et al., 2022). These data support a wide range of analyses, including trajectory and movement metrics analysis and home range estimation (Seidel et al., 2018), behavioral classification (e.g., jaguar behavior classification; Garcia Fontes et al., 2021), and inference of habitat use (e.g., space use prediction of red deer via paths of least spatio-temporal costs; Ho and Loraamm, 2023).

Among large mammals, black and white rhinos have been the focus of numerous studies, in particular black rhinos, which are classified as critically endangered by the IUCN and are highly threatened by poaching for their horn (IUCN, 2025). Combating poaching of endangered species has become a major focus in conservation science, with a wide range of techniques developed, including animal tracking (Kamminga et al., 2018). For example, Ihwagi et al. (2018) equipped elephants with GPS trackers and used changes in travel speed to detect potential poaching events. de Knegt et al. (2021) developed a poacher Early Warning System (EWS) based on the behavioral changes of tagged sentinels in a South African game reserve. Furthermore, the development of digital web and mobile platforms designed to support animal conservation, such as EarthRanger (Wall et al., 2024), has greatly empowered rangers in their anti-poaching efforts (Lynam et al., 2025). Additionally, many studies focus on studying these GPS data to automatically detect and classify behavior changes (Wang, 2019; Gundermann et al., 2023).

2 Methodology

2.1 Infrastructure and data collection

For data collection, rhinos are fitted with horn pods glued to the horn stump during the dehorning process (Fig. 1). The horn pod's electronics, firmware and housing have been developed specifically for this project and optimized over many trials. They are tracking devices that register GPS coordinates at regular intervals, e.g., once every hour, and send the location data to a central server using wireless transmission over LoRaWAN, Sigfox or satellite communication. LoRaWAN and Sigfox are both long-range, low-power wireless transmission technologies. LoRaWAN has a slightly shorter range of up to 20 km but allows users to build their own low-cost private network. Sigfox is operator-provided but can achieve longer ranges up to 30 km. Satellite communication does not require a local, ground-based infrastructure and can cover large areas. Horn pods have a lifetime of up to three years, depending on the recording intervals. The central server decodes the received information, stores it, and makes it available for data analysis.

Since 2021, more than 200 rhinos have been fitted with GPS horn pods, across seven natural reserves in South Africa and Mozambique. Transmission intervals of GPS data range from 6 hours for older horn pods to 20 minutes for newer ones. Around 2,000 new data points are collected each day and a total of about 1,000,000 positions have been collected so far.

2.2 3D Visualization development

We developed a web-based application (henceforth referred to as *Rhinos3D*) to help visualize GPS tracking data from trackers fitted to a number of rhino' horns. The application's technical architecture is presented in Fig. 2.

2.2.1 Software architecture

Rhinos3D has been developed as a collection of container images running on a Kubernetes cluster. The container images provide isolation and modularity and allow us to quickly prototype and iterate on the components of the platform. A description of each of these components is given below.

Rhinos3D-web

Rhinos3D-web is the front-end for our *Rhinos3D* application. It uses the NodeJS JavaScript framework, along with the CesiumJS library (Cesium, 2026), to render a dynamic representation of the rhino tracking data on a virtual earth-shaped globe.

Figure 1. Rhino with a horn pod GPS tracker glued to the horn stump during dehorning

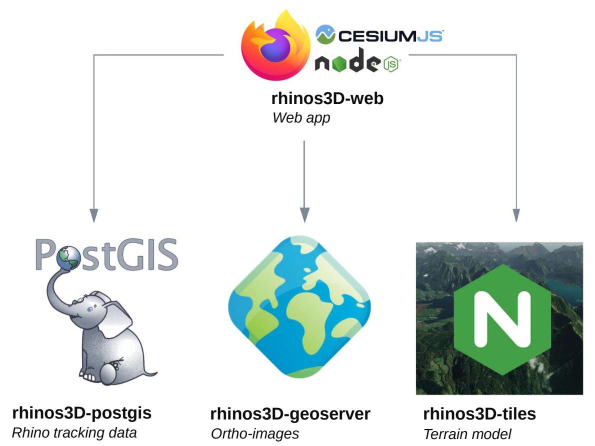

Figure 2. Architecture of the *Rhinos3D* web application

The *Rhinos3D-web* container fetches time-dynamic rhino tracking data from the *Rhinos3D-postgis* container. The tracking data are transferred from *Rhinos3D-postgis* to *Rhinos3D-web* and transformed into a CZML document, a format used to describe time-dynamic graphical scenes (rhinos' positions overtime) on Cesium.

