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Identification of individual tigers (*Panthera tigris*) from their pugmarks

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Abstract

An objective multivariate technique is described for identification of individual tigers *Panthera tigris* from their pugmarks. Tracings and photographs of hind pugmarks were obtained from 23 pugmark-sets of 19 individually known tigers (17 wild and two captive tigers). These 23 pugmark-sets were then divided into two groups, one of 15 pugmark-sets for model building and another of eight pugmark-sets for model testing and validation. A total of 93 measurements were taken from each pugmark along with three gait measurements. We used CV ratio, *F*-ratio and removed highly correlated variables to finally select 11 variables from these 93 variables. These 11 variables did not differ between left and right pugmarks. Stepwise discriminant function analysis (DFA) based on these 11 variables correctly classified pugmark-sets to individual tigers. A realistic population estimation exercise was simulated using the validation dataset. The algorithms developed here correctly allocated each pugmark-set to the correct individual tiger. The effect of extraneous factors, i.e. soil depth and multiple tracers, was also tested and pugmark tracings compared with pugmark photographs. We recommend collecting pugmarks from soil depths ranging between 0.5 and 1.0 cm, and advocate the use of pugmark photographs rather than pugmark tracings to eliminate the chance of obtaining substandard data from untrained tracers. Our study suggests that tigers can be individually identified from their pugmarks with a high level of accuracy and pugmark-sets could be used for population estimation of tigers within a statistically designed mark–recapture framework.

Key words: footprints, individual identification, multivariate analysis, *Panthera tigris*, pugmark, spoor, tiger, tracks

INTRODUCTION

The estimation of number of individuals of a species in a population is a key question in the field of ecology and wildlife conservation (Caughley, 1977; Seber, 1992). Population estimates of any species are required for formulation of a conservation strategy, prioritization and allocation of resources, as well as for evaluating the success of conservation programmes, and also for political reasons (Nowell & Jackson, 1996; Karanth, 2003). The tiger *Panthera tigris* is considered an icon for conservation in all ecosystems wherever it occurs. Owing to its endangered, umbrella and flagship status, accurate and reliable population estimates are critical for implementation and assessment of conservation measures and management practices (Nowell & Jackson, 1996). Population estimation of tigers, like that of other felids is difficult owing to their low densities, territoriality, nocturnal and cryptic behaviour (Bertram, 1979; Karanth & Nichols, 1998, 2000).

Currently three methods are being used for population monitoring of tigers:

(1) total count based on expert identification of individual tiger pugmarks in India (Panwar, 1979*a*; Choudhury, 1970, 1972; Karanth *et al.*, 2003) Nepal (McDougal, 1977, 1999) and Bangladesh;
(2) indices of snow track encounter rates calibrated to tiger densities used in the Russian Far East (Miquelle *et al.*, 1996; Hayward *et al.*, 2002);
(3) mark–recapture population estimates based on photographs of tigers obtained using camera-traps in a few selected tiger reserves (Karanth & Nichols, 2000; Kawanishi & Sunquist, 2004).

Of the above methods, the camera trap technique using the mark–recapture framework is statistically the most robust. For estimating the population of any endangered species, however, it is essential that the estimates are accurate as well as precise. Population estimates of tigers based on mark–recapture using camera traps suffer from problems such as high cost of equipment, risk of camera theft and low precision of density estimates especially in areas of low tiger density (Karanth & Nichols, 2000)

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because the technique relies on sampling tigers at only a few predetermined locations where camera traps are set.

Use of tracks for identifying individual animals

Attempts have been made to identify individuals of a species based on information from their tracks. Researchers and field managers could distinguish between individual mountain lions *Felis concolor* by using deformations and gross differences in size and shapes (Currier, Sheriff & Russel, 1977; Kutilek *et al.*, 1983; Fitzhugh & Gorenzel, 1985; Van Dyke, Brocke & Shaw, 1986), by one or more track measurements (Koford, 1976; Currier *et al.*, 1977; Fitzhugh & Gorenzel, 1985; Smallwood & Fitzhugh, 1993; Grigione *et al.*, 1999; Lewison, Fitzhugh & Galentine, 2001; Fitzhugh, Lewison & Galentine, 2000), in combination with radio-telemetry locations and distances between track sets (Currier *et al.*, 1977; Shaw, 1983; Fitzhugh & Gorenzel, 1985; Van Dyke *et al.*, 1986; Neal, Steger& Bertram, 1987), and by morphometric analysis of pad shape (Grigione & Burman, 2000). Successful attempts have also been made in identifying individuals of other species from their tracks, e.g. Asian rhinos (Strickland, 1967; Schenkel & Schenkel-Hulliger, 1969; Kurt, 1970; Borner, 1970; Flynn & Abdullah, 1983; Van Strien, 1985), black rhino *Diceros bicornis* (Jewell, Alibhai & Law, 2001), mountain tapir *Tapirus pinchaque* (Lizcano & Cavelier, 2000), pine marten *Martes martes* (Zalewski, 1999), snow leopard *Uncia uncia* (Riordan, 1998), and jaguar *Panthera onca* (M. Aranda & C. Miller, pers. comm.).

