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Censusing and monitoring black rhino (*Diceros bicornis*) using an objective spoor (footprint) identification technique

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Abstract

An objective, non-invasive technique was developed for identifying individual black rhino from their footprints (spoor). Digital images were taken of left hind spoor from tracks (spoor pathways) of 15 known black rhino in Hwange National Park, Zimbabwe. Thirteen landmark points were manually placed on the spoor image and from them, using customized software, a total of 77 measurements (lengths and angles) were generated. These were subjected to discriminant and canonical analyses. Discriminant analysis of spoor measurements from all 15 known animals, employing the 30 measurements with the highest *F*-ratio values, gave very close agreement between assigned and predicted classification of spoor. For individual spoor, the accuracy of being assigned to the correct group varied from 87% to 95%. For individual tracks, the accuracy level was 88%. Canonical analyses were based on the centroid plot method, which does not require pre-assigned grouping of spoor or tracks. The first two canonical variables were used to generate a centroid plot with 95% confidence ellipses in the test space. The presence or absence of overlap between the ellipses of track pairs allowed the classification of the tracks. Using a new ‘reference centroid value’ technique, the level of accuracy was high (94%) when individual tracks were compared against whole sets (total number of spoor for each rhino) but low (35%) when tracks were compared against each other. Since tracks with fewer spoor were more likely to be misclassified, track sizes were then artificially increased by summing smaller tracks for the same rhino. The modified tracks in a pairwise comparison gave an accuracy of 93%. The advantages, limitations and practical applications of the spoor identification technique are discussed in relation to censusing and monitoring black rhino populations.

Key words: spoor, footprint, black rhino, *Diceros bicornis*, monitoring, censusing

INTRODUCTION

Black rhino *Diceros bicornis* numbers have declined from an estimated 65 000 throughout Africa in 1970, to around 2500 today. Zimbabwe is one of the five major range states. In 1993, the Zimbabwean Department of National Parks and Wild Life Management (DNP), produced an emergency management plan (Department of National Parks, 1993) establishing four Intensive Protection Zones (IPZs) for the black rhino on state land. A major part of this initiative was recognized to be the effective censusing and subsequent monitoring of the population.

To facilitate protection and monitoring of the rhino, management operations, including de-horning, radio-collaring, fitting of transponders and ear-notching, were undertaken from 1992 to 1998 by the Veterinary Unit of the DNP and the Veterinary Department of the Ministry of Lands, Agriculture and Water Development. Problems associated with these invasive techniques (see Alibhai, Jewell & Towindo, 1996, 1999, 2001) indicated the need for non-invasive, cost-effective and sustainable techniques for monitoring black rhino. The identification of individual rhino from their spoor was considered a possible option.

Spoor identification by tracking is an age-old technique, still practised by many indigenous peoples for hunting and interpreting animal behaviour. Stander *et al.* (1997) suggested that tracking has been one of the fundamental skills shaping human evolution, and reported that the Ju/’Hoan San people were 94% accurate in identifying individual carnivores in a population of between two and 11 animals. Scientists have often excluded spoor identification as a useful monitoring

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technique because it has not been developed as a rigorous, objective and replicable method.

Most published work on rhino spoor identification is on Asian rhino populations from the late 1960s to early 1980s (Strickland, 1967; Schenkel & Schenkel-Hulliger, 1969; Kurt, 1970; Borner, 1979; Flynn & Abdullah, 1983; Van Strien, 1985). In all these studies attempts were made to census unknown populations using spoor identification, but it was not possible to confirm the actual number of rhino present, and therefore it was not possible to test the accuracy of the techniques. The identification of spoor in most of these studies also involved a high degree of personal interpretation and subjectivity.

Recent studies have attempted to introduce more objectivity to the identification of individual animals from spoor. Smallwood & Fitzhugh (1993) and Grigione *et al.* (1999), developed a technique to identify individual mountain lion from the spoor *in situ*; the second paper is a refinement of the first. Riordan (1998) also attempted to identify individuals accurately in a group of captive carnivores from spoor, and with a small sample set achieved very high classification accuracy with one of the two methods he used.

We first applied a spoor identification technique to separate a small number of black rhino in the Etosha National Park, Namibia (Alibhai & Jewell, 1997*a*,*b*) and a variant of the same technique, used for carnivores, was also reported by Grigione *et al.* (1999).

METHODS

The study area and black rhino population

The Sinamatella IPZ, an unfenced area of *c.* 1500 km^2, lies within the boundaries of Hwange National Park and the Deka Safari Area. It is an IUCN key-rated conservation area for the black rhino and holds the single largest population of this species in Zimbabwe. The soil in this area is predominantly sandy, although there are also areas of granite/gneiss and sandstone rocks, and clays.

Spoor were collected from 15 known (ear-notched or radio-collared) animals (12 adults, 2 sub-adults and 1 calf) which together constituted the study sample. These animals were regularly monitored on the ground by tracking with scouts, or by use of radio-telemetry. When a known rhino was tracked and located, the following data were recorded: date, time, GPS position, radio channel number and the status of the radio-collar if present, ear-notch pattern where possible, presence or absence of calf, and presence or absence of other rhino. Where fresh spoor were available, photographs were taken to be included in the spoor set for that animal.

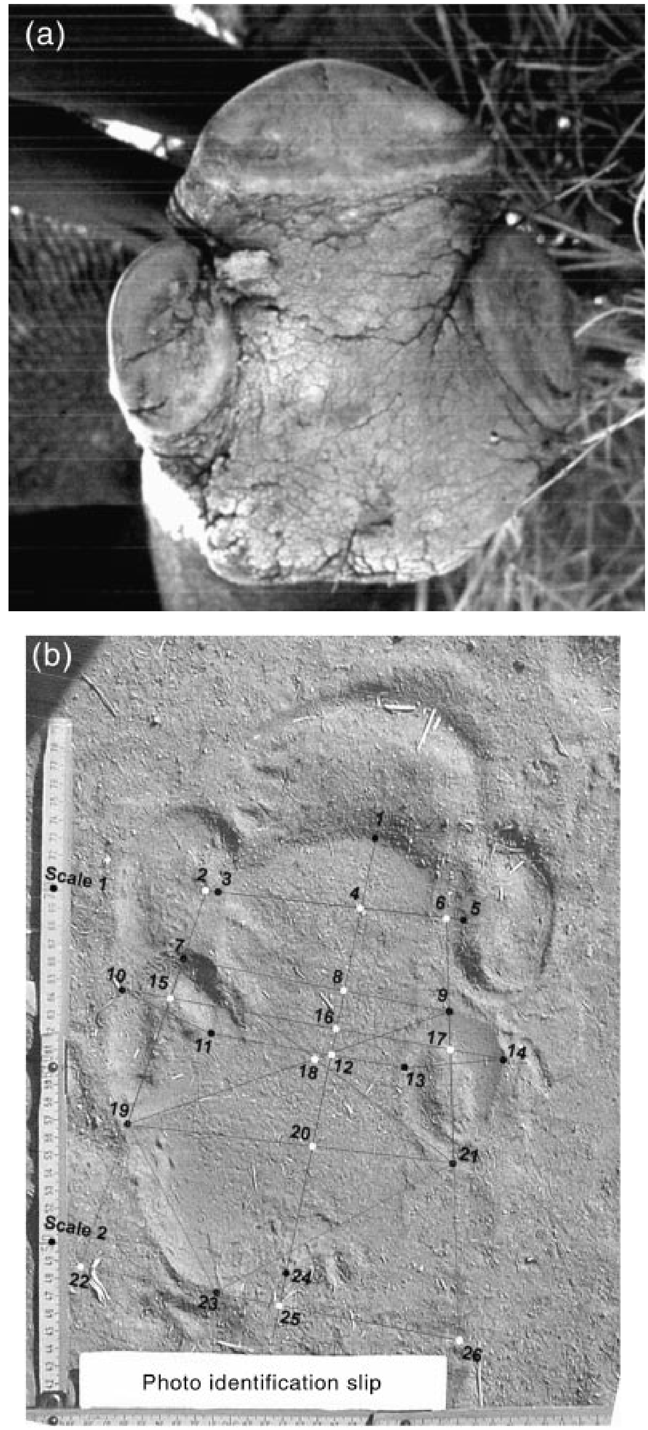

Fig. 1. (a) Black rhino *Diceros bicornis* left hind foot, showing the plantar cushion and three toes. (b) Spoor showing all landmark points (black dots) and derived points (white dots) with their respective numbers. The distance between scale points 1 and 2 is 20 cm. The remains of the front foot impression can be seen anterior to the hind foot impression. All points and measurements relate to the hind spoor image.

Black rhino foot anatomy

The black rhino (order Perissodactyla) has 3 toes on each foot. Anatomically these are digits 2 (medial), 3 (anterior) and 4 (lateral). The distal (third) phalanx of each digit is enclosed in a horny hoof. The plantar cushion helps support the distal metatarsals and digits where they make ground contact. Figure 1a shows the sole of a black rhino foot.

