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A non-invasive footprint technique for accurate identification of cryptic small mammal species: a sengi case study

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The acceleration of biodiversity loss highlights the need for practical, affordable species monitoring tools. A key requirement of monitoring is the accurate identification of species, a particular challenge with cryptic species. This study introduces a non-invasive footprint identification technology to classify two cryptic sengi species (*Elephantulus myurus* and *Elephantulus intufi*) - key bioindicators in the rapidly changing Southern African biomes. Front footprints were collected, using a custom Small Mammal Reference Track box, from live-captured individuals that were identified by experts in small mammal taxonomy and verified through genetic analyses. Morphometric features of the footprints (lengths, angles and areas) were extracted using JMP software. Linear Discriminant Analysis, based on nine key variables, achieved a mean classification accuracy of 94–96% across training, validation, and test datasets, robustly distinguishing the two species using a single footprint image. By integrating our field capture locations with data from the IUCN expert-defined ranges and the Global Biodiversity Information Facility, we demonstrate that FIT empowers non-experts to contribute reliable, high-resolution occurrence data. This scalable approach has the potential to transform community-science efforts, improving the accuracy of species distribution maps and ultimately strengthening conservation outcomes. Planned advancements include open-ended track tunnels and expanded machine learning models to monitor more small mammals in at-risk ecosystems. This approach offers a scalable, low-impact alternative to traditional trapping and genetic methods, reduces animal stress, morbidity and mortality, and empowers local communities to enhance data quality and monitoring through integration with traditional ecological knowledge.

KEYWORDS

sengi, cryptic species, footprint identification technology, species monitoring, footprints, track plates, ecological integrity

1 Introduction

Biodiversity is declining rapidly, yet accessible and cost-effective tools for species monitoring are few. This study presents a proof of concept for a flexible and non-invasive footprint identification technology (FIT), as a metric to assess and monitor biodiversity. FIT is based on traditional ecological knowledge making it particularly suitable for local community engagement.

Small mammal communities have been investigated as bioindicators in many different environmental contexts (see Avenant and Cavallini, 2007; Avenant, 2011), and are a key component globally of terrestrial ecosystems. In southern Africa they may contribute more than 30% of the total mammal species (Skinner and Chimimba, 2005; Monadjem et al., 2015). Their population dynamics and species composition react rapidly to environmental change including disturbances not indicated by plant species. As such, the group has been proposed as one of the most important components of biodiversity monitoring protocols and management plans in southern Africa (Turpie et al., 2014, 2016; Avenant and Du Plessis, 2008). Being able to accurately identify them is, therefore, crucial for understanding and managing habitat requirements, conservation planning and management.

Traditional methods of monitoring small mammal populations include live and snap-trapping (White et al., 2023). They rely on labor-intensive fieldwork, and are often expensive, requiring repetitive trapping exercises with expert identification and handling of species caught.

This study explores the use of FIT to distinguish two cryptic sengi species in South Africa from their footprints. The sengi are valuable components of small mammal communities used in ecosystem monitoring in Southern Africa, especially concerning the impacts of climate change (Engelbrecht et al., 2024).

Previously known as elephant shrews, sengis, native to Africa, are characterized by their long flexible snouts that are used to search for insectivorous and herbivorous food. The Order Macroscelidea currently encompasses 19 recognized species of sengis, twelve of which occur in the southern African subregion (IUCN, 2025). Sengis are widely distributed across southern Africa, and occur in a diverse range of habitats, from arid deserts to boulder-strewn outcrops and forests (Skinner and Chimimba, 2005; IUCN, 2025). The diversification of sengis has been closely tied to major climatic and geological events such as the aridification of Africa and the expansion and contraction of forests and savannahs (Hagemann et al., 2024). As such, they have ecological significance as indicators of the health of the specialized habitats they occupy.

This study focuses on the Eastern Rock sengi *Elephantulus myurus*, and the Bushveld sengi *Elephantulus intufi* (Figure 1). These two species occupy different microhabitats, but can occur geographically close together where suitable habitats are present (Heritage, 2018). *E. myurus* typically inhabits rocky outcrops and boulders in hilly terrain, using the cracks and crevices for cover and shelter from predators (Corbet and Hanks, 1968; Rathbun and Smit-Robinson, 2016). *E. intufi* prefers open grassland and scrub associated with loose, sandy soils and less cover (Faurie et al., 1996; Rathbun and Smit-Robinson, 2016a). Both species were found at Tswalu during this study (see genetically verified gps locations below), and at one site within 120m from each other.

However, members of the genus *Elephantulus* are morphologically very similar, with only subtle differences in dimensions and color variation both seasonally and regionally (Corbet, 1974, 1995). Field identification on external variables is, for a number of these species, virtually impossible (Faurie et al., 1996; Stuart and Stuart, 2015).

Non-invasive sampling techniques in wildlife research are gaining traction due to their ability to prevent morbidity and mortality, and minimize stress and disturbance to animals, without compromising data validity (Jewell and Alibhai, 2013). These methods often yield unique insights that are unattainable through alternative methods (Zemanova, 2021). Several non-invasive techniques are routinely used to monitor wildlife, including non-invasive genetic surveys such as eDNA, camera traps, remote sensing, acoustic recordings, detecting footprints and citizen scientist reporting (De Bondi et al., 2010; Jachowski et al., 2024; Janečka et al., 2011; Moore et al., 2023; Shiels et al., 2025; Verhees et al., 2024; Wong et al., 2025; Zwerts et al., 2021). However, many of these are better suited to monitoring larger and visually distinguishable species.

Despite being near-ubiquitous biometric signals in natural environments, clear and complete footprints for small mammals are rarely found. However, clearer footprints can be obtained using a range of artificial substrates and inks/powders (Zielinski and Kucera, 1995; Ratz, 1997; Van Apeldoorn et al., 1993; Glennon et al., 2002; Mills et al., 2016) and provide the opportunity to investigate small mammal footprint morphology more closely.