Tracking tigers for hunting was a tradition among Indian hunters, which flourished under royal patronage (Sankhla, 1978; L. A. K. Singh, 1999). Champion (1929) and Brander (1930) were the first to describe characteristics of tiger pugmarks. It was claimed that sex, age, physical condition and also the individual identity of a tiger could be determined from its tracks (Corbett, 1944; Abramov, 1961; Choudhury, 1970, 1971, 1972; Sankhla, 1978; Panwar, 1979*a*,*b*; Jayarajan, 1983*a*,*b*; Sawarkar, 1987; Basappanavar, 1988; Gogate *et al.*, 1989; Rishi, 1997; L. A. K. Singh, 1999).

Use of pugmarks for monitoring tiger populations

The first attempt to enumerate tigers from their pugmarks was made by W. J. Nicholson of Imperial Forest Service in Palamau district, Bihar in 1934, which gave him a figure of 32 tigers for an area of 299 km^2 (Jayarajan, 1983*a*). A systematic methodological approach for recording pugmarks for individual tiger identification and their *census* was formally conceptualized and advocated by S. R. Choudhury (1970, 1971). He introduced the 'tiger tracer' and developed the methodology for a census of pugmarks. This method was again fine-tuned by Panwar (1979*a*), Sawarkar (1987) and Singh (1999). The basic premise of the method is that experienced persons can identify each individual tiger from their pugmark tracing (Panwar, 1979*a*,*b*; Sale & Berkmuller, 1988; Sharma, 2001). McDougal (1977, 1999) also identified a few resident individual tigers from their pugmarks in Chitwan National Park, Nepal.

The reliability of the pugmark census technique has often been questioned owing to its subjectivity and lack of validation on populations of known free-ranging tigers (Schaller, 1967; A. Singh, 1972, 1984; S. D. Ripley quoted in Sankhla, 1978: 190–191; Karanth, 1987, 1993, 1995, 1999, 2003; Karanth & Nichols, 2000; Karanth *et al.*, 2003). Critics of the technique believed that an individual tiger's pugmark changes in shape and size over different substrate (soil texture, moisture and depth). Another source of variability is the variation between different tracers' abilities to trace the features of the pugmark on the tracing sheet (Karanth, 1987).

The currently used technique of tiger population estimation based on pugmarks is believed to have the following drawbacks (Karanth *et al.*, 2003):

(1) poor data quality: pugmark tracings and plaster casts obtained by several field personnel are often inconsistent and of poor quality;
(2) individual tigers are believed to be identifiable from these substandard data by supervisory officials;
(3) the method assumes total enumeration of tigers by obtaining pugmarks of all tigers that are subsequently identified to individuals.

Attempts have been made to quantitatively and objectively assess the individual identification of tigers based on pugmarks (Gogate *et al.*, 1989; Gore *et al.*, 1993; Das & Sanyal, 1995; Riordan, 1998). These studies suggest that pugmarks do possess quantifiable information that could permit individual identification. Owing to the limitations of experimental design and the lack of an appropriate sample size of pugmark data from known tigers, however, these studies were not conclusive. Recent more definitive studies on the tracks of mountain lions (Smallwood & Fitzhugh, 1993; Grigione *et al.*, 1999; Lewison *et al.*, 2001), black rhinos (Jewell *et al.*, 2001), mountain tapirs (Lizcano & Cavelier, 2000), snow leopards and tigers (Riordan, 1998), jaguars (C. Miller, pers. comm.) and pine martens (Zalewski,1999) used a quantitative approach for discriminating amongst individuals on the basis of a group of track sets.

In the present study, an objective approach is proposed for identifying individual tigers from their pugmark-sets that has potential for use in population estimation and monitoring. A multivariate model is developed based on nine variables from tiger pugmarks and two gait variables using discriminant function analysis (DFA) that permits individual identification of tigers. Once the individual identity of a tiger is ascertained, we propose to use this information in a mark–recapture framework (Pollock *et al.*, 1990) for population estimation and monitoring.

STUDY AREA AND STUDY DESIGN

To achieve the objective of this study, sets of tiger pugmarks with reasonable replicates from definitively known

Table 1. Details of the pugmark-sets collected from individually known tigers *Panthera tigris* from different study areas between November 2000 and April 2001

Site no.	Study site	No. of pugmark-sets collected	No. of individual tigers represented by the pugmark-set	No. of pugmarks collected	Average no. of pugmarks per track-set (range of pugmarks)	No. of pugmark photo-sets of individual tigers
1	Keoladeo National Park, Rajasthan	3	1	22	7 (6–10)	1
2	Ranthabhore Tiger Reserve, Rajasthan	8	8	80	10 (8–12)	5
3	Kanha Tiger Reserve, Madhya Pradesh	7	6	78	11 (10–14)	3
4	Bandhavgarh Tiger Reserve, Madhya Pradesh	2	2	16	8 (6–10)	1
5	National Zoological Garden, New Delhi	6	2	33	11 (8–12)	2
	Total	26	19	229	10 (6–14)	12