Most of the weight of the rhino is carried at the front of the body. Partly because of this, hind feet impressions are less subject to distortion from pace or posture and tend to be more consistent in quality. Hind feet impressions are also more easily obtained than the front, since the hind feet usually step on the impressions made by the front feet (Fig. 1b). The impression made by the foot can reveal clear outlines of the outside edge of each hoof, and also the outline of the hind part, or heel, of the digital cushion. The plantar cushion can also provide information about the identity of an individual through indentations or cracks which are present on its surface and which seem to be unique to each animal. These indentations can be seen as raised ridges on very fresh spoor and are often used by trackers in the field as a visual recognition aid. However, in this paper, the differences in spoor geometry, or 'geometric profile', of the foot provide the basis of individual identification.

Table 1. The number of spoor per set (rhino), the number of tracks per set and the minimum and maximum number of spoor per track for 15 black rhino

Rhino (set)	No. of spoor per set	No. of tracks per set	No. of spoor per track Min	Max
01	24	4	4	8
02	21	3	7	7
03	20	4	3	6
04	24	3	5	9
05	17	3	5	6
06	12	2	3	9
07	21	4	4	6
08	23	5	3	7
09	19	3	4	8
10	29	4	6	8
11	14	3	4	5
12	16	3	3	8
13	18	4	4	5
14	14	2	6	8
15	18	4	3	5

Factors affecting spoor quality

Many factors were found to influence spoor quality including: age of spoor, substrate, wind strength, light quality, pace of animal, slope of terrain and presence of other animals. Only fresh and undistorted spoor, showing good detail, were used in the study. Black rhino are most active at night, and photography was typically done early in the morning when light contrast was good.

Spoor, tracks, sets and libraries

For each known rhino, many spoor images were collected on different occasions. A spoor is defined as a single footprint. Each spoor was therefore a part of a 'track' (a pathway made by the animal on any 1 occasion) and the total number of spoor available for each animal at the end of the study period constituted the 'set' (all the spoor in all the tracks). The total number of spoor available for all the animals in the study made up the 'library'. The 'library' in the present study consisted of 290 spoor from 15 known rhino (see Table 1).

Identifying individual animals from their spoor

This process involved photographing spoor in the field, extracting a set of measurements (the geometric profile) from each spoor image, and analysing these measurements using statistical techniques.

Photographing spoor

Photography was standardized, as follows, to minimize variation resulting from extraneous factors. Only left hind spoor were used. When a suitable track was located, good spoor were identified for photography. A carpenter's wooden scale (cm), was placed to the left and bottom of the spoor, leaving about 2 cm clear on both edges between the spoor and ruler (Fig. 1b). UTM co-ordinates for the location were read with a Trimble Ensign GPS and written on a photo-identification paper slip, along with the date, name of photographer, identity of animal and code for each spoor. If natural contrast was insufficient to define the edges of the spoor, artificial contrast was supplied by means of an overhead umbrella to block incident overhead light and a photographic reflector to cast indirect angled light over the spoor.

In the earlier part of the study, Pentax 35mm K-100 cameras were used with 50 mm lenses. Subsequently Agfa e-photo 1280 digital cameras were employed. The Agfa camera was aligned directly over the spoor, with the long axis of the spoor on the long axis of the camera frame. Using the digital camera's preview feature, each exposure was checked to ensure that the frame was filled and that both ruler and spoor were clearly in focus. Unsatisfactory photographs were retaken until acceptable. This process was repeated for as many good spoor as possible in each track. Photographs were taken at medium resolution (1024×768 pixels) on camera smart cards and downloaded onto Agfa PhotoWise software for storage.

Taking measurements to provide a geometric profile of the spoor

Since it was not known which, if any, features of the spoor might provide a unique geometric profile of a particular animal, many measurements were taken from each spoor.

Using Adobe Photoshop software, downloaded image quality was first optimized and colour information

Table 2. Definitions of 113 spoor measurements investigated for use in classification of spoor

Measurement V1–47 (lengths)	Definition e.g. L2–7 is length from point 2 to 7	Measurements V48–77 (angles)	Definition e.g. A7, 1, 8 is angle formed between intersection L7–1 and L8–1	Combined measurements CV78–113 (lengths and angles)	Definition e.g. V1–4 is measure 1 to 4 inclusive
V1	L2–7	V40	L19–18	CV78	V1–4
V2	L7–15	V41	L18–9	CV79	V2–3
V3	L15–19	V42	L3–8	CV80	V5–6
V4	L19–22	V43	L8–5	CV81	V5–7
V5	L1–4	V44	L19–25	CV82	V5–8
V6	L4–8	V45	L25–21	CV83	V5–9
V7	L8–16	V46	L19–23	CV84	V5–10
V8	L16–20	V47	L23–21	CV85	V6–7
V9	L20–24	V48	A7,1,8	CV86	V6–8
V10	L24–25	V49	A8,1,9	CV87	V6–9
V11	L6–9	V50	A7,2,3	CV88	V6–10
V12	L9–17	V51	A8,3,4	CV89	V9–10
V13	L17–21	V52	A4,5,8	CV90	V11–14
V14	L21–26	V53	A5,6,9	CV91	V12–13
V15	L2–3	V54	A7,4,8	CV92	V15–16
V16	L3–4	V55	A8,4,9	CV93	V15–18
V17	L4–5	V56	A8,7,4	CV94	V16–17
V18	L5–6	V57	A4,9,8	CV95	V17–18
V19	L7–8	V58	A18,7,8	CV96	V19–20
V20	L8–9	V59	A18,9,8	CV97	V22–23
V21	L10–11	V60	A15,7,18	CV98	V25–28
V22	L11–12	V61	A18,9,17	CV99	V26–27
V23	L12–13	V62	A16,15,7	CV100	V29–30
V24	L13–14	V63	A16,17,9	CV101	V31–33
V25	L10–15	V64	A13,12,8	CV102	V32–33
V26	L15–16	V65	A19,18,21	CV103	V38–39
V27	L16–17	V66	A15,19,18	CV104	V40–41
V28	L17–14	V67	A18,19,20	CV105	V48–49
V29	L19–20	V68	A17,21,18	CV106	V54–55
V30	L20–21	V69	A18,21,20	CV107	V56 + 58 + 60
V31	L22–23	V70	A25,19,20	CV108	V58–60
V32	L23–25	V71	A23,19,25	CV109	V59–61
V33	L25–26	V72	A22,19,23	CV110	V66–67
V34	L7–1	V73	A23,21,20	CV111	V68–69
V35	L1–9	V74	A25,21,23	CV112	V70–71
V36	L7–4	V75	A26,21,25	CV113	V73–75
V37	L4–9	V76	A23,22,19		
V38	L7–18	V77	A25,26,21		
V39	L18–21				

discarded. Thirteen landmark points were then manually placed on each spoor image. These points were established as the most consistently identifiable points on the spoor, i.e. outside edges of toes and heel (Fig. 1b). The first 2 landmark points, 7 and 9, were placed on the spoor, a connecting line drawn and the image then rotated until the line was horizontal and the front toe at the top of the frame. This rotation standardized the alignment of each imported image, and positioning of subsequent landmark points. All landmark points were placed using a cross-hair tool in Adobe Photoshop, which made the process more objective. Once the image was aligned, the other 11 landmark points were placed according to their defined positions. Scale points were then marked from a ruler image.

The spoor image, with landmark points in position, was then exported into customized NiSAS software. NiSAS is spoor-measuring software developed by the authors in conjunction with the SAS Institute (Wittington House, Medmenham, Buckinghamshire SL7 2EB, U.K.) to enable the rapid generation of spoor measurements (distances and angles), and increase efficiency and flexibility in development. NiSAS enables an input algorithm to define, and then position, further 'derived' points from the landmark points, and then also to define and take measurements between all points, using the input scale points as reference. With the input algorithm used in the present study, NiSAS generated 13 derived points from the landmark points, and then 77 measurements (47 lengths and 30 angles) using all the points. Some of these measurements were subsequently combined to test whether combinations provided better classification accuracy, giving an overall total of 113 measurements (Table 2). Duplication between measurements was avoided during statistical analyses.