Track plates and track tunnels, for example, are a widely adopted method for collecting small mammal footprints. Typically, the identification has been done by visual examination or simple measurements (Brehme et al., 2019).

Some studies have also taken this a step further, using morphometric analysis of footprint variables (e.g. distances, lengths or areas) to identify species, where the variables are then subject to discriminant analysis (Palma and Gurgel-Gonçalves, 2007). Russell et al. (2009) reported an analytical template-matching technique for three very similar species of rat with around 70% accuracy.

Footprint identification technology (FIT), presented in this paper, leverages cutting-edge tools, such as image processing, advanced statistical analysis and machine learning to deliver very high accuracy classification by species, individual, sex and age-class from footprints (Tucker et al., 2024; Alibhai et al., 2023; Jewell et al., 2020). Animal tracks have aided species identification for millennia, and tracking skills have played a key role in human evolution (Liebenberg, 1990). FIT has primarily been applied to monitoring endangered species on natural substrates (Jewell and Alibhai, 2013) and track plates (Tucker et al., 2024), where tracks are typically used for species, individual and sex identification.

While FIT was initially developed to differentiate and monitor large iconic species using footprints on natural substrate, the technology is easily adapted to classify them from track plates. It

FIGURE 1
Elephantulus intufi and *Elephantulus myurus* are typically difficult to distinguish from external characters such as shape, size and coat colour (Image credit: M. Oosthuizen).

has demonstrated utility in identifying 17 species of European small mammal, although the authors did not test the method with cryptic or 'sister' species.

In this study we present the following novel material:

1. The potential of a widely applicable, non-invasive and accurate method of discriminating between two closely-related cryptic species with a high level of accuracy.
2. The demonstration of a SMaRT box to collect initial reference sets of small mammal footprints with minimal handling and stress to the animal, and allowing for field processing to provide quick release after footprinting.
3. The integration of small mammal data preparation and annotation, feature extraction, a custom statistical package and data visualization output within one pipeline in JMP software.
4. A demonstration that more robust field identification could make a significant contribution to small mammal range assessments, demonstrated by plotting points for the Global Biodiversity Information Facility and the IUCN Expert Range Maps, two of the most commonly used international resources for species distribution mapping.

2 Materials and methods

2.1 Terms and definitions

Footprint: A single visible impression made by the sole of a foot.

Track plate: A level surface, prepared with paper or charcoal, for footprint collection.

Track tunnel: Tunnel with a track plate allowing animals to pass through and leave footprints.

SMaRT (Small Mammal Reference Track) box: a custom enclosure for collecting reference prints from small mammals.

2.2 Study sites

Eastern Rock sengi (*E. myurus*) footprints were collected from rocky outcrops in the Telperion Nature Reserve, situated on the border of the Mpumalanga and Gauteng Provinces in South Africa (25,7016°S, 28,9985°E). This reserve is characterized by a variety of habitats such as grasslands, rocky outcrops, gorges and wetlands (Brown et al., 2022). Telperion is situated in the summer rainfall area of South Africa, with annual precipitation ranging between 570 mm and 730 mm (Mucina et al., 2006). Average temperatures in the summer range from daily minimums of 15.1°C to maximums of 26.4° C. February is the hottest month of the year and July is the coldest, with an average daily maximum of 18.4°C and minimum of 4.2°C (Brown et al., 2022). The area is characterized by undulating hills, open plateaus and steep slopes (Coetzee, 2011). It is located within the broader Bankenveld vegetation unit (Acocks, 1988), and the area comprises mesic Highveld grassland with rocky mountainous sections interspersed (Mucina et al., 2006).

Bushveld sengi (*E. intufi*) all originated from sandy dune troughs in the Tswalu Kalahari Reserve. This private reserve is located on the edge of the southern Kalahari and has diverse bushveld, plains and mountain shrubveld, duneveld and calcareous scrubveld habitats, supporting a rich variety of wildlife (Tokura et al., 2018). The Tswalu Kalahari Reserve is situated in the dry southern Kalahari region of South Africa. Rainfall typically occurs in summer (December to February), while the winters (June to August) are dry. Mean annual rainfall is 360 ± 170 mm (Tokura et al., 2018). Air temperature ranges from *c.* 6°C in winter to 41°C in summer (Panaino et al., 2023). The landscape is characterized by sandy plains and parallel sand dunes, while the quartzitic Korannaberg Mountains can be found in the eastern half of the reserve. Five different vegetation units can be found: the Koranna-Langeberg Mountain Bushveld, Gordonia Duneveld, Gordonia Plains Shrubveld, Olifantshoek Plains Thornveld, and the Kathu Bushveld (Rutherford et al., 2006),

The localities at which *E. intufi* and *E. myurus* were sampled are indicated in Table 1.

TABLE 1 The capture site GPS locations for *E. myurus* (Telperion and Tswalu Kalahari sites) and *E. intufi* (Tswalu Kalahari site).

Research site name	Transect GPS	Species caught
Telperion	S25.7017° E28.9985°	*E. myurus*
	S25.7005° E28.9995°	*E. myurus*
	S25. 6759 E29.0104°	*E. myurus*
	S25.7019 E29.0005°	*E. myurus*
	S25.7199° E29.0001°	*E. myurus*
Tswalu Kalahari	S27.3091° E22.5279°	*E. myurus*
	S27.2578° E22.4668°	*E. myurus*
	S27.2375° E22.5207°	*E. myurus*
	S27.3295° E22.5379°	*E. myurus*
	S27.3510° E22.4499°	*E. myurus*
	S27.3297° E22.4664°	*E. myurus*
	S27.2949° E22.3503°	*E. intufi*
	S27.2934° E22.3506°	*E. intufi*
	S27.36758° E2244481°	*E. intufi*
	S27.2198° E224767°	*E. intufi*
	S27.2570° E22.4656	*E. intufi*

2.3 Distribution mapping from open-source datasets

To understand potential uncertainties and discrepancies in current range maps for these two sengi species, and the potential of footprint identification for refining small mammal ranges, we mapped existing data from the ranges defined by IUCN experts (IUCN, 2025), and overlaid this with capture locations for the two species from the Global Biodiversity Information Facility (GBIF) and iNaturalist (Rathbun, 2015). We also plotted the genetically verified capture site locations from this study to examine their relative positions to the established locations.