Rhinos3D-postgis

Rhinos3D-postgis contains a PostGIS database server in which the geo-referenced data points corresponding to each rhino position, as well as pre-calculated analysis results such as home ranges are stored. This data is ready to be queried by the *Rhinos3D-web* container for display.

Rhinos3D-geoserver

Rhinos3D-geoserver hosts a Geoserver instance (Aime et al., 2024), used for serving geospatial data. For our *Rhinos3D* application, it serves as a Cascading Web Map Service (WMS) providing close range ortho-imagery from the CDNGI WMS server in South Africa (DLRRD, 2024). For far-range views, CesiumJS' Sentinel-2 imagery asset (EOX IT Services GmbH, 2024) is used directly.

Rhinos3D-tiles

Rhinos3D-tiles contains a nginx-based web-server serving quantized mesh terrain data to the *Rhinos3D-web* container. The terrain originates from South Africa's Copernicus DEM (GLO-30, 30m resolution; European Space Agency, 2024) provided as GeoTIFF, which is converted to quantized-mesh tiles (`.terrain`) using Gaia3D's mago-3d-terrain tool (Gaia3D, 2026). These tiles are then streamed to CesiumJS for real-time 3D visualization.

2.3 Exploratory analysis of rhino behavior

To attest how rhino behavior could be inferred from the collected data, and what could be displayed on the 3D visualization, an exploratory analysis was conducted on a one-year sample, spanning from July 2024 to July 2025. It contains 78,234 records of 25 Black rhinos (12 Female / 13 Male) and 14 White rhinos (8 F / 6 M) in Hluhluwe-Imfolozi game reserve, South Africa. Hluhluwe-Imfolozi game reserve is situated in the East of South Africa spanning nearly 1,000 km^2. It is characterized by a dry and cold (April-September), and wet and hot (October-March) season.

Preprocessing: To identify and remove outliers, the time lag and step length between each record and its preceding and following points were calculated (time window=1). Records showing values exceeding a defined threshold (4 km/h) were discarded, as well as those indicating no movement for at least one day. Such cases likely represented tracker malfunction, detachment, or animal death. The dataset was then subsampled to retain one record per hour. Each remaining record was annotated with the season (dry or wet), as well as with the corresponding time of day (dawn, morning, midday, afternoon, dusk, post-dusk, midnight, pre-dawn) based on daily sunrise and sunset times obtained via the Sunrise-Sunset API (https://sunrise-sunset.org/api). Time of day categories were defined as follows: dawn corresponded to sunrise (around 7:00), midday to solar noon (around 14:00), and dusk to sunset (around 20:00). The intermediate periods were determined by adjusting these reference time within a ± 1 hour window. All analyses were performed using R Statistical Software (v4.5.0; R Core Team, 2025)

Traveled distance: After preprocessing, step lengths were analyzed to assess differences across both species, sex, time of day, and season. Because there were some recording gaps, step length was only calculated between records that were less than 80 minutes apart. To evaluate the influence of the variables, we fitted a Linear Mixed Model (LMM) (Bates, 2005) with log-transformed step lengths as the response variable. We handled the two species separately. Fixed effects then included sex, season, and time of day, as well as their interactions. Individual identity was included as a random effect to account for repeated measures within animals. Post-hoc pairwise comparisons were performed using Tukey-adjusted contrasts based on estimated marginal means (EMMeans).

Home ranges: Finally, the home range of each individual was estimated using the R package *adehabitatHR* (Calenge and Fortmann-Roe, 2024). The Minimum Convex Polygon (MCP) (Worton, 1987) method was applied to derive two spatial metrics: the 95% home range, representing the animal's overall area of use, and the 50% core home range, which corresponds to the area where the individual spends most of its time. To minimize temporal autocorrelation between consecutive GPS recordings (de Lange et al., 2024), the dataset was subsampled to include only one fix per day. Following recommendations of Plotz et al. (2016), only rhinos with a minimum of 30 recording days per season were retained for analysis. Variations were tested through LMMs on log transformed area.

2.4 Data and Software Availability

For the purposes of reproducibility, the analysis code, the geovisualization tool and a sample dataset are available on Zenodo. However, due to confidentiality requirements to protect the safety of the monitored rhinos against poaching or other dangers, original data cannot be made available.

3 Results and discussion

3.1 *Rhinos3D*: 3D Visualization prototype

The current version of the *Rhinos3D* platform, allows us to visualize the positions of the rhinos tracked between June 2024 and June 2025 in a 3D environment. To enhance the 3D visualization, the altitude is artificially inflated, and three visualization options are proposed: orthophoto, elevation, or slope. Figure 3 illustrates the current user interface.