Table 3. Definitions of (a) landmark point positions and (b) derived point positions placed on left hind rhino spoor image. L, line between points; E, extension of a line

Point no.	Definition of position on left hind foot
(a) Landmark point positions	
1	Highest point of front toe
3	Most lateral point of front toe
5	Most medial point of front toe
7	Highest point of lateral toe
9	Highest point of medial toe
10	Most lateral point of lateral toe
11	Most medial point of lateral toe
13	Most medial point of medial toe (nearest midline of foot)
14	Most lateral point of medial toe (furthest from midline of foot)
19	Lowest point of lateral toe
21	Lowest point of medial toe
23	Lowest point of heel
24	Point where perpendicular to L7–9 dropped from point 1 intersects heel
(b) Derived point positions	
2	Intersection (EL5,3) with (EL19,7)
4	Intersection (L1,24) with (L3,5)
6	Intersection (EL3,5) with (EL21–9)
8	Intersection (L1–24) with (L7–9)
12	Intersection (L1–24) with (L11–13)
15	Intersection (L7–19) with (10–14)
16	Intersection (L1–24) with (L10–14)
17	Intersection (L9–21) with (L10–14)
18	Intersection (L7–21) with (L9–19)
20	Intersection (L1–24) with (L19–21)
25	Extension of (L1–24) to create 25, where (L23–25) parallel to (L7–9)
22	Intersection (EL7–19) with (EL25–23)
26	Intersection (EL9-21) with (EL23–25)

Landmark and derived points on an optimised and rotated spoor are shown in Fig. 1b. The measurements produced from these points were considered the geometric profile of the spoor and are defined in detail in Table 3a, b.

Statistical methods

JMP Statistical Discovery Software (SAS Institute Inc.) was used for all statistical analyses. Two multivariate methods were used to classify spoor or tracks: discriminant analysis and the canonical centroid plot method (for a review of these techniques see Williams, 1983).

Discriminant analysis is a standard method used to assign individuals (in this case spoor, tracks or sets) to pre-determined groups on the basis of their predicted identities, given several measurements for each group. The method is based on the closeness of a set of measurements to the multivariate means of the levels being predicted, as determined by the Mahalanobis distance (Manly, 1994). It is possible from this analysis to predict the classification of a spoor for which the true group (e.g. rhino) is not known, on the assumption that it does come from 1 of the pre-assigned groups. Also,

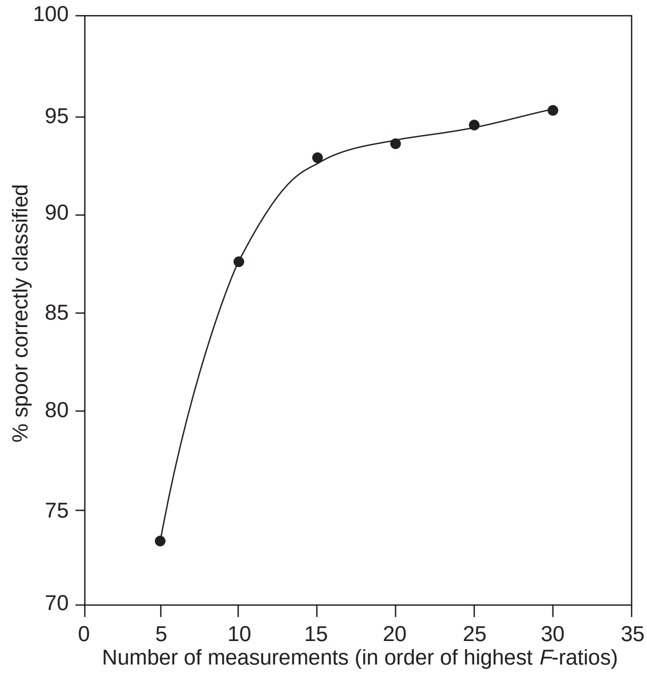

Fig. 2. Relationship between the number of spoor measurements used in order of highest *F*-ratios and resulting percentage of spoor correctly classified using discriminant analysis.

since all our data came from known rhino, it was possible to further test the efficacy of this method by subjecting it to Jacknife classification. This involved excluding each spoor (or each track) in turn from the pre-assigned (known) group means, to test the accuracy of the predicted grouping, i.e. each spoor (or track) was input in turn as an 'unknown' to see which rhino it was predicted to belong to. For spoor classification, each individual spoor was either correctly classified, or 'misclassified' if assigned to the wrong rhino. For track classification, each track was considered misclassified when $\geq 50\%$ of the spoor making up the track was incorrectly assigned, and 'unclassified' when $\geq 50\%$ of the spoor was not assigned to any 1 rhino (e.g. in a track with 10 spoor, three were assigned to 1 rhino, 3 to another and 4 to a third individual).

To determine which measurements to use for the discriminant analysis, we tested 3 techniques: (a) principle component analysis (PCA); (b) selecting measurements with highest *F*-ratios; (c) selecting measurements geometrically in order to avoid redundancy. All 3 techniques gave very similar levels of accuracy of *c*. 95% when matching pre-assigned to predicted categories for each spoor. We decided to use the *F*-ratio technique because it is objective, quicker to use and more consistent with the method used for the centroid plot analysis (see below). We also tested, using discriminant analysis, the relationship between the number of measurements with the highest *F*-ratios and the percentage of spoor correctly classified for 15 sets of rhino spoor. The polynomial fit (Fig. 2) shows the accuracy levelling out at *c*.15 measurements (92.8%), increasing to only 95.2% with 30 measurements. We decided to opt

Table 4. Spoor measurements used in discriminant analysis and canonical centroid plot technique. The 30 measurements listed were selected from a possible 113 (Table 3) on the basis of the best *F*-ratios. All 30 were used in discriminant analysis, but only the first nine (*) were used in canonical centroid plot technique

F-ratio rating	Measurement definition
1*	CV82
2*	CV98
3*	CV103
4*	CV104
5*	CV97
6*	CV96
7*	V34
8*	CV90
9*	CV78
10	CV100
11	V36
12	CV94
13	V42
14	V21
15	V35
16	V43
17	CV101
18	V47
19	V44
20	V24
21	V57
22	V46
23	CV89
24	CV106
25	V37
26	V61
27	CV105
28	V65
29	CV111
30	CV113

for the higher level of accuracy with 30 measurements since the analysis could be carried out in JMP just as expediently. Table 4 shows the 30 measurements with the highest *F*-ratios used in the analysis.

Despite the high classification accuracy given by discriminant analysis (95.2%), the major limitation of this method is that groups must be given a pre-assigned identity; it does not allow the classification of unknown individual(s) which may not belong to 1 of the pre-assigned groups.

The second method we used was canonical analysis, which generates centroid plots (Mardia, Kent & Bibby, 1980; SAS Institute, 1995). Centroid plots can be used to produce a more visual assessment of classification. The centroid values (multivariate least-square means) are plotted on the first 2 canonical variables formed from the test space, with circles (ellipses) corresponding to 95% confidence limits. In the present analysis, the presence or absence of overlap of the ellipses was used as the classifying indicator. The advantage of this method is that it allows the classification of unknown individuals which may not belong to a pre-assigned group.

There are 3 potential limitations with the canonical centroid plot method. First, it uses only the first 2 canonical variables. The inclusion of the third canonical would produce a centroid plot in a 3-dimensional space with 95% confidence 'ellipsoids' and would be likely to provide greater accuracy. Grigione *et al*. (1999) made a similar observation. However, since we achieved sufficient separation using only the first 2 canonicals we did not test this option with the current dataset. The second limitation is that the size of the ellipses will vary according to the variation in the measurements and sample size (see Fig. 6). This may or may not affect the overlap of ellipses and thus accuracy of classification. In the present study, with the measurements used and the spoor sample size varying from a minimum of 12 to a maximum of 29, the level of accuracy of classification obtained was still high. The third limitation is that the distance between the centroid values of 2 or more sets of measurements is relative rather than fixed in the test space. For example, for 2 groups alone the canonical is determined by the matrix of within-group variations and the relative-position vector of the 2 group centroids, therefore the addition or removal of individuals or tracks from the analysis can alter the position of the centroid values (and therefore the ellipses) dramatically. Neither altering the number of measurements employed nor comparing with a standard set or track at a time reduced this problem. We did, however, overcome this problem using 2 modifications. First, we standardized the method so that sets or tracks were tested using the centroid plot technique on a pairwise basis, i.e. only 2 tracks or sets compared against each other at 1 time. Second, we found that we were able to bring more accuracy and stability to the system by introducing a third entity, which we called the 'reference centroid value' (RCV), formed from the entire library, as a reference for each comparison of any 2 test groups. In the present example, the library consisted of 290 spoor from all 15 rhino. Thereafter we included the RCV as a third entity in each pairwise comparison. The resulting between-group variation was then expressed by means of the 2 test group centroids relative to the RCV exclusively. When the entire library is large relative to the test group sizes, the within-group variation of the library can be expected to dominate the within-group variation of the test groups thus stabilizing the test centroid values in the test space. A mathematical explanation is provided in the Appendix.

With regard to measurement selection for pairwise comparison in centroid plots, we again found that the best results were obtained with the highest *F*-ratios. To establish how many measurements to use, we tested all choices of between 6 and 15 measurements with the highest *F*-ratios and found that the first 9 measurements produced the most accurate classifications. Including more measurements led to increased separation of ellipses between self tracks, and reducing the number of measurements led to increased overlap of ellipses between self and non-self tracks. Table 4 shows the 9 measurements used for the canonical centroid plot technique.