2.4 Reference library acquisition

Developing footprint identification models for small mammal species classification requires the collection of a reference database of footprints from each species of interest, with which to train the model. This is a one-time process. The two sengi species were captured using small mammal PVC live traps (7.5 x 7.5 x 29.6 cm) arranged in numerous trap lines of 50 traps each, spaced 5m apart to increase the chance of catching all species on these transects (Ferreira and Avenant, 2003). Traps were baited with the standard mixture of peanut butter, oats, and Marmite (a commercially available yeast extract spread, known for its strong, salty, and savory flavor that attracts shrews and sengis) and contained a ball of cotton wool to provide insulation against potentially extreme temperatures (Avenant, 2011). Traps were checked twice daily.

Footprints were collected from trapped animals at a shady, quiet and relatively cool temporary field laboratory within *c.* 300m from the point of capture, and released at the exact point of capture immediately after footprinting.

To collect the reference footprints for species model development, the animals were individually released into a custom small mammal reference track (SMaRT) box. This closed wooden box (inside dimensions 550 x 270mm, with depth 175mm), features four wooden sides with a perspex slider roof (Figure 2A). Two movable cardboard strips were placed on the roof to create a darkened, minimal stress environment for the animal while still allowing observation (Figure 2B). Nocturnal species were kept in a darkened and quiet environment when not handled.

Adhesive kitchen contact paper, approximately 430mm in length and the width of the SMaRT box was attached to the floor of the box (we used Gorilla Grip Peel and Stick Liner), placed sticky side up. Charcoal dust was brushed in a very fine layer at either end of the short side of the contact paper. The animal entered the box at one end, and walked over the charcoal, collecting a fine layer of non-toxic charcoal powder on their foot soles. Footprints were then transferred to the paper. Once sufficient footprints had been collected the animal was guided back into the trap and released again at the exact location where it was initially captured. Lactating females were processed and released first. Figure 3A shows the process of setting up the trackplate, and Figure 3B shows the animal on the trackplate having made tracks.

Once the animal was removed from the SMaRT box, the track plate contact paper was imaged with a label recording date, site, transect number and species (Figure 4. Metric scales were included in the image on two lengths of the track sheet. The hard copy was inserted in a clear plastic folder as a backup.

Footprint images were then processed using a statistical morphometric pipeline in JMP Statistical Discovery software (JMP, 2025).

2.5 Image preprocessing in JMP software

2.5.1 Foot selection

Front feet were used for the discrimination of these two species, for two reasons:

a. As for other FIT implementations (Jewell et al., 2001), requiring only one of the four possible footprints simplifies data collection. Additionally, FIT implemented for other species has typically found that either front or hind footprints are clearer, varying by species and gait, making a selection easier.
b. For these sengi species, there was considerable variation in the hind footprints. We observed that sengis sometimes use

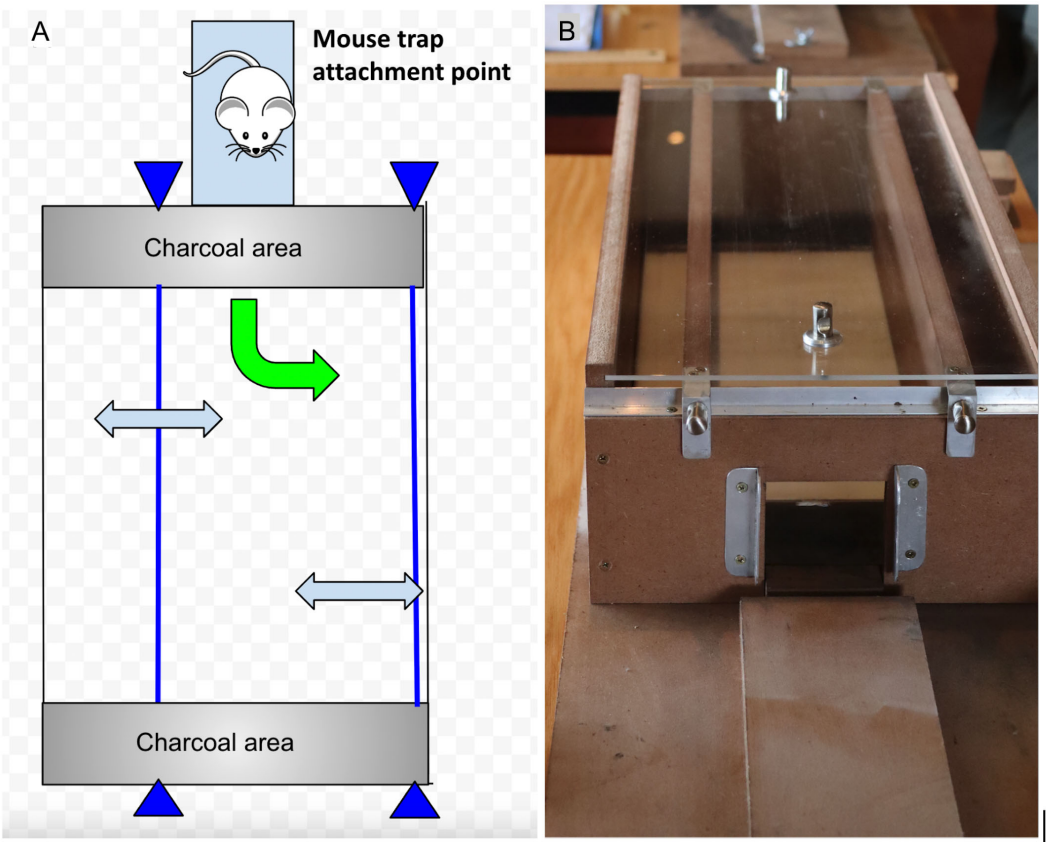


FIGURE 2
(A) Shows the base of the SMaRT box being prepared with a fine layer of charcoal powder brushed on at each end, and a length of adhesive paper in between, sticky side up and attached to the base with adhesive tape. **(B)** Shows *Elephantulus myurus* released onto the base and having crossed the charcoal, leaving footprints on the adhesive paper before returning to the trap and being released at the field site.