individual tigers were needed. This was achieved by sampling sets of tiger pugmarks from different tiger reserves and zoos in India (Table 1). Tracings or photographs of right and/or left hind pugmarks from a pugmark-set was collected if > 5 pugmark replicates of the same known tiger were found from a fresh pugmark trail. We ensured that individual pugmark-sets that were sampled within a tiger reserve were from different tigers, primarily by direct sighting of tigers ($n = 10$ tigers). In the few cases where pugmark-sets were separated by distances > 50 km and formed within the past 12 h, they were considered to be from two different tigers. Most of the pugmark-sets were collected from a long series of pugmarks, where the tiger had walked in normal gait. The gait was judged as normal after examining the pugmark trail for consistency in stride length and pattern of foot-fall (Sawarkar, 1987).

Pugmarks from well-beaten dirt roads having a finely pulverized soil depth of 0.5–1.0 cm, over flat terrain were traced on acetate sheets using indelible ink pen following the standard pugmark tracing technique (Choudhury, 1971; Panwar, 1979*a*; Fjelline & Mansfield, 1989; Sharma, Jhala & Sawarkar, 2003). Pugmarks were also photographed from a fixed height using a pugmark-photography stand (Sharma *et al.*, 2003). Five to 10 samples of gait variables, i.e. stride, straddle and step, were also measured for each pugmark-set recorded (L. A. K. Singh, 1999; Zielinski & Kucera, 1995) (Fig. 1).

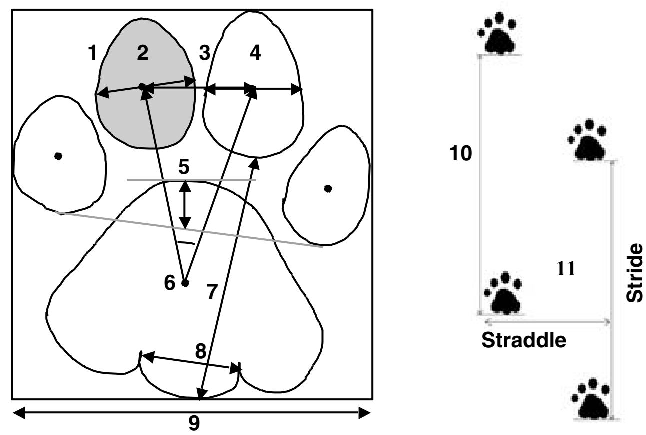

Fig. 1. Eleven final predictor variables used in the analysis of tiger *Panthera tigris* pugmarks and gait: nine measurements were taken from the pugmark while the remaining two measurements were gait measurements taken from the field. 1, Area of toe no.3 (AT3); 2, length of minor axis of toe no. 3 (MiT3); 3, distance between toe no. 2 and toe no. 3 (DT2T3); 4, length of minor axis of toe no. 2 (LT'2); 5, distance between main pad top to toe base-line (H); 6, angle between toe no. 2 and toe no. 3 (QT2T3); 7, heel to lead toe length (HLTL); 8, distance between notch 1 and notch 2 (DN1N2); 9, width of the pugmark (Wpg); 10, stride; 11, straddle.

Assessing tracer's variability and substratum effect

The major sources of variability likely to influence individual identification from pugmarks were:

(1) the variability in pugmark shape and size due to soil depth;
(2) variability associated with the different tracers and their tracing skills.

Pugmark-sets of a known solitary tigress in Keoladeo National Park, Bharatpur (Rajasthan) were traced and photographed at 3 different soil depths of < 0.5 cm, 0.5–1 cm and 2 cm, respectively, over 3 days.

To address the issue of multiple tracers' variability, 3 of us (SS, YVJ, VBS) traced the same 28 pugmarks from the pugmark-sets of 1 male and 1 female tiger at the National Zoological Garden, New Delhi.

Image analysis of pugmark tracings and photographs

The pugmark tracings and photographs were scanned using a flatbed scanner to convert them to digital images for further analysis. A 5-cm line was introduced in every tracing during the scanning for calibrating various measurements obtained from the pugmark. Assignment of centroids and morphometric measurements were obtained using Arc Info 8.0.2 (Environmental Systems Research Institute Inc., Redlands, CA, U.S.A.), Arc View 3 (Environmental Systems Research Institute Inc., Redlands, CA, U.S.A.) and Sigma Scan Pro 4 (SPSS Inc.) software.

A total of 93 measurements that were likely to cover most aspects of the geometry of a pugmark were measured from left and from right pugmarks of the hind feet. The reason for measuring a large number of variables was to extract the maximum possible information from the pugmark and to determine which measurements probably had the maximum discriminating power between tigers. Many of the same variables that earlier studies (Gogate *et al.*, 1989; Gore *et al.*, 1993; Das & Sanyal, 1995) had identified as being useful were used. Out of the 93 variables measured, 47 were linear, 7 were area, 11 were angle, 18 were ratio and 10 were shape variables.

Comparison of tracings and photographs of the pugmark

To assess the use of pugmark photographs in place of pugmark tracings, photographs and tracings were taken of 3 different pugmark-sets and then statistical comparisons performed.