Table 5. Discriminant analysis cross-table plot of assigned *vs* predicted spoor for 290 spoor from 15 black rhino using 30 spoor measurements with the highest *F*-ratios

	Assigned spoor															
Predicted spoor	R01	R02	R03	R04	R05	R06	R07	R08	R09	R10	R11	R12	R13	R14	R15	TOT
R01	22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	22
R02	0	21	0	0	0	0	0	0	0	0	0	0	0	0	0	21
R03	0	0	20	0	0	0	0	0	0	0	0	0	0	0	0	20
R04	0	0	0	23	0	0	0	0	0	0	0	0	0	0	0	23
R05	0	0	0	0	17	0	0	0	0	0	0	0	0	0	0	17
R06	0	0	0	1	0	12	0	0	0	0	0	0	0	0	0	13
R07	0	0	0	0	0	0	18	0	0	0	0	0	0	1	0	19
R08	0	0	0	0	0	0	0	22	1	0	0	0	0	0	0	23
R09	0	0	0	0	0	0	0	1	18	0	0	0	0	0	0	19
R10	0	0	0	0	0	0	0	0	0	29	0	0	0	0	0	29
R11	0	0	0	0	0	0	0	0	0	0	13	0	1	0	0	14
R12	0	0	0	0	0	0	0	0	0	0	0	15	0	0	0	15
R13	0	0	0	0	0	0	1	0	0	0	0	1	17	0	1	20
R14	0	0	0	0	0	0	1	0	0	0	1	0	0	12	0	14
R15	2	0	0	0	0	0	1	0	0	0	0	0	0	1	17	21
TOT	24	21	20	24	17	12	21	23	19	29	14	16	18	14	18	290

When performing pairwise comparisons using the centroid plot technique, each track from each individual rhino was first tested against the remaining self set and then each track against every other non-self set (e.g. for rhino 01 which had 4 tracks making up a set of 24 spoor, each track was tested against the remaining spoor in that rhino set (self-set) and then against the other 14 rhino sets (non-self sets)). Each track was then tested against every self-track (same rhino) and every non-self track (different rhino) in a similar way. Finally, having established that the level of accuracy was dependent on track size the analysis was carried 1 step further. Small tracks were artificially grouped within sets to create 'modified' tracks containing a minimum of 8 spoor to see if the accuracy was improved. Original tracks which had a minimum of 8 spoor were left unmodified. With the new track sizes where all the tracks had a minimum of 8 spoor, every track was tested once more against each self track and non-self track.

RESULTS

Table 1 shows the number of spoor per set, the number of tracks per set, and minimum/maximum track sizes for the 15 black rhino used in the analysis.

Discriminant analyses

Using 30 measurements with best *F*-ratios we first carried out a test of assigned against predicted classification for each individual spoor for all 15 animals. As Table 5 shows, of the 290 spoor from 15 rhino subjected to discriminant analysis, 14 were misclassified, giving an accuracy of 95.2%. Five sets (rhinos) had no misclassifications, seven sets had a single misclassification each, one set had two and one set had three spoor misclassified.

Each spoor was then excluded in turn (Jacknife technique) and the test of assigned against predicted classification was repeated. Of 290 spoor, 37 were misclassified giving an accuracy of 87.2%.

Next, each track was excluded in turn and the test of assigned against predicted classification was repeated. Where $\geq 50\%$ of spoor within a track were assigned to the wrong group, the track was categorized as misclassified. Of the total of 51 tracks, none were misclassified but six were unclassified (none of the six tracks had $> 50\%$ of their spoor assigned to any of the 15 sets); an accuracy of 88.2%. Of the six unclassified tracks, two of the tracks actually had 50% of the spoor correctly assigned. If these tracks were considered correctly classified, then the level of accuracy would be 92%.

In order to establish how many spoor were required per track for good classification accuracy, we looked at the relationship between the percentage of spoor misclassified and track size. Misclassification of spoor was calculated by retaining each track in turn, excluding the rest of the set and then testing to see how the excluded spoor in the set would match the track from the same set, e.g. for rhino R01, the first track R01A with eight spoor was retained from the set and the rest of the 16 spoor from the set were tested by Jacknifing to see how many were classified correctly using discriminant analysis. Figure 3 shows the relationship between percentage misclassification of spoor and track size to be highly significant ($F_{1,49} = 17.61$, $P < 0.001$). The predictive model indicates that a minimum of eight spoor would be required in a track (which would constitute the initial set) against which either unknown spoor or tracks could be compared, to give 90% or better accuracy for classification.

The minimum set size used in this study was 12 spoor. For monitoring rhino in a 'closed' system, where all individual rhino are identifiable, we would recommend a safety margin and use 15 spoor per set.

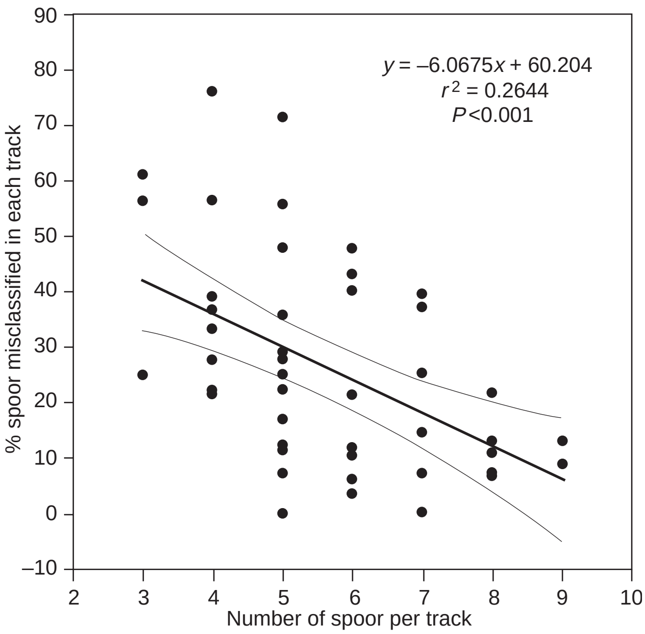

Fig. 3. Relationship between track size (number of spoor per track) and percentage spoor per track misclassified (using Jacknife technique in discriminant analysis).

Canonical centroid plots

Figure 4 shows a centroid plot generated from the first two canonicals for all 15 rhino spoor sets (R01–R15) using nine measurements. Of the total of nine canonical variates available, examination of the eigenvalues showed that the first two accounted for 80.55% of the variation. The ellipses around the centroid values indicate 95% confidence limits and the bi-plot rays show the direction of the measurements in the test space. The overall mean for the data (Grand) appears in the centre of the test space. Although there was a certain amount of ellipse overlap, MANOVA showed that the difference between the means was statistically significant (whole model for 15 rhino spoor sets, Wilks' lambda, $F_{126,2054} = 23.46$, $P < 0.001$). Similarly, pairwise comparisons showed that differences between all pairs were statistically significant ($P < 0.001$). However, just using the ellipse technique, classification of tracks which had been separated from the parent sets against all 15 sets was not always successful. For example, as Fig. 4 shows, the ellipses for set R10 and self-track R10A show correct classification; a clear overlap with self but not with any non-self set. But for set R01, self track R01A shows an incorrect classification; overlap with self but also four non-self sets. Similarly Fig. 5 shows that the attempted separation of several tracks from two different sets gave variable results; in some cases classification was reasonable (a), in others (b) very poor. This suggested a pairwise comparison of tracks or sets, would produce better classification.

When carrying out pairwise comparisons, we first attempted to test the classification excluding the RCV. As the example in Fig. 6 shows, track R01A of set R01 would have been incorrectly classified against self set and correctly classified against non-self set. However, the inclusion of the RCV gave a much higher degree of accuracy. Figure 7 shows correct classification of track R01A, i.e. presence of overlap when compared against self set (R01) and no overlap with non-self set (R02) when the RCV is included. Furthermore, with the RCV included, the presence and absence of overlap correlated with MANOVA values (R01A against R01, Wilks' lambda, $F_{8,15} = 0.73$, $P = 0.66$ and R01A against R02, Wilks' lambda, $F_{8,20} = 33.09$, $P < 0.001$).

So, including the RCV in pairwise comparisons, each track was first tested against the remainder of the self set. Of the total 51 tracks, three were misclassified (did not overlap with self set), giving 94% accuracy. Of these three tracks, two had three spoor per track and one had five per track. Each track was then compared against each non-self set. Of the 714 possible track–set interactions, none were misclassified (that is none overlapped with non-self sets) giving 100% accuracy.