FIGURE 3
(A) The collection of small mammal footprints. **(A)** Shows the Design of the Small Mammal Reference Track box (SMaRT box) with an attachment for a PVC live-trap, and two strips of charcoal at either end of a length of sticky paper, which is placed adhesive side up and held in place with adhesive tape. **(B)** Shows the finished construction with a base, four walls that slot over it, and two internal movable dividers to help direct the movement of the animal, ensuring even coverage of footprints on the sticky paper. A perspex top panel rests within a groove and can be slid in or out as needed.

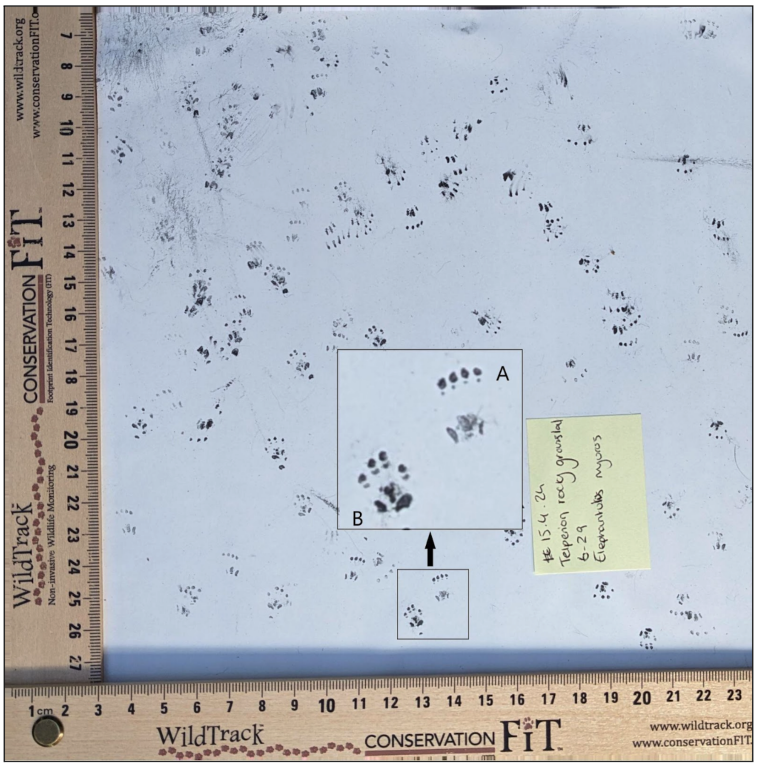


FIGURE 4
An image of a track sheet with footprints collected from *Elephantulus myurus*, with a scale in place. The inset section shows an enlargement of the footprint images, with more detail of hind **(A)** and front **(B)** images.

their back feet to 'drum' (an alarm communication) while on the track sheet and theorize that this contributed to track variation. We also observed that their very long hind feet imprinted differently with posture and gait, occasionally showing the tarsal pads in addition to the metatarsals.

Figure 5 shows examples of the front/hind and left/right footprints for both species.

2.5.2 Feature extraction

Extraction of geometric profile and all statistical analyses detailed below were undertaken in JMP statistical software (JMP Statistical Discovery LLC, 2025). Images were imported into a customized add-in in JMP software for feature extraction. This allowed image manipulation and the placement of seven landmark points (Figure 6) selected as being consistently recognizable by eye across a large number of footprints. A further 21 derived points were generated in JMP, based on interactions of the landmark variables. Using the scale on each image, we then coded for a wide range of potentially significant metrics with an automated extraction of 77 distances, 14 angles and eight areas. This process has been described for other species including those with diverse foot anatomies, gaits and evolutionary origins such as fisher (Tucker et al., 2024), black rhinoceros (Alibhai et al., 2020), cheetah (Jewell et al., 2016), Lowland tapir (Jewell et al., 2018) and Giant panda (Li et al., 2018).

3 Results

3.1 Discrimination between cryptic species using footprints

Front footprints were collected from 18 individuals of *Elephantulus intufi* and 19 of *Elephantulus myurus* with a balanced sex ratio. The number of individuals, sex and the number of extracted front footprint images for each species is shown in Table 2.

3.1.1 Variables with best discriminating power

Nine variables were selected stepwise according to their F-ratios in LDA (excluding correlated variables), and arranged in order of their level of significance. Table 3 identifies these variables, and relates them to the landmark points as shown in Figure 6. For example, the top discriminating variable for the two species was V7, the distance connecting the centroid of the medial toe (point 1) to the centroid of the medial carpal pad (point 7).

Figure 7 shows the classification accuracy based on V7 alone was 99.9% ($p<0.0001$). However, basing the classification on a single variable is unsafe because this approach is highly vulnerable to misclassification due to natural variation, overlap between species, and external factors that can influence morphology in ways unrelated to species identity (Lonsinger et al, 2015).