Statistical methods

The 23 pugmark-sets were divided into 2 groups, set 1 ($n = 15$ pugmark-sets) for variable selection and model building and set 2 ($n = 8$ pugmark-sets) for model testing and validation. SPSS 8.0 (SPSS Inc.) was used for all statistical analysis. Since variables were of different scales, all were converted to their Z-scores before subjecting them to further statistical analysis (Zar, 1984).

Variable selection

The objective of this exercise was to reduce the data dimensionality, so as to achieve maximum discrimination with a parsimonious model containing few robust variables. We used the coefficient of variation (CV) ratio method and the F-ratio method as criteria to select variables.

In the CV ratio method, the coefficient of variation (CV) for each measured variable of a pugmark-set was computed for individual tigers (CV_t). A grand coefficient of variation (CV_g) was computed for the same variable from all pugmark-sets of set 1 (tigers). CV_g was then divided by the CV_t for each variable to get CV ratio ($CV_r = CV_g/CV_t$). This procedure was repeated for all variables. A large value of CV_r denotes that a particular variable has small variation within pugmark-sets relative to between the pugmark-sets (tigers). Such variables would have a greater capability to discriminate between individual tigers.

For the F-ratio method, the following were computed for each variable: (1) the sum of squared deviations of individual variables from their mean for each pugmark-set (S_w^2); (2) the sum of squared deviations of group averages of each variable of each pugmark-set from the grand mean obtained from all pugmark-sets (S_b^2). The F-ratio is S_b^2/S_w^2 (Zar, 1984). A large value of F-ratio for a particular variable suggests that it is fairly consistent within the same pugmark-set but differs between the pugmark-sets of different tigers. Such variables would have better ability to discriminate between different tigers.

Although the left and right pugmarks of the same tiger were not mirror images of each other, it seemed probable that some of the variables measured were similar between the left and right hindfoot. If some of these variables of the left and right pugmark could be pooled for the analysis, then the number of variables in the model would be reduced thereby giving a more parsimonious model. Simultaneously the sample size of pugmarks in a pugmark-set would increase (left and right together) thereby increasing the discriminating power of the model (Johnson & Wichern, 1992). The variables selected by the maximum CV, and F-ratios were paired for left and right pugmarks of the same pugmark-set and tested by a paired t-test (Zar, 1984). Pearson's correlation coefficients were computed for those variables that were not statistically different between left and right pugmarks of the same tiger. Only one of a pair of highly correlated variables ($r > 0.8$, $P < 0.05$) was selected for further analysis.

Ability to discriminate individual tigers

Multiple group stepwise DFA was used for discriminating between individual pugmark-sets (tigers). The smallest F-ratio method with a probability of 0.05 for variable entry and 0.1 probability for variable removal from the model was selected.

Validation of model for individual discrimination of tigers by pugmark-sets

The model was validated by using the variables selected above in a predictive DFA to correctly assign unknown pugmark-sets to individually known tigers (Williams, 1983; Johnson & Wichern, 1992). For predictive DFA, each pugmark-set (set 1 and 2, $n = 23$ pugmark-sets) of 19 tigers was divided into 2 halves, by randomly picking 50% of the pugmarks from all pugmark-sets. The first half of this dataset was used as the training dataset to develop discriminant functions. The remaining dataset of pugmarks was used as a test set. Class assignment pattern for each pugmark to their respective pugmark-set was examined.

Since the entire pugmark-set (a series of continuous pugmarks made by the same tiger) and not a single pugmark implies the identity of a tiger, it was the accuracy of correct classification of the pugmark-sets and not the individual pugmark, which were of relevance. The decision rule for correct classification of a pugmark-set was devised based on the correct classification of > 50% of pugmarks of that test set to the correct training pugmark-set (tiger). Considering a rare event, when 50% of the test set of pugmarks was classified into 2 or more training sets, then the training set which had the larger average probability of classification of pugmarks from the test set was considered to be the group assigned by the model.

This exercise was repeated 5 times by randomly assigning 50% of the pugmarks from each pugmark-set as the training set and the remaining as a prediction or test set.

Estimating the sample size of pugmarks in a pugmark-set for accurate identification

To estimate the number of pugmarks in a pugmark-set that would be needed to accurately predict the identity of an individual tiger; a dataset of 10 tigers was used that had a minimum of 10 pugmarks each in their pugmark-sets. An attempt was made to discriminate between these tigers by starting with 2 pugmarks in each pugmark-set and then incrementing the pugmark-set by 2 pugmarks for each run of predictive DFA. The average per cent accuracy of individual identification *vs* the number of pugmarks in a pugmark-set was plotted.

Tiger population estimation exercise

In the previous exercise, the actual number of tigers was known a priori and the model was tested to predict the correct grouping of each pugmark-set to individual tigers. In a field population estimation exercise, however, several pugmark-sets could be recorded without knowing the identity of the tiger. An analytical technique needs to be developed that permits recognition of a set of pugmarks as belonging to a 'new' tiger or assigning the pugmark-set to a tiger whose pugmarks have been recorded earlier. In a typical field situation it is probable that multiple pugmark-sets of the same tiger from different locations are obtained.

