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Identifying individual mountain lions *Felis concolor* by their tracks: refinement of an innovative technique

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Abstract

This study refines a method reported by Smallwood and Fitzhugh (Smallwood, K.S., Fitzhugh, E.L., 1993. A rigorous technique for identifying individual mountain lions *Felis concolor* by their tracks. Biological Conservation 65, 51–59) that attempted to discriminate between individual mountain lions by certain measurements of their tracks in the field. During the months of January–March 1996, we followed 10 radio-collared mountain lions in the Sierra Nevada of California and obtained photographs of their tracks in the soil and snow under many different environmental conditions. Linear and area measurements were determined from track photographs and Fisher's discriminant analysis was used to differentiate between each track set. Unlike the Smallwood and Fitzhugh analysis, we were certain about the identity of most of the mountain lions that made tracks. Our results indicate that track sets had both correct and incorrect "groupings" and that these groupings were sensitive to the type of substrate in which a track set was found, the time of day it was photographed, and the number of tracks in a set. In general, it is important to minimize variation associated with substrate and time of day between track sets and to concentrate on sets that contain three or more tracks. This technique has potential application in wildlife conservation; however, the cautionary guidelines, developed in this paper, should be considered.

Keywords: Mountain lion; Tracking; Population estimation; Individual identification

1. Introduction

To determine the viability of large carnivore populations, basic demographic data are required. Enumerating population size depends on distinguishing among individual animals. Most large predators are sparsely distributed, cryptic, nocturnal or crepuscular, and often solitary (Seidensticker et al., 1973; Beier et al., 1995), making it difficult to count all individuals in a population simultaneously and making it necessary, therefore, to recognize individuals to distinguish them. Field and analytical methods are being developed to identify individuals by animal sign, such as tracks in soil or snow, which linger longer than the animals themselves.

Mountain lions *Felis concolor* usually occur at low densities, and radio-telemetry has been used to study their movement patterns and general ecology in California (Neal et al., 1987; Hopkins, 1989; Padley, 1990; Beier et al., 1995). These methods are labor intensive and costly and may result in small sample sizes that yield imprecise inferences about population-level patterns and processes (Smallwood and Schonewald, 1996). Given the amount of habitat that large carnivores utilize, dependable tracking methodologies have potential implications for inventorying and monitoring these animals over large geographical ranges at lower costs and with less effort than radio-telemetry techniques.

Despite the potential usefulness of tracking methodologies, objective and quantitative approaches to tracking have been slow to develop. Among large carnivores, tracking has been used to determine the sex of tigers *Panthera tigris* (Gore et al., 1993; Karanth, 1995) and to distinguish between individual tigers (Gore et al., 1993) and leopards *Panthera pardus* (Miththapala et al., 1989). Stander et al. (1997) reliably distinguished tracks within and among several African carnivore

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species, such as African lions *Panthera leo*, leopards and cheetahs *Acinonyx jubatus*. Smallwood and Fitzhugh (1993) developed a quantitative approach to track identification by using multi-group discriminant analysis to separate track sets from different mountain lions. These authors collected multiple track measurements from individual mountain lions and attempted to discriminate among the animals based on a distribution of measurement values. Using tracings (found on dusty, dirt roads) of two to six tracks from each rear foot of nine mountain lions from three regions of California, the multi-group discriminant analysis correctly assigned to each track set 100 and 94% of the tracks from the left and right rear feet, respectively. Smallwood and Fitzhugh (1993) assumed that tracks collected in geographically distinct regions were made by different mountain lions and based their statistical analysis on that assumption.

Whether or not this approach can distinguish tracks from an unknown number of individuals occupying the same geographical area is uncertain. Therefore, we analyzed mountain lion tracks from a population of free ranging, radio-collared individuals in order to address four primary questions: (1) Are tracks from the same mountain lion, made at different locations under a variety of environmental conditions, identifiable as being from the same animal? (2) Are tracks from different mountain lions, made under similar environmental conditions, identifiable as being from different animals? (3) Are tracks from the same track set, taken over time during different times of day and under variable cloud cover, identifiable as being from a single mountain lion? (4) How does the age of track sets affect statistical discrimination?