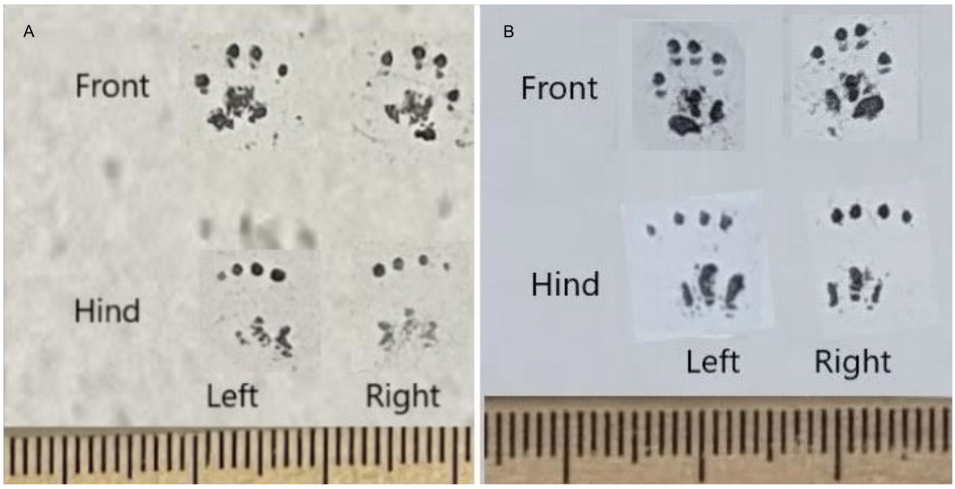


FIGURE 5
Examples of front/hind and left/right images for **(A)** *Elephantulus intufi* and **(B)** *Elephantulus myurus*..

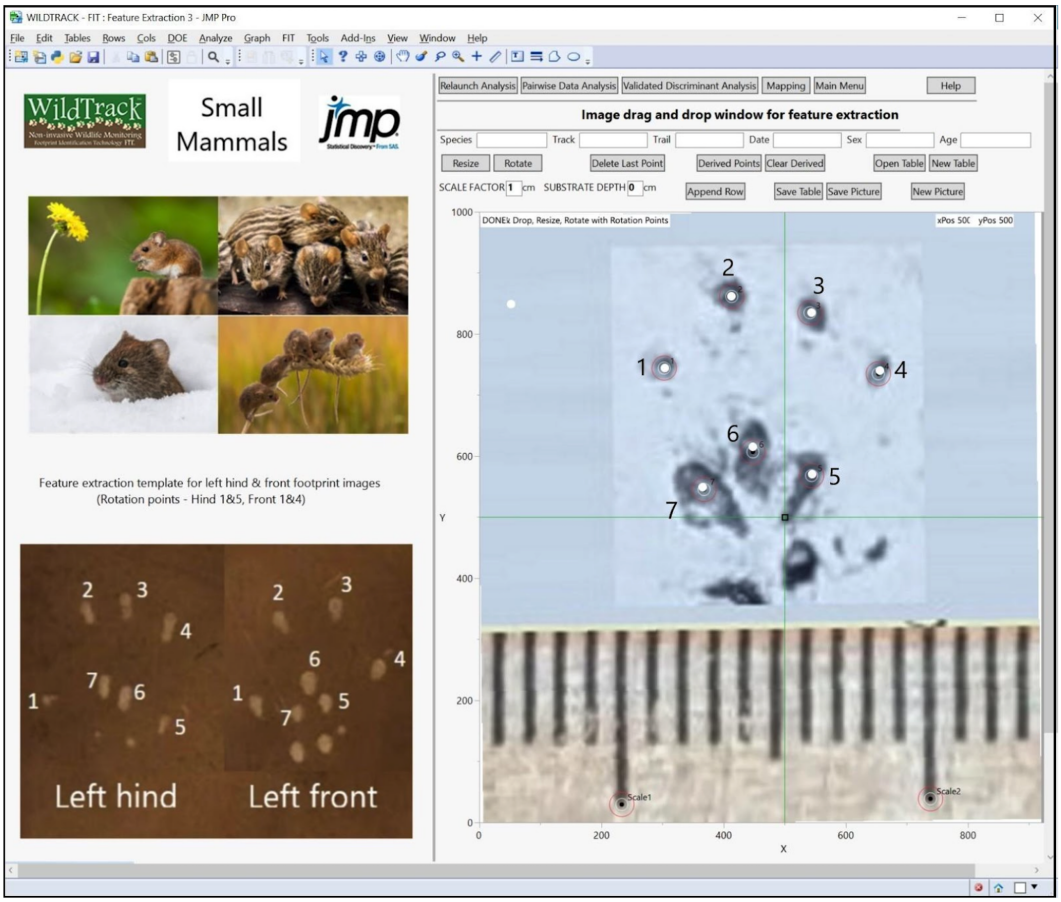


FIGURE 6
Feature extraction window in JMP software. The right-hand side of the figure is the interactive window showing the placement of seven landmark points on a left front foot image. The location of points was identified on the basis of consistency and clarity. Only images with clearly defined anatomical points were included.

TABLE 2 The number of individuals, sex and the number of extracted front footprint images (in brackets) for *Elephantulus intufi* and *Elephantulus myurus*.

Dataset	*Elephantulus intufi*	*Elephantulus myurus*
No. of individuals (No. of images	18 (116)	19 (111)
No. of males (No. of images)	9 (65)	10 (39)
No. of femals (No. of images)	9 (51)	9 (72)

3.1.2 Level of accuracy of species classification based on a single footprint image

To ensure that we were selecting the optimum number of variables to provide good classification without over-fitting, we plotted the number of variables selected against the resulting accuracy of species classification. Figure 8 shows the number of variables used in LDA and the level of accuracy of species classification based on the metrics of a single footprint image. The asymptote was reached at nine variables.