To address this problem, a population of pugmark-sets of 15 known tigers (set 1, *n* of pugmarks in pugmark-sets were 6–10) and 8 pugmark-sets (set 2, *n* of pugmarks in pugmark-sets were 10–14) from tigers whose identity needed to be ascertained was used. The 8 pugmark-sets (set 2) represented 4 new tigers and 2 pugmark-sets of tigers that were already present in the population of the 15 known tigers. Our model (built from set 1) was tested to see if it could correctly classify these 8 pugmark-sets to the already known individuals and identify the new tigers as additional to the simulated population to predict the correct number of tigers represented by these 23 pugmark-sets.

Each of the 8 new pugmark-sets was entered in the model for discrimination 1 at a time. Half of the data of each new pugmark-set was randomly split into 2 groups. One of the groups was given the identity of the pugmark-set (training set) and the other left unassigned to any group (test set). This data (new pugmark-set along with 15 known tiger pugmark-sets) was then analysed using variables selected by the earlier model developed from set 1 with DFA. The predicted group membership and probability of group assignment was examined for the new pugmark-set. The pugmark-set was considered as a new tiger where all the pugmarks of an entire pugmark-set were classified as a distinct group. If, however, some of the pugmarks of the pugmark-set were classified into 2 or more groups, then the probability of group assignment for each pugmark into those groups was examined.

Assessing effect of soil depth, multiple tracers and comparison between pugmark photographs and tracings

DFA was used to discriminate between pugmark-sets of 5 tigers whose pugmark size was similar to that of the tiger whose pugmark-sets were traced from soil depths of < 0.5, 0.5–1.0, and 2 cm (comparison of 8 pugmark-sets).

DFA was used to compare the classification of pugmark-sets from tracings and photographs of the same pugmark-sets. Six pugmark-sets of 2 known tigers traced by 3 different tracers were compared with pugmark tracings of 5 other tigers (comparison of 11 pugmark-sets) by DFA.

RESULTS

Variable selection

By using a combination of maximum CV ratio and maximum *F*-ratio, 33 variables were selected out of the 96 variables, that maximized information from a tiger's pugmark for discriminating between individuals. Variables that differed between left and right hind pugmarks (paired *t*-test, $P < 0.05$) were removed from further analysis. After removing one of a pair of highly correlated variables ($r > 0.8$, $P < 0.05$) from the remaining variables, 11 variables were left, which were used as predictor variables in the stepwise DFA (Fig. 1). All of the 11 variables were found to contribute significantly to the discriminant functions which correctly classified all 15 pugmark-sets to individual tigers.

Model validation

In all the five test runs of the model validation, the test dataset was correctly classified to the individual tiger. DFA analysis of the entire dataset (19 tigers, set 1 and 2) gave 11 significant ($P < 0.05$) standardized canonical discriminant functions that correctly discriminated between tigers (Table 2). Pugmarks from most of the pugmark-sets had a high probability of correct classification. The average probability of correct classification of pugmarks to the correct pugmark-set was 0.92 (SD 0.083).

Variability owing to substratum and multiple tracers

The pugmark-sets of the same tiger taken from two different soil depths (< 0.5 cm and 2 cm) showed a wide dispersion and mixing with pugmark-sets from other tigers. However, the pugmark-set of the same tiger from a soil depth of 0.5 to 1.0 cm formed a distinct cluster (Fig. 2).