2. Study area

Our study area was located in Round Valley (118°35′ W, 37°25′ N), immediately east of the Sierra Nevada, in Inyo and Mono counties, CA. Round Valley, encompassing c. 250 km^2, is an important wintering area for a population of mule deer *Odocoileus hemionus* that migrates to the west slope of the Sierra Nevada during spring, and returns to this winter range in late autumn each year (Kucera, 1988). Vegetation is typical of that occurring in the Great Basin of western North America, and dominant shrub species include bitterbrush *Purshia* spp., blackbrush *Coleogyne ramosissima*, Ephedra *Ephedra* spp., and desert peach *Prunus andersonii*. Stringers of riparian vegetation, consisting largely of water birch *Betula occidentalis*, willow *Salix* spp., and wild rose *Rosa* spp. occur along several streams that flow through the study area. Vegetation in Round Valley occurs largely on alluvial fans of Ulymeyer gravelly loamy coarse sand. A network of dirt roads traverses Round Valley, which facilitates access throughout the study area.

Round Valley is inhabited by a population of mountain lions that prey primarily on mule deer (Pierce and Bleich, 1995). As part of an intensive investigation of the effects of mountain lion predation on the population dynamics of mule deer wintering in Round Valley, nearly every mountain lion that has occurred there since 1991 has been captured and radio-collared (Davis et al., 1996; Pierce et al., 1998).

3. Methods

3.1. Recording tracks

During January–March 1994, 10 radio-collared adults used the study area. Our sampling unit was a track set, defined as a group of four or more tracks from any foot made by the same mountain lion at one particular point in time. We used a 35 mm camera on a tripod and color slide film (ASA 100) to photograph tracks and placed a scale next to each track as a standard for measuring. In all cases, the photographer was accompanied by an individual who used telemetry equipment to confirm the identity of the radio-collared mountain lion responsible for each track set. The identity of each mountain lion was, however, not revealed to the primary author until data analyses were completed. Thus, a double-blind experimental design was employed.

Tracks were photographed: (1) in a variety of substrates, including snow and several types of soil from sandy loam to clay, with different amounts of soil moisture; (2) in different terrain: only tracks on slopes $<35\%$ were photographed because tracks on steeper slopes generally lacked clear borders; and, (3) during different times of day and under variable cloud cover. We used filters, flashes, and umbrellas to enhance or diminish the natural light and to test whether these media could be used interchangeably. In addition, the same track sets were photographed from fresh (several hours) to 1 week old in order to determine when the statistical discrimination declined.

We studied 12 track sets, nine sets from three different individuals and three sets whose identity was uncertain because they came from two mountain lions that were in close proximity to each other.

3.2. Track measurements

We obtained three linear and one angle measurements from each track photo, as used by Smallwood and Fitzhugh (1993), and five area measurements, consisting of each toe and heel pad (Fig. 1) to increase the level of discrimination by adding non-linear parameters.

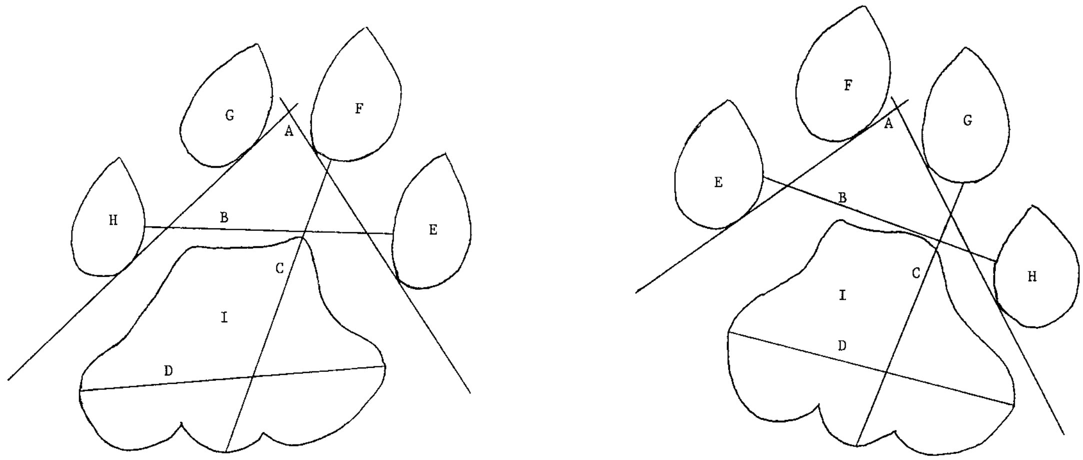

Fig. 1. Track set measurements of mountain lions. (A) angle between toes; (B) outer toes spread; (C) heel to lead toe length; (D) heel width; (E) area of inner toe; (F) area of second toe; (G) area of third toe; (H) area of outer toe; (I) area of heel pad.