3.1.3 Results of linear discriminant analysis

However, we conducted an LDA to provide a robust assessment of the level of accuracy of species classification using the nine selected variables in Table 3. The LDA returned an accuracy for the training dataset of 94.8%, and for validation and test sets of 95.6%. Based on a single image, the overall accuracy of species classification was 96%.

3.1.4 Holdout validation and testing.

We further tested the accuracy of classification by iterating the analysis shown in Figure 8, through 10 sequential random partitions of the data into training, test and validation categories with the same ratio (60:20:20). The mean accuracy was approximately 94-95% for each of the three categories (Table 4).

TABLE 3 Nine variables, selected stepwise according to their F-ratios in LDA (excluding correlated variables), and arranged in order of their level of significance.

Variable	Variable description (points refer to the landmark points)
V7	Distance - points 1 to 7
V60	Distance - point 3 intersects with the line joining points 2 & 6
V111	Angle - defined by points 3, 7 & 2
V59	Distance - point 3 intersects with the line joining points 1 & 6
V21	Distance - point 6 meets the intersections of points 1 & 4 and 2 & 7
V94	Angle - defined by points 2, 3 &4
V89	Angle - defined by points 1, 5 & 6
V47	Distance - line joining intersections of points 3 & 6/5 & 7 and 5 & 7/4 & 6
V104	Angle - defined by points 5, 1 & 6

3.2 Comparing the species ranges using data sourced from IUCN expert-defined range outlines, global biodiversity information facility occurrence points, and field data from this study

By plotting ranging data for the two species from IUCN expert-defined ranges and GBIF/iNaturalist occurrence points, we observed clear differences in range estimation between the two datasets (Figure 9). Some species occurrence points for each of the two species fell outside the expert-defined ranges. If the species range overlap were to be defined using GBIF/iNaturalist occurrence points, these points would contribute to a greater overlap.

Table 1 shows the capture site GPS locations for *E. myurus* (Telperion and Tswalu Kalahari sites) and *E. intufi* (Tswalu Kalahari site).

In this study alone, we opportunistically found both species within 120 meters of each other at the Tswalu Kalahari site, the western purple point in Figure 9, where their preferred rocky and sandy habitats meet. Notably, this detection site falls outside the expert-derived range overlap area for *E. myurus*.

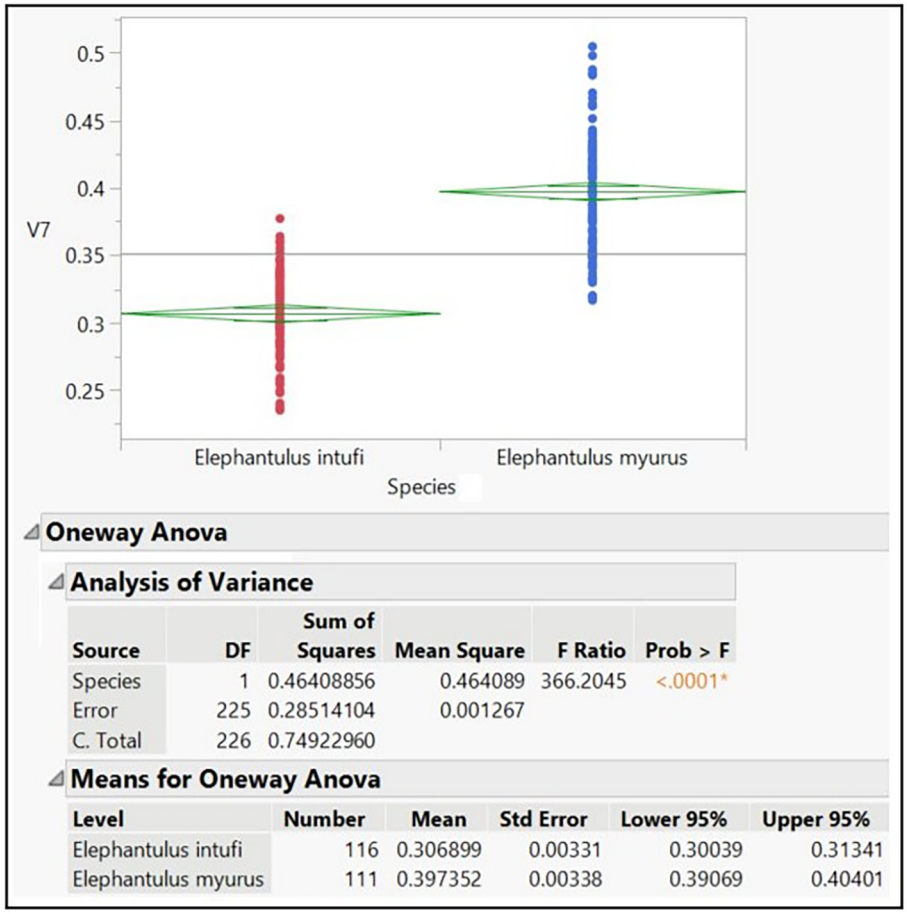
4 Discussion

4.1 Footprint identification to distinguish cryptic species

This study demonstrates that the FIT robustly distinguishes two cryptic *Elephantulus* species, achieving a classification accuracy of 96% with cross-validated accuracy of 94-95% across iterative random data partitions. This methodological advance potentially enables non-invasive monitoring and highlights FIT's reliability for field applications.

Palma and Gurgel-Gonçalves (2007) conducted a study to classify a wide range of small mammal species in Brazil using footprints. Although sengis are not present in Brazil, the authors obtained good classification accuracies of 74% for anterior and 88.3% for posterior footprints among Rodentia species that closely resemble sengis in size using discriminant analysis. No information was given about the visual similarity of the species, but the authors did state that the best accuracies were obtained in comparing smaller sub-sections of the taxa they studied, and when comparing species from different size classes. In contrast to our study, they found that the hind footprints are better classifiers of species, likely due to the peculiarities of gait and behavior of sengis.