The user has the option to track any selected individual through the reserve. The trail left behind each rhino as it moves around on the ground, speed up or down the passage of time, can also be displayed. This trail is computed client-side as an interpolation of all positions previously displayed. Finally, for this prototype, the home range of each rhino was computed for each month to visualize its evolution (Fig. 4). Future developments for the platform will also include a dashboard displaying information about rhino characteristics (species, sex, age), as well as their temporal behavior (daily, monthly, and annual patterns).

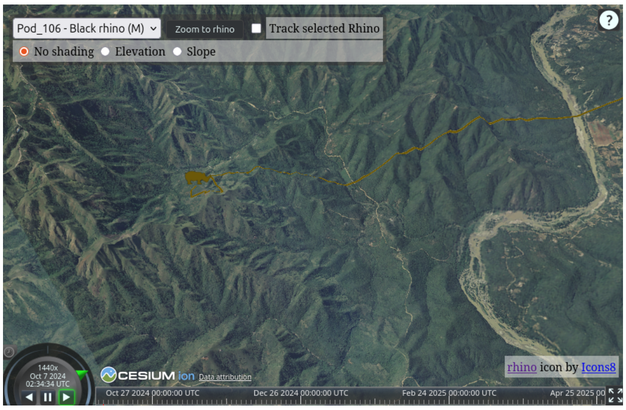

Figure 3. *Rhinos3D* user interface

Figure 4. Displayed home range for a selected individual

3.2 Exploratory analysis: black rhino behavior

To illustrate the use of the *Rhinos3D* platform by conservationists, we provide some analysis examples. Our focus is on the spatial analyses of such dataset, without claiming any contribution to ecology or conservation science. In this analysis, we assessed the differences in traveled distances and home range between the black rhinos from our limited sample.

3.2.1 Traveled distance

To compare step length across sex, season, and time of day, data from all 25 black rhinos (12 females and 13 males) were analyzed.

EMMeans showed differences in distances traveled between males and females with males moving significantly longer distances, on average 1.5 times greater than females, when averaged over season and time of day (contrast F - M = -0.414 ± 0.093 SE, $p < 0.0001$). Females exhibited no significant difference in movement between dry and wet seasons (contrast dry - wet = -0.0107 ± 0.025 SE, p = 0.9960), whereas males slightly reduced their movement during the dry season (contrast dry - wet = -0.1003 ± 0.030 SE, p = 0.0010).

LMMs indicated a significant effect of time of day on step length ($p < 0.001$). Across the full recording period, the analysis shows clear bimodal activity patterns for both sexes, with peaks in activity around 2:00-4:00 (midnight to pre-dawn) and 19:00-20:00 (dusk), and a marked decline near 14:00 (midday) local time (Fig. 5). Seasonal differences were also detected by the EMMeans (Fig. 6): in particular, the activity peak was more pronounced during the dry season, with males being 17.3 times more active at dusk than at midday (contrast dusk - midday = 2.853 ± 0.0806 SE, $p < 0.0001$), whereas in the wet season, the difference was less marked, with males being 2.88 times more active at dusk than at midday (contrast dusk - midday = 1.059 ± 0.0993 SE, $p < 0.0001$).

In summary, these sample analysis showed that black rhinos appeared to cover similar overall distances across seasons but showed differences in their daily activity patterns. Males tended to travel longer distances than females. During the dry season, activity appeared more concentrated around dusk, whereas in the wet season, it appeared more evenly distributed throughout the day. These results show patterns that are consistent with studies such as Shrader et al. (2025), which indicate that black rhinos are primarily crepuscular, showing peak activity during the early morning and evening hours, and reduced movement during midday, the hottest part of the day. Similarly, Seidel et al. (2019) examined 24-hour movement patterns in black rhinos in northern Namibia and reported that males generally move more than females. They also observed a seasonal effect, with reduced movement during the wet season, in line with the trends detected in our sample.

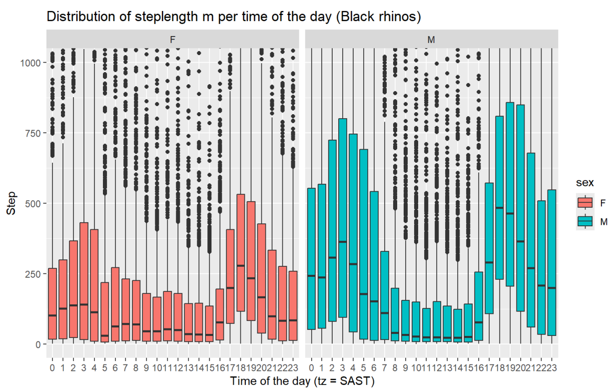

Figure 5. Exploratory description of step length (m) distributions by hour of day from a sample of female and male black rhinos