Each photograph of a track was scanned into a computer and the level of contrast, clarity, and color was manipulated with a software program (Adobe Photoshop). A second software program (Aldus Freehand) outlined areas of the track that were not clear. We then digitized each track using ArcInfo (Environmental Systems Research Institute, Redlands, CA) to make an outline of all toes and each heel pad and computed appropriate measurements of each track using ArcInfo. In contrast, all manual measurements (linear, area, and angle) were made by placing photographs in a slide projector and tracing their images onto paper. We analyzed computer-generated measurements and manual measurements separately. We combined tracks photographed in most ecological conditions (excluding snow vs soil tracks) because our data set was not large enough to allow separate analysis for each type of condition (Table 1).

3.3. Statistical methods

We used multi-variate analysis of variance (MANOVA) to compare linear, area, and angle measurements from left and right rear tracks from each track set in order to determine if tracks from left and right rear feet could be combined for analysis. We used Fisher's method for discriminating among several populations (Johnson and Wichern, 1988) to analyze the track data. Eigenvalues, which correspond to each discriminant function, describe how much of the total between-group variability is explained by each discriminant function. The radius of the 95% confidence ellipsoid for a track set is comprised of the square root of the ratio $\chi^2(2, 0.05)/n$, where a value of 5.991 is the upper 5% point of the chi-square distribution with 2 degrees of freedom and n is the number of tracks in the track set. The larger the number of tracks in a track set, the smaller the radius of the confidence ellipsoid. Hence, the probability of the results being "real" is increased because confidence ellipsoids will intersect less.

Unlike multi-group discriminant analysis, Fisher's method does not require that the number of mountain lions be estimated and the data grouped before the analysis is begun, therefore, our data were grouped by track set and not by individual mountain lions. Fisher's method does not attempt to classify data into fixed

Table 1
Ecological variables associated with each mountain lion track set obtained in Round Valley, CA, January–April 1994

Track set[a]	Substrate	Slope	Time	Cloud cover
1 (7)	Dry soil with dust	Flat	09:20	Sun
3 (12)	Dry soil with dust	Flat	12:30	Sun
4 (7)	Sandy	Flat	11:15	Sun
5 (16)	Dry soil without dust	Flat	15:30	Sun
9 (9)	Snow and wet soil/mud	Uphill 30%	14:15	Sun, part cloud
12 (7)	Dry soil with dust	Uphill 15%	15:15	Sun, part cloud
13 (4)	Wet soil and melted snow	Flat–downhill 30%	10:30	Snow, clouds
14 (8)	Pebbly soil, sandy	Flat–uphill 35%	07:30	Sun, part cloud
16 (5)	Pebbly soil, sandy	Flat	11:40	Sun

[a] Sample size of each track set in parentheses.

groups of mountain lions. Rather, it associates track sets with one another, using confidence intervals or ellipsoids (Appendix). Tracks from a single mountain lion should group together in discriminant space regardless of when they were collected or on what substrate they were found (i.e. ellipsoids should intersect). Tracks from different mountain lions should group in different parts of discriminant space. An analysis with correct groupings requires both to be true.

4. Results

The sample size in this study was small: nine track sets comprised the final analysis with 4–16 tracks per track set. MANOVA indicated that linear, area, and angle measurements, from the left and right rear tracks of the same mountain lion, were not statistically different (Wilk's test statistic = 0.93109, d.f. = 10, 81, $p = 0.810$). Thus, we combined left and right rear tracks to increase the level of statistical power. All front tracks were deleted from the analysis because the amount of data collected on front tracks was meager; mountain lions frequently walk over their front tracks with their rear feet. We also combined tracks photographed in most ecological conditions (excluding snow vs soil tracks) because our data set was not large enough to allow separate analyses for each ecological condition (Table 1).