The balanced dataset and integration of cost-effective, locally available hardware, combined with an end-to-end pipeline in JMP software, minimized sampling bias and streamlined collection,



Oneway Anova

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Species	1	0.46408856	0.464089	366.2045	<.0001*
Error	225	0.28514104	0.001267		
C. Total	226	0.74922960			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
Elephantulus intufi	116	0.306899	0.00331	0.30039	0.31341
Elephantulus myurus	111	0.397352	0.00338	0.39069	0.40401

FIGURE 7
A one-way ANOVA species classification based on the variable with the highest F-ratio, V7 shows a 99.9% accuracy based on a single footprint image.

annotation and analysis. The discriminatory variables identified by stepwise F-ratio selection and validation via 10 random partitions further confirm FIT's robustness for cryptic species identification.

The major innovation is the objective identification of morphologically similar species using equipment that can be sourced locally, is inexpensive, reduces handling stress, risk of injury and disease transmission. The FIT is also suitable for elusive or trap-shy species and scalable for broader conservation and ecological research.

4.2 Footprint identification as a method to enhance confidence in range mapping

The FIT offers a rapid and accurate method to support monitoring and range mapping for small mammals, a key group in ecosystem assessments, comprising 30-40% of global mammal diversity. With knowledge of small mammal responses to environmental change (Rowe and Terry, 2014), FIT has the potential to make a significant positive impact on our understanding of the health of these ecosystems.

Comparisons between IUCN expert boundaries, GBIF/iNaturalist observation points, and field capture sites from this study reveal marked discrepancies in range predictions for *E. myurus* and *E. intufi*.

Importantly, we do not present these GBIF/iNaturalist points and IUCN boundaries as faithful representations of actual species ranges; however, these datasets are routinely utilized in range mapping exercises across a wide range of species, and we present their discordant results to highlight the limitations of current approaches to the identification of the two sengi species in this study, and possibly other cryptic species. Differences stem partly from the high proportion of community-sourced records in GBIF/iNaturalist versus IUCN's reliance on expert judgment, and both are vulnerable to issues like misidentification, sampling bias, incomplete temporal coverage, and the lack of absence data (Boitani et al., 2008). While integrating both data sources can mitigate some biases and improve complementary mapping (Dasgupta et al., 2024; Zurell et al., 2016), the observed

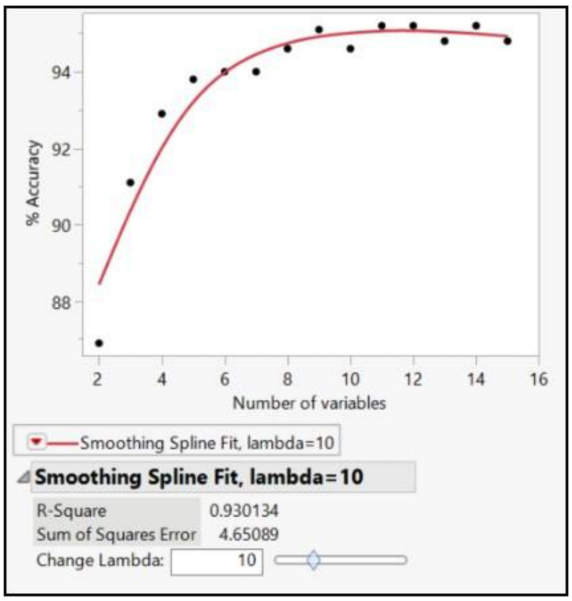


FIGURE 8
Plot of the number of variables selected stepwise (with correlated variables excluded) against the level of accuracy for species classification based on footprint metrics.

inconsistencies highlight the urgent need for more reliable and rapid methods of species identification, especially for closely related taxa. Such improvements could greatly enhance the accuracy of range maps and support targeted biodiversity surveys in poorly studied or data-deficient regions.

While we anticipate that small mammal specialists will always be needed to identify animals for reference and training datasets, the method described in this paper could reduce and ultimately remove the need for continuous capture. It could also make species identification accessible to non-experts in sengi classification and community scientists, allowing for more accurate and frequent data collection, and delivering more certainty to species range maps.

4.3 Limitations and potential shortcomings

This study uses footprints from only two cryptic sengi species and a defined number of individuals. More work is required to describe a wide range of South African small mammal species across different ecosystems using the same method.

The method relies on some skill and experience in handling small mammals to collect the reference data set.

The morphometric interpretation of the images requires some familiarity with footprint anatomy. Non-experts would need initial training in data analysis.

Our comparison of IUCN expert maps and GBIF observation datasets serves just as a starting point to reveal substantial, often overlooked differences in species range estimations. By exposing how widely-used datasets can yield conflicting results, this work powerfully illustrates the urgent need for robust, scalable identification methods. Expanding this approach to larger geographic areas would allow a rigorous evaluation of FIT's potential to transform species mapping accuracy and address longstanding gaps in biodiversity knowledge.

TABLE 4 The dataset of a total of 227 front foot images was randomly partitioned using a ratio of 60% (Training), 20% (Validation) and 20% (Test) on 10 separate, random, iterations.

	Misclassifications					
	Training (135)		Validation (45)		Test (46)	
Iteration	Number	Percent	Number	Percent	Number	Percent
1	05	3.70	05	11.11	0	0
2	07	5.19	02	4.44	01	2.17
3	06	4.44	01	2.22	04	8.70
4	04	2.96	04	8.89	03	6.52
5	06	4.44	03	6.67	01	2.17
6	06	4.44	03	6.67	03	6.52
7	07	5.19	02	4.44	03	6.52
8	07	5.19	01	2.22	01	2.17
9	07	5.19	01	2.22	02	4.35
10	04	2.96	03	6.67	03	6.52
Mean of misclassifications	5.9	4.37	2.5	5.56	2.1	4.56
Mean % accuracy		95.63		94.44		95.44

LDA for species classification was performed, and the number of misclassifications was recorded for each category and iteration. The same nine variables (Table 2) were used on each occasion. The overall accuracy for the three categories remained consistently between 94-95%.