Then testing track against track, each track was first tested against self tracks. Of the 66 possible self track interactions tested, nine were misclassified giving 86.4% accuracy. Of the possible 1209 track against non-self track interactions, 63 were misclassified, giving 94.8% accuracy. However, when we examined actual classification accuracy per track (that is where a track correctly matched with self, but did not match with any non-self track) we found that of the 51 tracks tested, 33 were misclassified, giving an overall accuracy of only 35.3%.

Since track sizes varied from three to nine, we suspected that there might be a relationship between track size and degree of misclassification. To test this, the frequency distribution of the sum of spoor in each tested pairwise track interaction was plotted against whether the classification of that track was correct or incorrect (Fig. 8). It was clear that there was a disparity between the two frequency distributions. When the pooled spoor number was large many more tracks were correctly classified. The difference between the two distributions was highly significant ($\Sigma\chi^2 = 16.77$, d.f. = 4, $P < 0.005$). When the pooled spoor size for the two tracks was ≥ 15 there was a very high probability for correct classification. To test this track sizes were modified artificially, pooling smaller tracks within the same set (where possible) to give a minimum track size of eight, and a summed value of 16 for pairwise comparisons. This resulted in a total of 30 tracks for 15 rhinos: three rhino had three tracks each, nine rhino had two tracks each and three rhino had one track each.

We then subjected these modified tracks to pairwise comparison using the centroid plot technique. Of the 18 possible interactions for track against self track, only one was misclassified, giving 94.4% accuracy. Of the 417 possible self against non-self track interactions, another one was misclassified, giving 99.8% accuracy, suggesting that this method would provide a very accurate monitoring tool.

For census use, the same tests showed that of 30

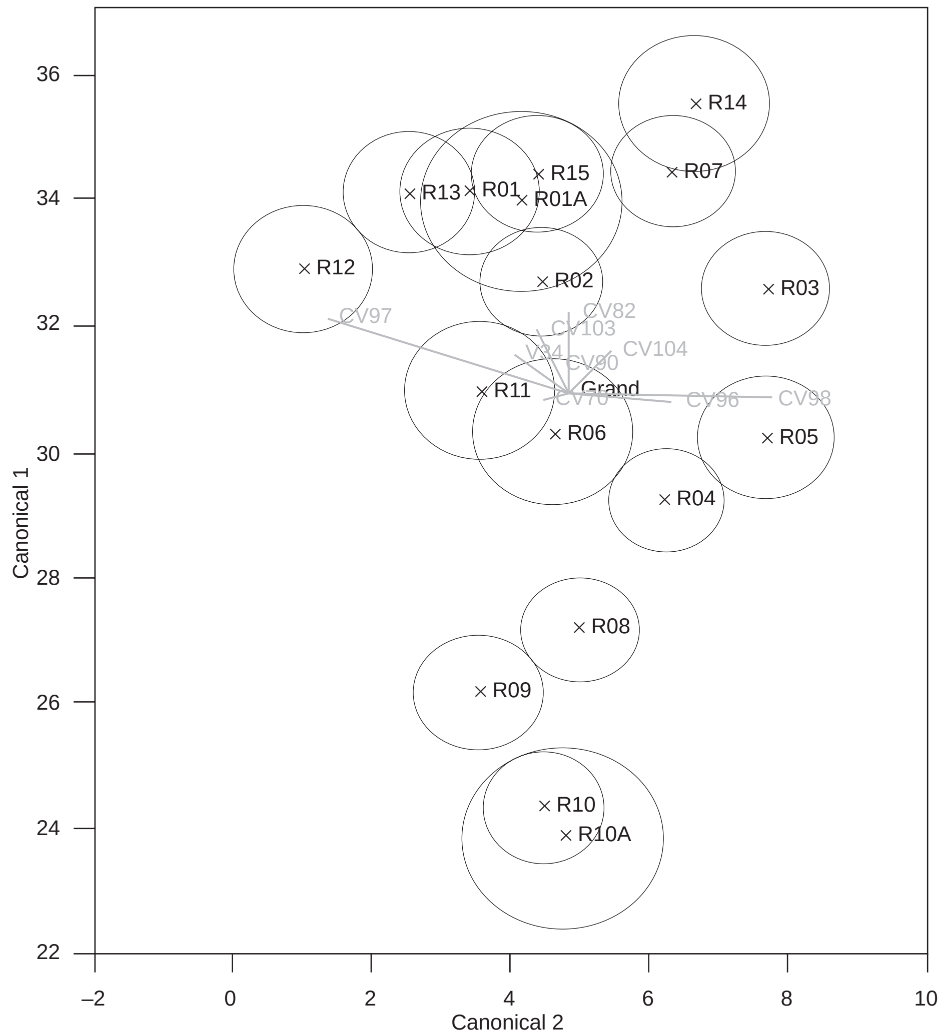

Fig. 4. Bivariate plot of canonical 1 *vs* canonical 2 with centroid values and 95% ellipses for 15 black rhino (R01–R15) using nine measurements. Each ellipse with its centroid value represents a spoor set, i.e. a rhino. The bi-plot rays show the direction of the nine measurements in the test space. The figure also shows track R10A for rhino R10 giving correct classification when matched against the rest of the spoor in that set (self-set) but track R01A shows overlap with the self-set R01 and four other rhinos.

tracks tested, two were misclassified. One failed to correctly match self and one incorrectly matched non-self, giving an overall accuracy of 93.3%. In practical terms, only the inaccuracy of the track against self would have created a false group in the form of a new ellipse. This system would therefore have given a figure of 16 animals for a population of 15 animals, giving 93.8% census accuracy.

DISCUSSION

Factors important in optimizing accuracy of classification

Various techniques have been used in an attempt to identify individual animals of the same species from spoor. To our knowledge, this paper is the first to report the use of a spoor technique giving good classification accuracy with spoor gathered *in situ*, and one which can be used for both monitoring and censusing. Several criteria seem to have been important in achieving a reasonable degree of accuracy in classification.

Standardizing the extraction of information from spoor was extremely important. The use of digital cameras helped in enabling checking of image quality at the field site. Also, because classification methods depend on the optimization of the ratio of between-set to within-set variation, enough spoor must be collected as outlined in the results section. NiSAS software enabled us to take many measurements of each spoor quickly and efficiently, reduce subjectivity, vary algorithms to test other measurements, and process large numbers of spoor. The use of crosshairs and photographic optimization with Adobe Photoshop software also increased accuracy and reduced subjectivity.

We selected measurements for discriminant and canonical analyses on the basis that they could be obtained objectively, gave a high level of accuracy and could be used in the analysis in a simple and straightforward

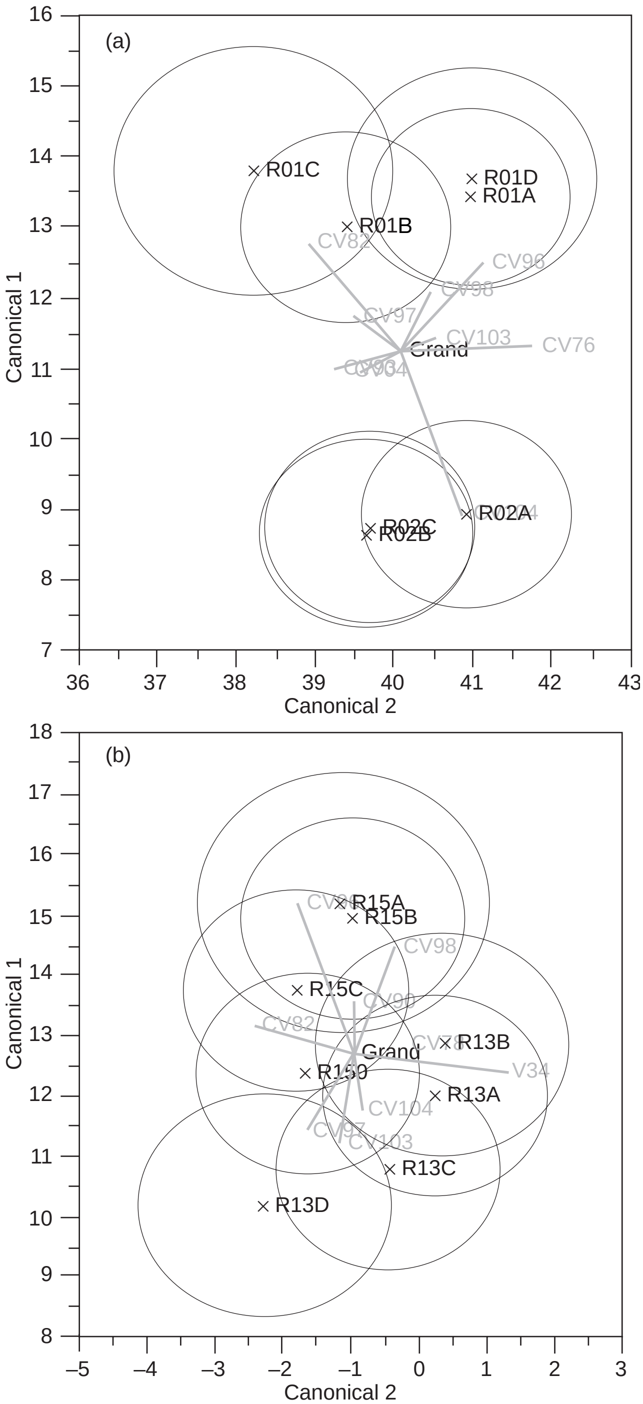

Fig. 5. Use of centroid plot technique to distinguish between multiple tracks from different rhinos with each ellipse representing a track. Canonical centroid plots (excluding reference centroid value) show: (a) spoor tracks of two rhino (R01 with four tracks and R02 with three tracks) correctly separated; (b) spoor tracks of another set of two rhino (R13 and R15 with four tracks each) indistinguishable from each other.