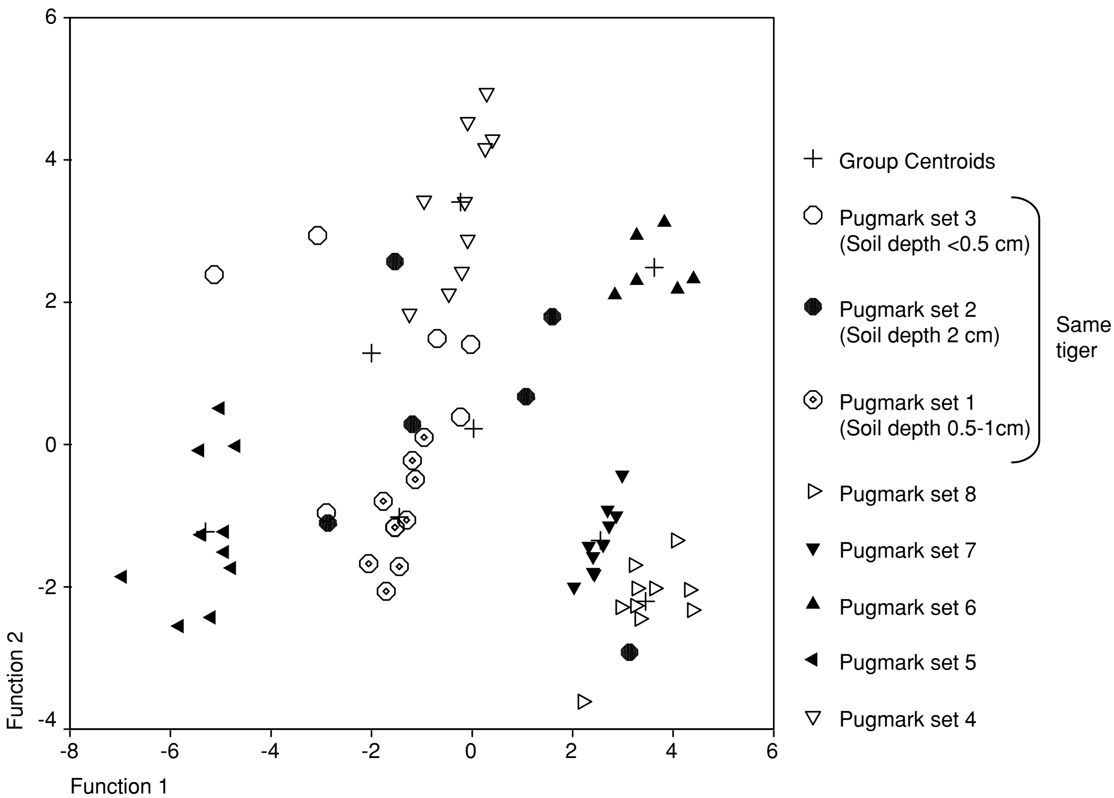

Fig. 2. Group centroids and pugmark clusters of eight tiger *Panthera tigris* pugmark-sets on canonical function axis, using 11 variables. Pugmark-sets no. 1, 2, and 3 are of the same tiger traced from three different soil depths (<0.5, $0.5-1.0$ and 2 cm). Pugmarks of pugmark-set 3 forms a single cluster, whereas pugmarks from pugmark-set 1 and 2 are intermixed and dispersed in canonical space. The remaining five pugmark-sets (pugmark set nos 1, 2, 3, 4 and 5) are different tigers forming distinct clusters.

Table 2. The discriminant function model coefficients and relevant statistics for the significant ($P < 0.01$) canonical functions explaining > 95% of variation for a population of 19 known tigers *Panthera tigris*

	Functions				
Variables	1	2	3	4	5
AT3	0.321	0.003	0.692	−0.318	0.325
MiT3	−0.232	0.211	−0.433	−0.117	−0.007
D23	−0.222	0.037	0.728	0.548	−0.546
LT'2	0.221	0.145	−0.315	0.398	0.451
H	0.375	0.213	0.339	−0.501	−0.658
QT2T3	−0.002	−0.251	0.178	0.369	0.321
HLTL	−0.338	0.012	0.187	0.144	0.359
DN1N2	0.192	0.209	0.179	−0.096	0.114
Wpg	0.289	−0.134	−0.145	−0.672	0.241
Stride	0.373	0.917	−0.299	0.238	−0.235
Straddle	0.788	−0.579	−0.148	0.277	−0.05
Eigen value	18.68	10.36	2.18	1.81	1.33
% of variance	51.94	28.82	6.05	5.03	3.69
Cumulative %	51.94	80.76	86.81	91.84	95.53
Wilks' lambda	0	0	0.01	0.04	0.12

The DFA correctly classified 11 pugmark-sets belonging to seven different tigers where six pugmark-sets from two known tigers were traced by three different observers (one set per tiger by each observer) (Fig. 3).

Variability between pugmark tracing and pugmark photos

The results of this analysis showed that DFA could not differentiate between tracings and photographs of pugmarks. On examining the classification table, it was found that pugmark tracings and pugmark photographs for the same tiger were classified as a single group.

Sample size of pugmarks in a pugmark-set

Accuracy of pugmark classification to the correct pugmark-set increased as sample size of pugmarks in the pugmark-set increased (Fig. 4). A sample of 10 pugmarks per pugmark-set ($n = 10$) gave an average accuracy of 96.2% (SE 7.9) of correct classification of pugmarks to the correct tiger (pugmark-set), while using 12 pugmarks per pugmark-set gave 100% classification accuracy for a sample of four pugmark-sets.

Population estimation exercise

After considering the predicted group memberships and the probabilities of group classification, all eight pugmark-sets (six sets representing four new tigers and two sets