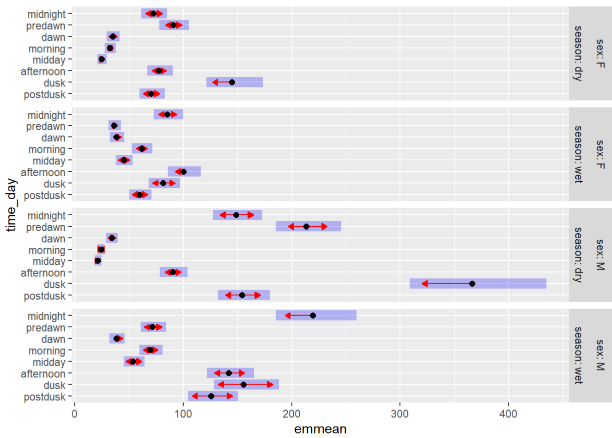

Figure 6. EMMeans of step length (m) by time of day from a sample of female and male black rhinos across dry and wet seasons

3.2.2 Home ranges

After filtering individuals with at least 30 recording days per season, 11 black rhinos (6 females and 5 males) remained for analysis.

In our analysis example, male black rhinos exhibited larger home ranges than females (Tab. 1), although the difference was not statistically significant (LMM: sex M = 0.6983, 0.3480 SE, p = 0.068), likely due to the limited sample size and large variations between individuals.

Season appeared to influence female home ranges, which tend to be smaller during the wet season (HR size reduced by 15%; LMM season wet = -0.1612, 0.0689 SE, p = 0.036).

Sex	Season/Time	Area (km^2)	SE	Min	Max
F	Overall	19.5	11.79	5.22	41.3
M	Overall	37.1	25.38	15.06	81.4
F	Dry	23.71	17.06	5.62	55.9
F	Wet	17.48	8.27	5.09	29.4
M	Dry	41.47	22.79	18.56	75.1
M	Wet	41.34	31.97	15.80	97.4

Table 1. Exploratory description of MCP 95% home range size (km^2) by sex and season from a sample of black rhinos

In relation to step-length results, this suggests that although females did not appear to exhibit differences in movement intensity across seasons, they nonetheless covered smaller areas during the wet season in this data sample.

Comparison of home range size and variability across studies remain challenging (Plotz et al., 2016; Shrader et al., 2025), as estimates depend strongly on multiple factors: the type of data collection (e.g., direct observations during the day, GPS tracking, camera traps), the analytical method used (e.g., MCP, KDE), the local environment conditions (e.g., rainfall, vegetation availability), the reserve characteristics (e.g., rhino density, topography, presence of predators), and individual traits such as age, population establishment history (Pfannerstill et al., 2022), or management status (e.g., dehorned individuals; Duthé et al., 2023).

3.3 Exploratory analysis: white rhino behavior

The sample included a smaller number of white rhinos: Specifically, only six white rhinos (four females and two males) had more than 30 days of recordings per season, which was insufficient to reliably estimate variations in home range size across explanatory variables. Consequently, only the difference in distance traveled is analyzed and presented.

3.3.1 Traveled distance

To compare the step length between sex, season, and time of day, all 14 WR (8 F / 6 M) were used.

No significant differences between sex were detected in the sample data (EMMeans: Contrast F - M = -0.00497 $\pm$ 0.12, p = 0.9670). However, white rhinos appeared to exhibit clear seasonal differences: they appeared to move significantly less during the wet season, with movement distances being approximately 28% lower compared to dry season (EMMeans: Contrast dry - wet = -0.332 $\pm$0.0396, p <0.0001).

Figure 7 displays the distribution of steps per hour of the day and per season, and Fig. 8 shows the EMMeans results. The analysis example showed that during the dry season, white rhinos exhibited clear bimodal activity, with pronounced peaks around 7:00-8:00 (dawn) and 17:00-19:00 (afternoon, dusk). Activity was lowest between 2:00-5:00 (midnight, predawn) and 11:00-13:00 (morning, midday). The EMMeans analysis showed a significant reduction in activity from dawn to midday (contrast midday - dawn = -1.626 $\pm$ 0.0795, p<0.0001). In the wet season, activity appeared more evenly distributed throughout the day. Rhinos still appeared to display peak periods around 8:00 (dawn) and 16:00-17:00 (afternoon), although these peaks were less pronounced. Minimal activity occurred near 4:00 (predawn), and no clear midday decline was observed, as supported by EMMeans results (contrast midday - dawn = -0.248 $\pm$ 0.1300, p = 0.5400).