Table 2 lists r^2 values for single-factor analysis of variance. These values represent a unit free measure of variation associated with each track measurement. The greater the r^2 value (adjusted r^2 values take degrees of freedom into account), the better the measurement discriminates between track sets. For our analyses, area measurements (excluding heel pad) appeared to be the most useful variables because they varied the most between groups. Heel width and area of heel pad, in contrast, showed the least variability between groups, and were therefore less useful for discrimination.

The correlations between manual and computer-based area measurements, with respect to the interpretation of track set groupings, were strong ($r = 0.807$, 0.911, 0.889, 0.928, 0.949 for heel pad area and area for each of the four toes, respectively) and suggested that manual and computer measurements could be substituted for one another. Therefore, we used manual measurements in our analysis.

Table 2
r^2 values and adjusted r^2 values for mountain lion track data

Track measurement	r^2 values	r^2-adjusted values
Angle	0.34	0.23
Heel to lead toe length	0.34	0.23
Heel width	0.26	0.14
Outer toes spread	0.47	0.39
Area of heel pad	0.27	0.16
Area of inner toe	0.59	0.52
Area of second toe	0.57	0.50
Area of third toe	0.54	0.47
Area of outer toe	0.66	0.61

In general, two patterns emerged from our analysis: track sets that had correct groupings and those that had incorrect groupings. The data are presented as a collection of group centroids with 95% confidence ellipsoids around the center of each group centroid (Fig. 2). Each confidence ellipsoid has been coded with a unique pattern, which corresponds to a particular mountain lion. Ellipsoids that intersect suggested that the measurements of track sets are statistically indistinguishable. Ellipsoids that did not intersect suggested that track sets are made by different mountain lions. Sample sizes for each ellipsoid varied from 4 to 16 tracks (Table 1).

Fig. 2 shows track sets made by three mountain lions. Track sets TS14 and TS9 had intersecting ellipsoids, suggesting that these track sets are statistically indistinguishable. These track sets were, in fact, made by one mountain lion. The same comment applies to track sets TS1, TS3, TS4, TS5, TS13, and TS16 which were made by a second mountain lion; they are grouped together, indicating that they are statistically indistinguishable from one other. In contrast, track set TS12 was made by a third individual but overlaps the group of track sets made by the second. In this case, two separate mountain lions would be counted as the same mountain lion. Our analysis indicates that the group of track sets in Fig. 2 were made by two mountain lions when they were actually made by three mountain lions.

One track set was monitored over time to determine when discrimination declined (Fig. 3). Each ellipsoid (TS2, TS7, and TS6) has a different number to distinguish between the day and time the tracks from this one track set were photographed. TS6 did not overlap the other two sets taken a few days earlier and a few days later, suggesting that two different mountain lions were responsible when, in fact, they were made by a single animal.

Increasing the amount of discriminant functions from two to three (or four) with 95% confidence ellipsoids enhanced our ability to distinguish between mountain lions (Table 3). In our analysis, the eigenvalues corresponding to the first four discriminants are 15.26, 9.54, 5.21, and 1.40, respectively; the sum of all nine eigenvalues is 32.88. Hence, the first two discriminants explain 75% of the total variability between groups, the first three explain about 91%, and the first four explain about 96%. This finding suggested that a three-dimensional graph with the first three discriminants would be preferable to a two-dimensional one. However, it seems that there may not be much gained with the addition of a fourth dimension. Values of zero, or close to zero in Table 3, suggest that two track sets intersect. Each track