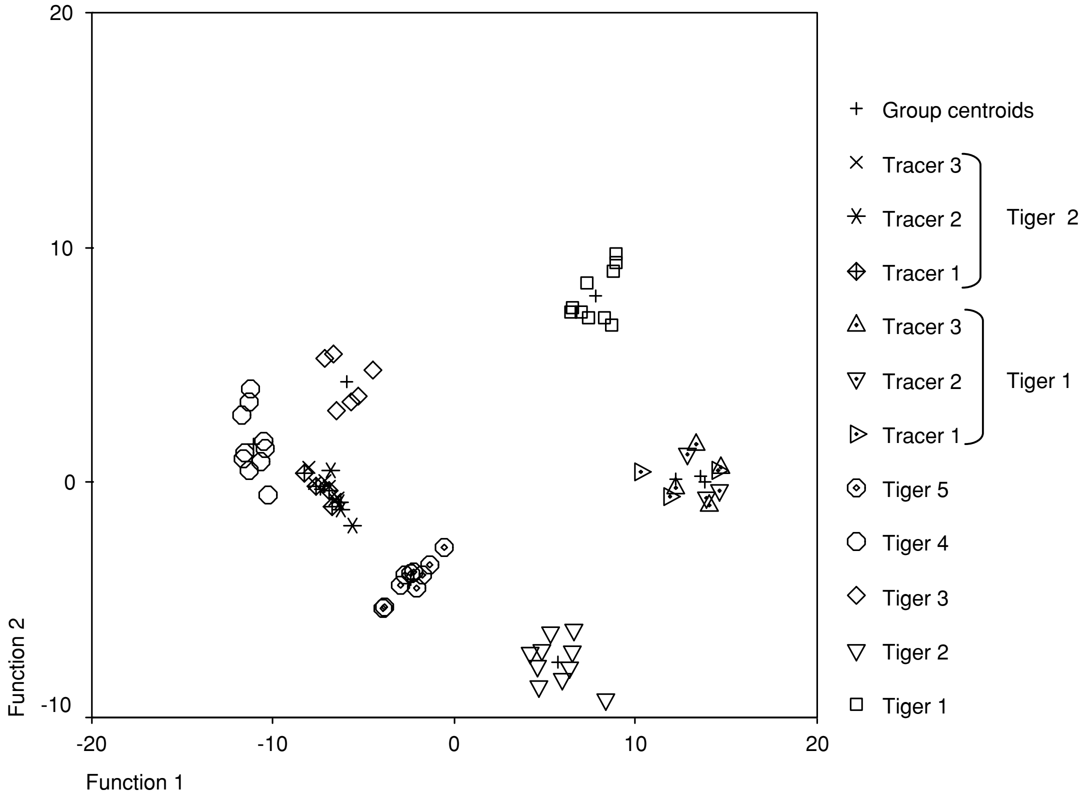

Fig. 3. Group centroids and pugmark clusters of 11 pugmark-sets of 7 different tigers *Panthera tigris* on canonical function axis, using 11 variables. Three different observers traced six pugmark-sets of two different tigers. These are seen forming two distinct clusters here ascertaining that those six pugmark-sets belong to two distinct tigers. The other five clusters represent five different tigers.

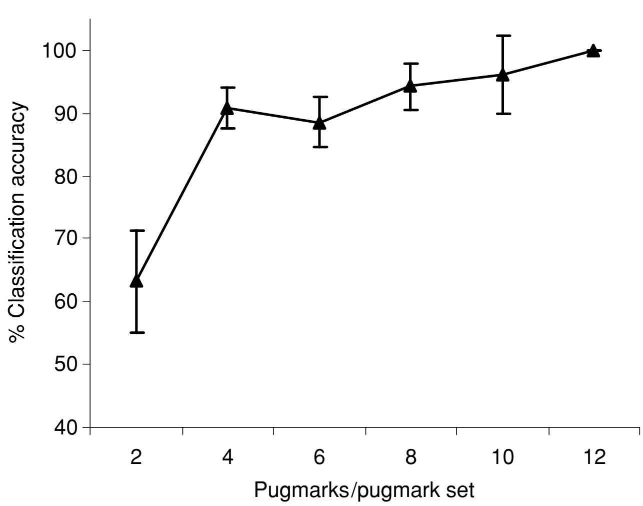

Fig. 4. Sample size estimation of the number of *Panthera tigris* pugmarks needed in a pugmark-set for accurate classification. Error bars are standard errors.

belonging to already existing tigers within the simulated pugmark-set population) were correctly classified either as new tigers or as belonging to the already existing tigers (represented by the 15 known tiger pugmark-sets). When the newly entered pugmark-set belonged to a new tiger, the classification was unambiguous in our dataset. When a pugmark-set that entered the model belonged to an already existing tiger within the dataset, however, there was intermixing of the test-set pugmarks with the training set and with the pugmark-set of the same tiger in set 1. The average sum of probabilities of intermixing of pugmarks belonging to the same tiger but from different pugmark-sets was 0.713 (SE 0.072 with a 95% lower bound of 0.64).

DISCUSSION, CONCLUSIONS AND MANAGEMENT IMPLICATIONS

Our dataset, though limited to 23 pugmark-sets of 19 tigers, strongly suggests the potential of using pugmark and gait variables for identifying individual tigers. Individual identification would be the first step for population estimation and monitoring. Total counts of tigers based on this method may only be feasible in very small reserves with a few tigers. In an average tiger reserve with even a moderate density of tigers, however, total counts would be difficult to obtain (Karanth, 2003; Karanth *et al.*, 2003). Models based on a mark–recapture framework (Pollock *et al.*, 1990) could provide population estimates when coupled with identifying individual tigers from their pugmark-sets.

In most tiger reserves in central and western India, conditions are conducive for obtaining good data on pugmark-sets. Sampling pugmark-sets has several advantages compared to sighting–resighting based on camera traps, which is limited to predetermined sites and therefore needs much more effort in achieving required sample sizes for precise estimates of abundance, especially in areas of low tiger densities (Karanth, 1999; Carbone *et al.*, 2001). In contrast, owing to the tiger's habit of using trails, obtaining pugmark-sets is relatively easy. Sufficient samples of pugmark-sets could be obtained even from low-density areas by intensive search.