For both species, differences in daily activity peaks appeared less pronounced during the wet season, possibly reflecting the cooler temperatures that no longer restricted their movements. White rhinos are known to limit their activity to the coolest part of the day (Owen-Smith, 1973), a pattern consistent with our observations in the dry season. Tichagwa et al. (2020) studied white rhinos in Matobo national park, Zimbabwe, and found that weather conditions had a stronger influence on activity pattern than season, which was not a significant factor in their

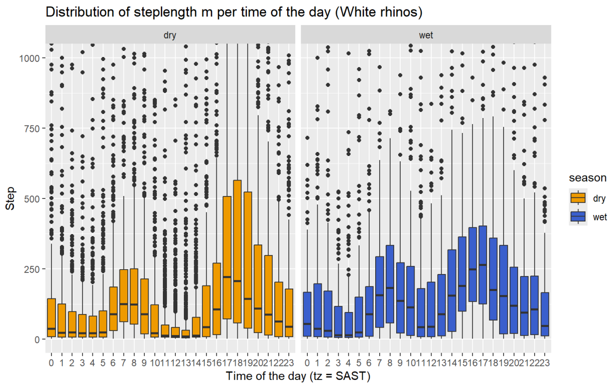

Figure 7. Exploratory description of step length (m) distributions by hour of day from a sample of white rhinos across dry and wet seasons

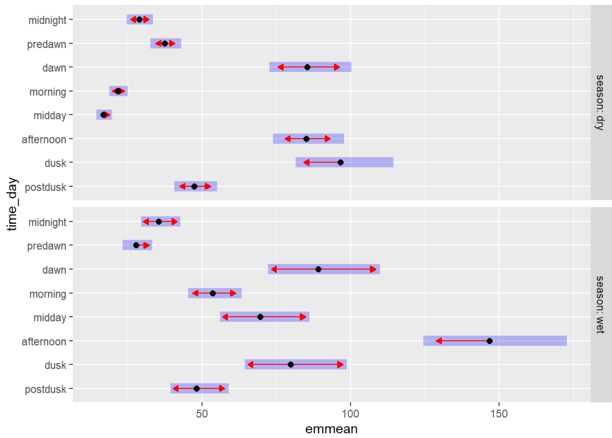

Figure 8. EMMeans of step length (m) by time of day from a sample of white rhinos across dry and wet seasons

analysis. Other relevant variables included habitat type, moon phase, and sex/age. These results suggest that future analyses should include additional environmental and biological factors to better explain variation in activity pattern.

4 Conclusion and future research

In this paper, we presented the infrastructure developed for tracking black and white rhinos, *Rhinos3D*, a 3D visualization prototype for movement data, and demonstrated its usability and purpose through an exploratory analysis.

To date, hundreds of rhinos have been equipped with GPS trackers as part of a conservation program across game reserves in South Africa and Mozambique, supporting field rangers in monitoring and protecting these critically endangered species. At the same time, the use of biologging technologies raises concerns regarding data security and animal welfare, including the risk of sensitive location data exposure and questions about whether scientific benefits outweigh potential harm (Cooke et al., 2017; Arrondo and Pérez-García, 2025). Balancing knowledge sharing with rhino security remains particularly challenging. To mitigate these risks, access to the data is restricted to field rangers and some researchers, and tracker deployment coincides with horn removal, a common anti-poaching practice, despite its potential effects on social behavior (Duthé et al., 2023). Overall, this study suggests that, for highly endangered species, tracking technologies can provide meaningful benefits for both conservation and scientific research.

Rhinos3D distinguishes itself from existing wildlife monitoring platforms (e.g., EarthRanger; Wall et al., 2024) by integrating 3D terrain visualization and the ability to display analysis results. The 3D visualization provides additional information to interpret results such as home ranges and traveled distances. It may enable additional analyses such as poaching risk or habitat selection. While the current implementation supports home-range visualization, future developments will enable real-time data integration, analyses across selectable time periods, and an interactive dashboard presenting the evolution of individual rhino characteristics (e.g., step length, activity levels). By incorporating additional variables (e.g., vegetation, weather), *Rhinos3D* aims to move toward a digital twin approach. Such comprehensive modeling is particularly important for conservation planning, especially in the context of climate change and future climate scenarios (Mamba and Randhir, 2024).

Conflicts of interest

The authors declare that they have no conflict of interest.

Declaration of Generative AI in writing

The authors utilized Generative AI tools, exclusively for language editing, improving grammar, and sentence structure, but not for generating scientific content, research data, or substantive conclusions. All intellectual and creative work, including the analysis and interpretation of data, is original and has been conducted by the authors without AI assistance.

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