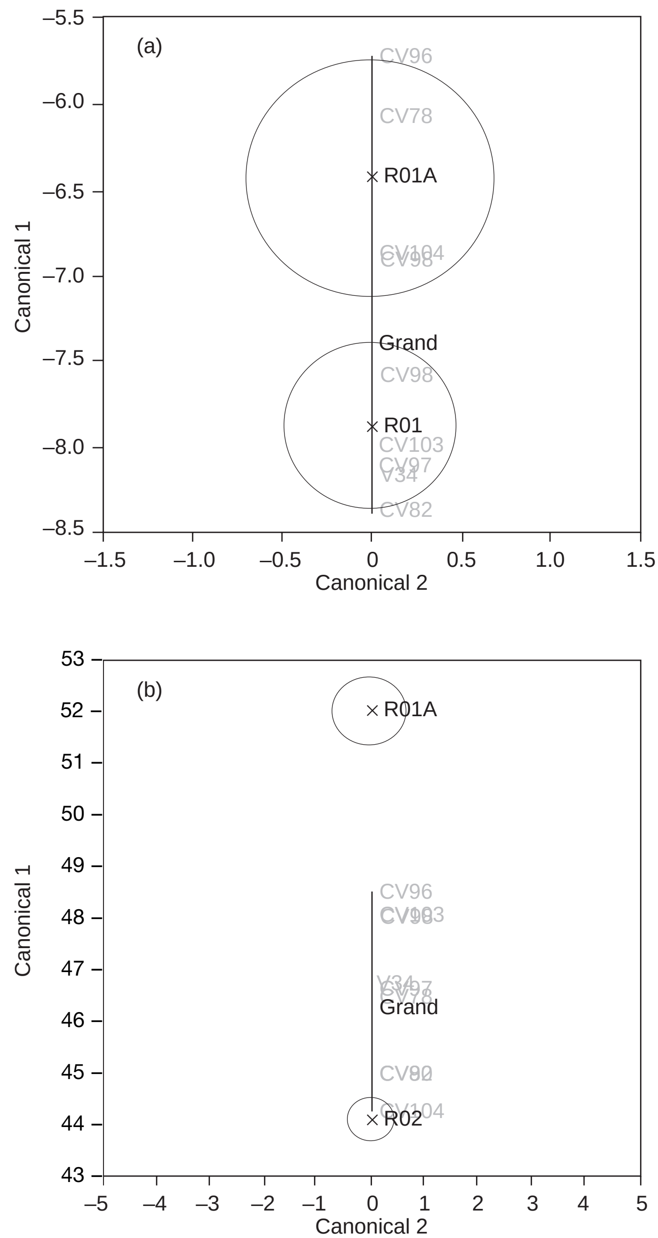

Fig. 6. Use of centroid plot technique in pairwise comparisons of tracks excluding reference centroid value. Canonical centroid plots show no overlap between the ellipse of track R01A and (a) ellipse of its self-set R01 (incorrect classification), and (b) ellipse of another rhino R02 (correct classification).

way. The measurements with the highest *F*-ratio values (Table 4) indicated that virtually all the information required for the centroid plot technique seemed to be contained within the boundaries determined by the three toes.

The use of pairwise comparisons, and the introduction of the RCV into the canonical centroid plot technique were central to the success of the spoor identification. In practical terms, the pairwise comparison method will, with further planned development of NiSAS, allow a fully automated field system, in which measurements produced from each incoming spoor or track can be systematically compared to the sets of known rhinos from that geographical location. If no match is found, the track will then be systematically compared to sets for known rhinos from adjacent locations, and so on.

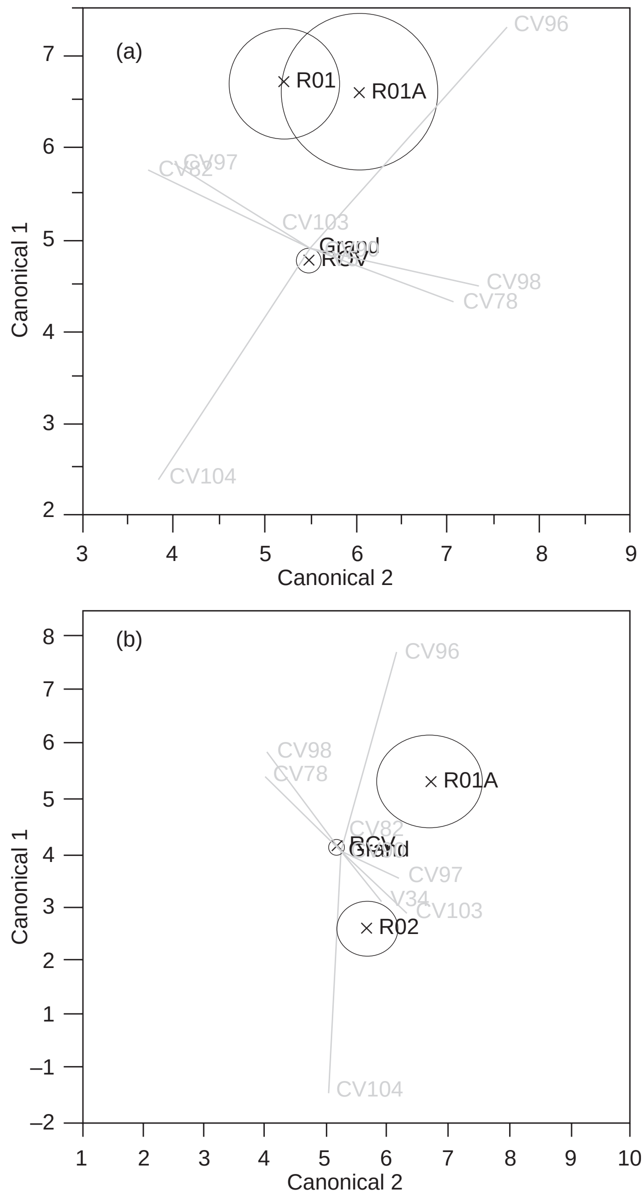

Fig. 7. Use of centroid plot technique in pairwise comparisons of tracks including reference centroid value. Canonical centroid plots show: (a) ellipses of track R01A overlapping with the rest of its self R01; (b) ellipse of track R01A separated from the spoor set of R02. Track R01A is correctly classified on both counts.

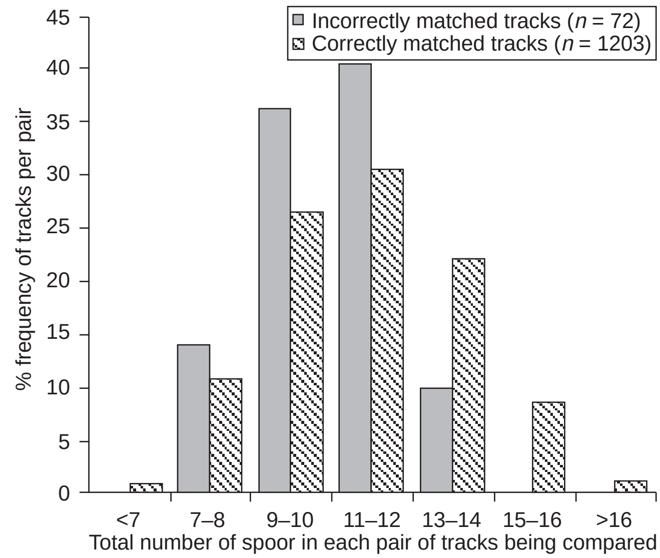

Fig. 8. Percentage frequency distributions of number of spoor in each pair of tracks compared using the centroid plot technique. The frequency distribution for correctly matched spoor shows a significant shift ($\Sigma\chi^2 = 16.77$, d.f. = 4, $P = 0.005$) to the right indicating that many spoor tracks are correctly matched when the number of spoor in each track pair is higher.

The practical application of the spoor technique for censusing and monitoring

Figure 9 summarizes the analytical procedures for monitoring and censusing black rhino populations.