A prerequisite for the currently available mark–recapture models is that the identity of a captured animal is known with certainty. Within our limited dataset, this level of accuracy of identifying each tiger uniquely from its pugmark-sets was achieved. This may not, however, be possible for all pugmark-set data. There may be some pugmark-sets whose identity may not be known with certainty. Our data suggests that a minimum of 10 pugmarks per pugmark-set should be recorded to determine the identity of a pugmark-set with a high level of certainty in a pugmark-set population of *c.* 20.

Pugmarks from a pugmark-set would be classified into a group with a probability ranging from 0 to 1. One approach would be to set cut-off bounds based on large datasets from known tigers. For this dataset, the average probability of a pugmark being correctly classified to its pugmark-set group was 0.92 (SD 0.083). When two pugmark-sets from the same tigers were considered, the average sum of cross-classification probability was 0.71 with a 95% lower bound of 0.64. Thus, if a new entrant pugmark-set gets mixed with a pre-existing pugmark-set and the average sum of this probability (of intermixing) is > 0.64, then the two pugmark-sets could be considered as belonging to the same tiger. In rare cases, a pugmark-set may get dispersed into several groups with small probabilities of classification in these groups, although no such case was seen in our data. An approach to incorporate the error probabilities of uncertain identification into the population estimation model as reported for genotyping errors in mark–recapture studies (Lukacs & Burnhum, in press) would need to be developed. In the eight pugmark-sets used for the population estimation exercise, each set had data ranging from 10 to 14 pugmarks. Larger numbers of pugmarks (> 10) recorded for each pugmark-set would increase the probability of correct classification in the model. Data was used from 15 known tigers as training data to which a new entrant pugmark-set was added for comparison and classification. It is essential to have a training dataset of a minimum of five to eight known tigers. Preferably, these pugmark-sets should be from both sexes and of varied sizes (age groups). Each time a new tiger is added, the training dataset increases in size. When a pugmark-set is classified as belonging to a pre-existing tiger (in the training data) then the new pugmark-set gets the same identity as that of the pre-existing set, thereby increasing its sample of pugmarks.

It is probable that the accuracy of correct classification of pugmark-sets may drop as the number of pugmark-sets being compared becomes large. For any meaningful comparison the number of pugmark-sets that actually need to be compared would be 10–35. It would be pointless to compare tiger pugmark-sets separated in space by > 40 km and time by < 12 h. Even considering sample sizes for multiple mark–recapture sessions (Pollock *et al.*, 1990) it is unlikely that comparisons within and between sessions would exceed 35 pugmark-sets even in high tiger density areas (as is seen from camera trap data in tiger habitats (Karanth & Nichols, 2000). Our data strongly suggest that a high level of accuracy is likely to be achieved in individual identification of tigers within these sample sizes. Studies such as this would need to be replicated to ensure that this level of accuracy is replicable with pugmark-set data from other tigers.

The availability of suitable substrate is a limiting factor for obtaining useful pugmark-sets. Thus, the method can be used only in those areas where the substrate is conducive for the registration of pugmarks, e.g. in tiger habitats of central and western India and not in tropical rainforests, *terai* floodplains or mangrove swamps. Even with our limited data, pugmarks registered in soil depths > 1 cm were likely to give imprecise results.

Population monitoring based on pugmarks has potential for monitoring other large carnivores including felids, canids and ursids. With intensive data-collection this method could also be used for studying the gross ranging pattern of individual tigers when more invasive and expensive technology such as radio-telemetry is not feasible. The method has been effectively demonstrated for obtaining sex-ratios in tiger populations (Sharma *et al.*, 2003) and can be further developed to provide information on stage-based population structure. The technique for individual identification based on pugmarks also has potential for identifying problem tigers and resolving conflicts.

The methodology for individual identification proposed in this paper uses the quantifiable information from hindfeet pugmarks and gait variables. Unique information could also be extracted from measurements of front feet pugmarks as also observed in mountain lions (Smallwood & Fitzhugh, 1993). Obtaining front feet pugmarks of tigers is not always possible as the hindfeet pugmarks overlap the impressions of the front feet, thereby obliterating them. It would also be possible to use non-quantifiable information in the form of various permanent idiosyncratic features such as seams and creases in the pad, irregular placement of toes, distinct shape of toes, etc., for individual identification. Amongst our dataset such irregularities were obvious in 11 out of 19 tigers. Such information, though not used in the current study, could be used in a logical framework to stratify pugmark-sets that should be compared statistically. Such an approach would probably increase the precision of individual identification by limiting comparisons between truly ambiguous pugmark-sets.

Monitoring of tiger populations from their pugmarks is cost-effective, non-invasive, rapid and a practical method in harmony with the traditional practice of the tiger *census* done by wildlife managers. Because of this, the method is likely to be acceptable and will fill an important void for an objective tiger population monitoring system in central and western India.

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