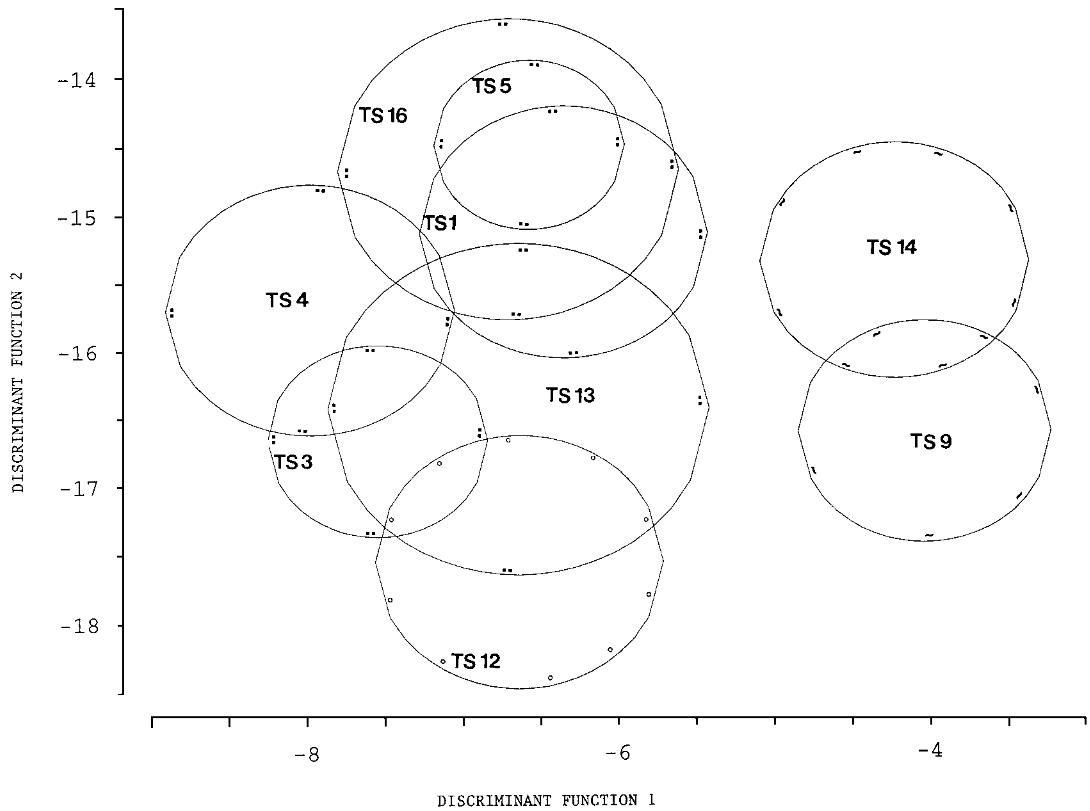

Fig. 2. Nine rear track sets of mountain lions shown as ellipsoids in discriminant space. Symbols within each ellipsoid denote three different individuals. Intersecting ellipsoids indicate track sets that are statistically indistinguishable.