Monitoring a population where all animals are identifiable. This would apply to a small to medium-sized population (e.g. < 30) where it was possible to identify all animals either by visual markings (e.g. ear notches) or radio-telemetry for long enough to enable an initial spoor library to be collected. The identification of new calf spoor could be made, as calves appear behind their dams.

Ideally 15 left hind spoor would be collected from each known animal. Discriminant analysis would enable the testing of assigned against predicted spoor classes, and if necessary a ‘calibration’ to local conditions and animal foot geometry performed with selected *F*-ratios. Having established an initial library, routine sampling and identification of even a single spoor from any of the known animals in the library would be possible. Canonical analysis could provide a more graphical method if preferred, giving classification of each incoming track against each set in the library. Correct classification should be obtained with between five and eight spoor in a track, since each library set would hold around 15 spoor. It would be advisable to ensure that all animals had similar set sizes for comparison.

Monitoring a population where at least five animals are known, but the identity and number of other animals are unknown. In this case, an initial set of 15 spoor would be collected from each known animal and subjected to discriminant analysis/*F*-ratios for ‘calibration’ to form the initial library. Canonical analysis would be used to identify each subsequent incoming track. The RCV, consisting of all the initial library spoor, would be input alongside each pairwise comparison between an incoming track (minimum eight spoor) and a test track from the library. As new animals were assigned a spoor identity, a visual link could be established by spoor tracking the rhino if required, to ascertain sex, and any individual features which could be linked to spoor identity for purposes of monitoring.

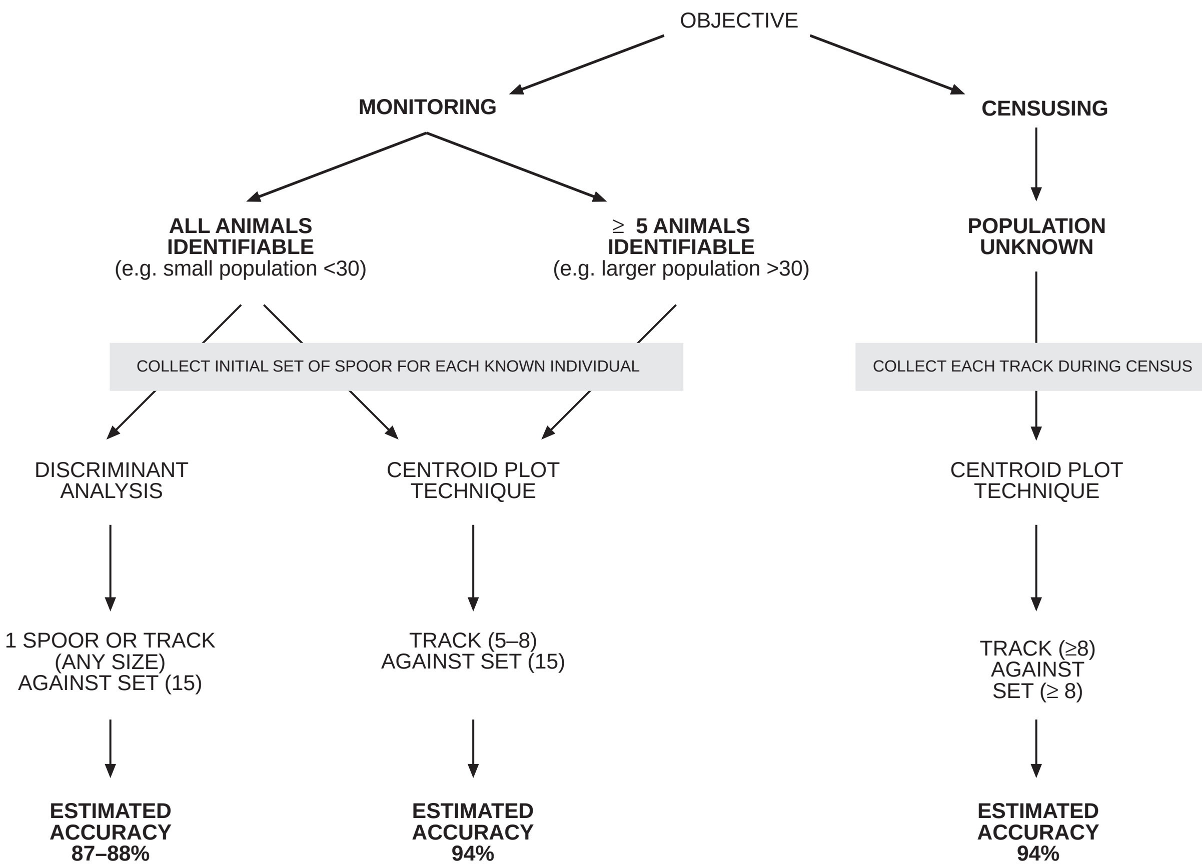

Fig. 9. A summary of suggested procedures for monitoring and censusing black rhino using the spoor technique.

Censusing an unknown population. As many spoor tracks as possible would be collected as part of a ground census, with a minimum of eight spoor per track. This track library would be input into canonical analysis as the RCV. Each track would then be compared pairwise against each other. Overlaps would be taken as self and non-overlaps as non-self. By a process of repeated pairwise comparisons one could categorize each track as belonging to a particular set.

If logistics prohibited a full census it should be possible to simply locate two cow/calf spoor pairs (where the calf spoor were obviously different sizes) and a single spoor track (from a single animal) and make these five the ‘known’ animals. If the spoor were taken from far apart in the census area, the likelihood of them being from five different animals would be high. This library would then form the basis of the RCV against which new incoming tracks could be compared where time or logistics permitted. It is possible that a comprehensive RCV from another population might be of use in a new census area, depending on the variability of spoor in different areas.

Collection of spoor under different environmental and operational conditions

Where law-enforcement patrols cover the monitoring area. Spoor photography would be done by scouts, or field rangers, as a normal part of law-enforcement patrol work. Initial training in use of cameras and GPS units at Sinamatella has shown excellent potential. Other management and research personnel could also carry cameras and take photographs where possible.

Where water sources are limited, but are accessible for monitoring. In many semi-arid/arid parts of their range, black rhino have to drink at known waterholes, usually at night. Their spoor can be collected from the waterhole at dawn, either by backtracking from close to the water point, or walking a wide circumference (*c*. 100 m out) around the waterhole. Where possible, either during full moon, or with night viewing equipment, their physical identities may be matched with spoor. A spoor library could be constructed for each waterhole, and regular pairwise comparisons made with adjacent waterholes for overlaps or apparently ‘new’ animals. We found that a small proportion of the black rhino population in Etosha National Park did visit more than one waterhole per night (Alibhai & Jewell, 1997*a*,*b*). However, waterhole monitoring alone does not provide information about animal distribution or ranging outside the waterhole areas. If this is required, supplementary coverage must be undertaken either by other methods of regular sampling, i.e. law-enforcement patrols, or census.

Integration of spoor data with database and mapping requirements for law-enforcement and research purposes

Once a spoor identity is assigned, it is fed into a database along with GPS data, and any other visual information gathered. These data can then be imported into a GIS or mapping tool, such as ArcView software, to plot rhino distribution and ranges. The most obvious use of range maps is in accurate and logical deployment of anti-poaching patrols. Because of the facility offered by NiSAS, such information can be made available rapidly and fresh data efficiently assimilated. In our experience, it often takes a whole day of groundwork to locate and record the position of one radio-collared animal, while a few hours of spoor photography can yield information on the positions of several animals.

Other aids in the classification of spoor

In situations where, for whatever reason, classification is unexpected, two other pieces of information may be useful in providing a check. First, if GPS positions of spoor are taken routinely and some idea of individual ranges is known, it is possible to compare expected with predicted distribution for a particular animal. Animals ranging within a defined area can be treated as sub-groups, and defined by sub-libraries. A spoor from that particular area is then first compared pairwise within its sub-library, and then outside. Even in a large population it is then possible to do limited pairwise comparisons for each ‘unknown’ track entered.

Second, the presence of an accompanying spoor may yield useful information, e.g. spoor can be used to monitor such demographic and behavioural factors as births and disappearance of calves, maturity of sub-adults, and even cows ‘exchanging’ sub-adults temporarily, as we have observed at Sinamatella (Alibhai *et al.*, 1996). In addition, since females in oestrus may be escorted by bulls for up to a week, spoor may provide retrospective information about paternity when a calf is born.

The advantages of this technique for censusing and monitoring

Identification by spoor is non-invasive and therefore does not affect the natural behaviour of the animal or compromise its fertility (Alibhai *et al.*, 2001). This may be particularly important when dealing with an endangered species.

It is cost-effective, particularly in comparison with other methods such as radio-collaring. The cost of monitoring a population of 60 black rhino using the spoor technique would be the initial cost of equipment (about US$10 000), with few recurrent annual costs. The cost of monitoring the same population using radio-collaring would be *c.* US$100 000 for the first year with recurrent annual re-collaring costs in the region of US$75 000 (Alibhai *et al.*, 1996).