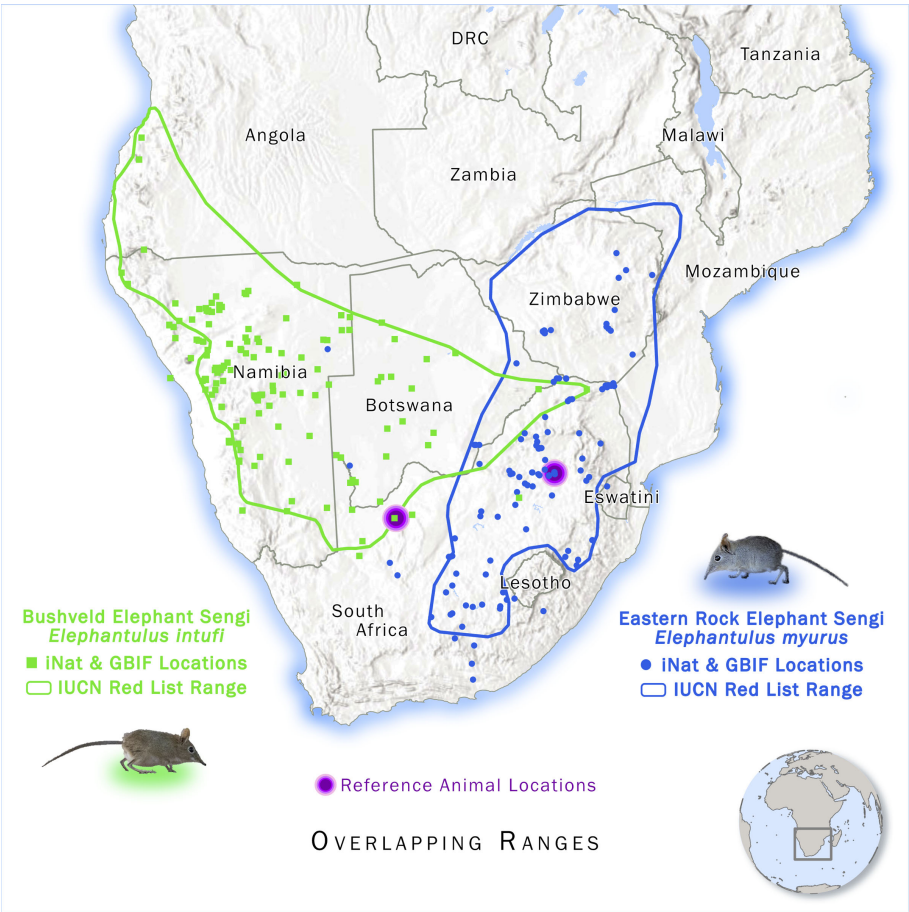


FIGURE 9
Expert-defined IUCN-sourced range maps for *Elephantulus intufi* and *Elephantulus myurus* in Southern Africa overlayed by GBIF/iNaturalist occurrence points. Note observation points from the latter database for both species lie outside the expert-defined areas (Rathbun, 2015; IUCN, 2025) (iNaturalist, 2025; Global Biodiversity Information Facility (GBIF), 2025). Our Tswalu field site (left, in purple) yielded both species, where *E.myurus* was outside the IUCN range.

To understand the full potential of this technique a study should be undertaken to compare in detail the applicability or accuracy of FIT identification with other alternative or complementary non-invasive techniques such as eDNA and camera-traps.

4.4 Next steps

More active engagement with local scientific communities and the integration of traditional ecological knowledge (TEK) in FIT-based monitoring will substantially improve data quality, conservation effectiveness, and long-term stewardship (Davis and Merenlender, 2023). Open-ended tunnels will allow for non-invasive, hands-off identification of even trap-shy species. Importantly, machine-learning models under development will enable rapid, species-level detection from footprints, providing scalable tools for tracking biodiversity and ecological integrity as habitats and climate shift. The FIT could emerge as a key catalyst—linking scientific expertise with Indigenous tracking knowledge, expanding access to advanced monitoring tools, and ensuring participatory, locally informed management and conservation outcomes (Davis and Merenlender, 2023; Liebenberg, 2013).

Data availability statement

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding author.

Ethics statement

The animal study was approved by the Ethics Committee of the National Museum, Bloemfontein (NMB ECC 2023/12). The Mpumalanga Tourism and Parks Agency and the Northern Cape Department of Environment and Nature Conservation (DENC) have issued research permits MPB 5884/2 and FAUNA 0485/2023 for our work in Mpumalanga and the Northern Cape provinces, respectively. The study was conducted in accordance with the local legislation and institutional requirements.

Author contributions

SA: Software, Writing – review & editing, Investigation, Formal analysis, Writing – original draft, Validation, Methodology, Data curation, Visualization, Project administration, Conceptualization. NA: Supervision, Investigation, Conceptualization, Writing – review & editing, Project administration, Validation, Writing – original draft, Methodology. MO: Writing – original draft, Methodology, Conceptualization, Investigation, Project administration, Writing – review & editing, Data curation. LC: Data curation, Writing – original draft, Conceptualization, Validation, Methodology, Software, Formal analysis, Writing – review & editing, Visualization. DM: Writing – original draft, Resources, Writing – review & editing, Supervision, Project administration. ZJ: Supervision, Data curation, Investigation, Visualization, Writing – original draft, Conceptualization, Software, Methodology, Writing – review & editing, Validation, Resources, Funding acquisition, Project administration, Formal analysis.

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Conflict of interest

Authors SA and ZJ were employed by the company WildTrack Inc.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The reviewer TS declared a shared affiliation with the author MO to the handling editor at the time of review.

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