It may be used where radio-collaring or direct visualization techniques are difficult to implement. Van Strien (1985) noted that direct observation of the Sumatran rhino was almost impossible in the dense tropical forests and the study of indirect evidence was the only feasible procedure for censusing or monitoring. Similarly, where animals exist at low density, the spoor technique may provide a very effective alternative to direct visualization techniques.

It provides comprehensive data about rhino distribution and ranging behaviour throughout the circadian cycle. Tracking and identification using ear-notch identification can only be done during the day, waterhole monitoring is usually only undertaken at night when animals come to drink and radio-telemetry is usually only undertaken during daylight. However, spoor can be collected at any time. Black rhino are usually most active at night, and as such their movements during the night may be of particular importance for effective law-enforcement and vital to scientific studies.

It uses the skills of indigenous people who are employed to protect the black rhino. Stander *et al.* (1997) also emphasized the importance of using indigenous skills when they concluded ‘Wildlife ecology and conservation studies may benefit greatly from the collaboration of skills from western science and traditional knowledge’.

It can be integrated with existing monitoring policies, and is able to work alongside existing radio-collaring, ear-notching and non-invasive visualization techniques if necessary, e.g. Alibhai & Jewell (1997*a*,*b*).

Supplementary information may be gained from spoor collection. Taberlet *et al.* (1997) measured spoor tracks of Pyrenean brown bears *Ursus arctos* to provide a census estimate to compare with a genetic analysis using DNA from dung taken at the same time. They showed that measurements of track size (two width measurements) substantiated the genetic identification of six bears. Simple spoor counts have also been used to provide indices of population density in carnivores (Stander, 1998) although individual animals were not identified.

The limitations of the technique

No spoor technique can provide an immediate visualization of the rhino. This may be a limiting factor if the exact position of each animal in the population must be known at any given time. However, the only way in which this could be practically accomplished is to ensure that each animal is radio-collared and constantly monitored, or that law-enforcement patrols individually follow animals. Either of these two options is unrealistic unless the population is very small and very accessible.

It can only be used where the substrate permits a footprint impression. Most black rhino range through areas that do have suitable substrates. Suitability of substrate does vary during the rainy season, but in our experience it is still usually possible to locate spoor given more time and effort. However, on very soft or consistently wet substrates it is usually not possible to collect useful spoor.

Other possible uses and adaptations of the spoor technique

It may be possible to assess age and sex from rhino spoor. Van Strien (1985) reported on growth of the spoor of calves, and our sample set included one calf and two sub-adult animals. It should be possible to develop a useful index for estimating juvenile age from spoor. Similarly, it may be possible to estimate animal sex from spoor for black rhino. Stander *et al*. (1997) reported that the Ju/'Hoan people were always able to visually recognize lion sex from spoor, and that their measurements of lion spoor showed adult male spoor to be significantly larger than those of adult females. Gore *et al*. (1993) and Karanth (1995) also used spoor to identify the sex of individual tigers in a similar fashion.

It may also be possible to develop complimentary pattern recognition techniques to identify black rhino from their individual heel cracks, which show clearly on fresh spoor from good substrate (R. Amin, pers. comm.)

Finally, the technique described in this paper could be adapted for censusing and monitoring other endangered species which leave a footprint. It would obviously be appropriate where the species exists at low density and is nocturnal, as are many carnivores.

CONCLUSION

We believe that the use of spoor for censusing and monitoring will play an increasingly important part in the conservation of certain endangered species. Whatever monitoring techniques are used, it is our scientific and ethical responsibility to ensure that intrusion into the lives of the animals we study is minimized. As such, non-invasive techniques which provide essential information for effective conservation strategies, particularly for endangered species, point the way forward.

In the near future we plan to conduct field trials to test the spoor identification technique under more diverse conditions, with different species and at the same time refining the automation and general accessibility of the technique.

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APPENDIX

With m groups of data, each datum represented by a P-vector x, the matrix B of between-group variation (i.e. the matrix of between-group SSPs) may be written

$$\mathbf{B}=\sum_{j=1}^{m} n_j(\bar{x}_j-\bar{x})(x_j-\bar{x})',$$

where the jth group has n_j elements and centroid $\bar{x}_j$, $\bar{x}$ is the mean of all the data, and the prime denotes the transpose operation. This expression may be readily derived by algebraic manipulation of the defining expression $\mathbf{B}=\mathbf{T}-\mathbf{W}$, where $\mathbf{T}$ and $\mathbf{W}$ are the matrices of total and within-group variation (i.e. SSPs), respectively.

Consider two groups G_1 and G_2, with centroids $\bar{x}_1$ and $\bar{x}_2$, respectively, of data and a third group R that is the reference library defining the RCV of the text. Denote by $\bar{y}$ the centroid of this library, i.e. the RCV itself, and suppose there are n data points in the library. The total set S of data comprising the data of these three groups constitutes the dataset of the canonical centroid plot analysis described in the text as a pairwise comparison of G_1 and G_2 including the RCV. The mean of the data comprising S is $\bar{x}$. Standard theory (Mardia, Kent & Bibby, 1979) yields two canonical variate functions derived from the eigenvectors associated with the two positive eigenvalues of the matrix $\mathbf{W}^{-1}.\mathbf{B}$ formed from this data. Using the relation

$$\bar{x}=\frac{n_1\bar{x}_1+n_2+n\bar{y}}{n+n_1+n_2}$$

one can eliminate $\bar{x}$ from the above expression for $\mathbf{B}$. With

$$d_1=\bar{y}-\bar{x}_1 \qquad d_2=\bar{y}-\bar{x}_2,$$

$$b_1=\frac{n_1}{n+n_1+n_2}[(n+n_2)d_1-n_2d_2] \qquad b_2=\frac{-n_2}{n+n_1+n_2}[(n_1d_1-(n+n_1)d_2]$$

one can express $\mathbf{B}$ in the form

$$\mathbf{B}=d_1(b_1)'+d_2(b_2)'.$$

Therefore,

$$\mathbf{W}^{-1}\,\mathbf{B}=(\mathbf{W}^{-1}.d_1)(b_1)'+(\mathbf{W}^{-1}.d_2)(b_2)',$$

from which form it follows that the eigenvectors corresponding to the two positive eigenvalues are linear combinations of the two vectors $\mathbf{W}^{-1}.d_1$ and $\mathbf{W}^{-1}.d_2$. The two eigenvalues themselves may be obtained as the roots of the quadratic equation

$$\lambda^2-(b_1\mathbf{W}^{-1}d_1+b_2\mathbf{W}^{-1}d_2)\lambda+(b_1\mathbf{W}^{-1}d_1)(b_2\mathbf{W}^{-1}d_2)-(b_1\mathbf{W}^{-1}d_2)(b_2\mathbf{W}^{-1}d_1)=0,$$

where for any two p-vectors u and v the expression $u\mathbf{W}^{-1}v$ stands for the matrix expression $(u')\mathbf{W}^{-1}v$. Indeed, as $\mathbf{W}^{-1}$ is a symmetric matrix it defines a bilinear form. With $w_{ij}{:}=d_i\,\mathbf{W}^{-1}d_j$, the eigenvalues are algebraic expressions in the three values w_{11}, w_{22}, and w_{12}. The corresponding eigenvectors are then linear combinations of the vectors $\mathbf{W}^{-1}.d_1$ and $\mathbf{W}^{-1}.d_2$ with coefficients which are again algebraic expressions in w_{11}, w_{22}, and w_{12}.

Thus, the quantities determining the two canonical variate functions available for a pairwise comparison with RCV may be expressed purely in terms of the two vectors d_1 and d_2, the within-group variation $\mathbf{W}$, and the three group sizes n, n_1, n_2. This result supports the contention in the text that the presence of the RCV plays a role of reference point for the centroids of the two groups being compared.

In contrast, without the RCV, there is only one canonical variate function, which is well known to be determined by the eigenvector $\mathbf{V}^{-1}.(\bar{x}_1-\bar{x}_2)$, where $\mathbf{V}$ is the matrix of within-group variation for the two groups G_1 and G_2.

Moreover, when the size n of the reference library is large compared to the sizes n_1 and n_2 of the test groups, one expects the within-group variation $\mathbf{W}_R$ of the library to dominate the within-group variation $\mathbf{V}$ of the two test groups so that the within-group variation $\mathbf{W}$ of S is given approximately by $\mathbf{W}_R$. Thus, the two canonicals for the pairwise comparison of G_1 and G_2 with the RCV are given approximately by the eigenvectors of $(\mathbf{W}_R)^{-1}.\mathbf{B}$, which will be linear combinations of $(\mathbf{W}_R)^{-1}.d_1$ and $(\mathbf{W}_R)^{-1}.d_2$, lending stability to the pairwise comparisons as the pairs change but the RCV remains constant.