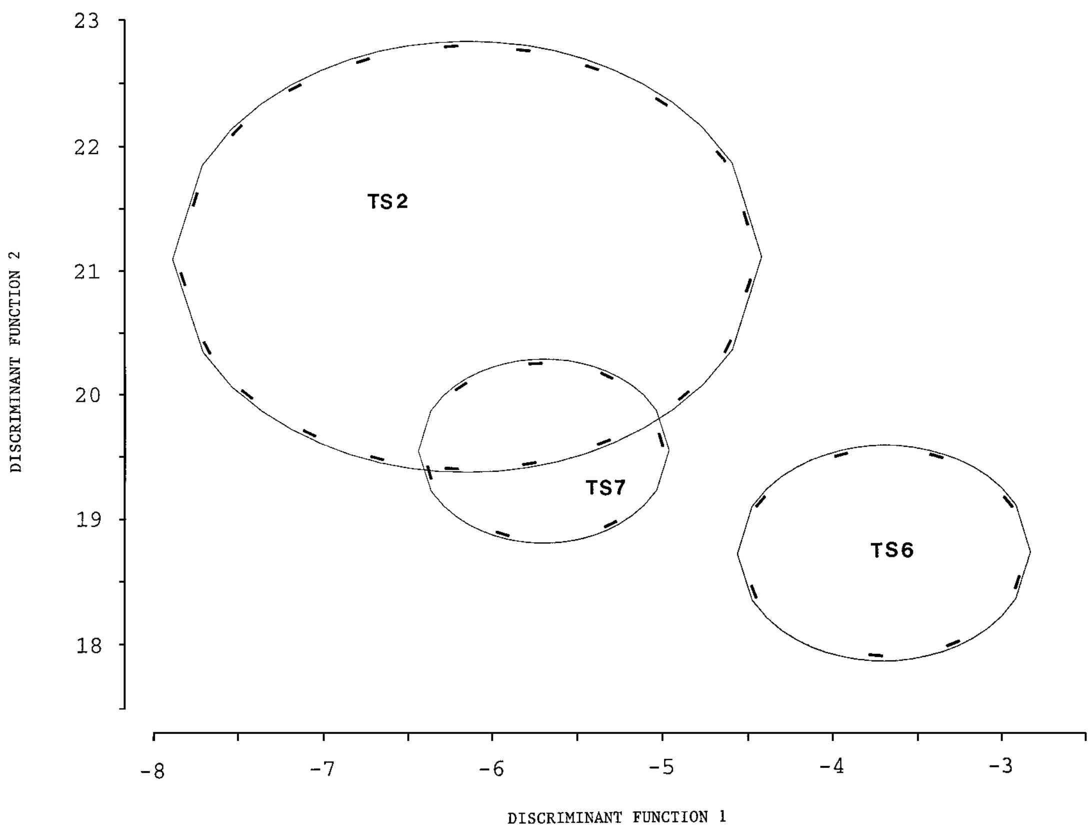

Fig. 3. Discriminant space of one track set photographed during different times of the day on three separate days. Track set 2 (TS2) is fresh, i.e. several hours old, taken at 0730; track set 6 (TS6) is several days old taken at 1730; and track set 7 (TS7) is 1 week old at 0730.

Table 3
Pairwise comparisons between track sets based on three discriminant functions with 95% confidence ellipsoids

Track set	1	3	4	5	9	12	13	14	16
1	0	0.92	0.38	0	1.6	0.84	0.15	0.63	0
3	0.92	0	0	1.2	2.2	0.11	1.3	2.4	0.85
4	0.38	0	0	0.50	2.6	0.73	1.1	2.2	0.49
5	0	1.2	0.50	0	2.1	1.7	1.6	1.3	0
9	1.6	2.2	2.6	2.1	0	1.5	2.3	0.51	1.8
12	0.84	0.11	0.73	1.7	1.5	0	0.40	1.7	1.3
13	0.15	1.3	1.1	1.6	2.3	0.40	0	1.4	1.1
14	0.63	2.4	2.2	1.3	0.51	1.7	1.4	0	1.4
16	0	0.85	0.49	0	1.8	1.3	1.1	1.4	0

set intersects with itself (value = 0) and may intersect with other track sets which would either belong to the same or different mountain lion. When compared to our 2-dimensional analysis, this 3- dimensional analysis indicates less intersection between track sets made by the *same* mountain lion because of increased discrimination.

5. Discussion

Fisher's method for discriminating among several populations does not offer complete reliability due, in part, to: (1) variability of substrates that tracks are found in; (2) photographing tracks during different times of day; (3) plotting track data in only two dimensions; and (4) measurement error.

Certain conditions will improve our ability to discriminate between individuals. Various substrates, such as fine soils, clays or soils with top layers of dust, enhance track borders and make measurements easier to obtain. Other soils, such as pebbly, sandy soils do not offer such clear border definition; hence, measurements are less accurate. Fresh snow is a good substrate but often melts quickly, distorting the size and shape of tracks. While certain substrates are better for tracking, the identification of individuals would be less reliable when different substrates are compared. For example, snow tracks should not be combined with soil tracks in the statistical analyses as tracks in clay and sand. In addition, it is important to consider time of day when photographing track sets, because different light conditions can alter shadows on the track. In a photograph, these shadows distort the appearance of the track by either enlarging or diminishing the metrics of a track, leading to potential errors. It appears that time of day may add more variability to track measurements than age of track set (Fig. 3).

The track set data consisted of two linear combinations plotted against one another. The first and second discriminant scores had the strongest ability to discriminate between track sets. Adding discriminant functions to the analysis decreased the level of intersection over all of the track sets, even those belonging to the same mountain lion. Thus, tracks made from the same mountain lion at different locations or from the same track set photographed during different days and different times of day would be expected to intersect less.

The use of photo-enhancement programs was unproductive because the majority of tracks did not benefit from enhancement. In addition, it was difficult for the computer to separate the areas of soil or snow that comprised the track from those that did not. Although photo-enhancement did not improve track quality, it did facilitate exporting the tracks into ArcInfo GIS. The use of ArcInfo GIS to make track measurements is time-consuming, but offers greater potential for recording measurements that might not be possible to make by hand, such as area center points. For the measurements made during this study, however, the increased accuracy of computer-generated measurements was not great enough to improve the track set groupings developed in the statistical analysis. Because of this, investigators without access to specialized computer software would still be able to perform the analysis effectively.

6. Conclusions

Indirect ways of enumerating populations of large carnivores, such as we describe here, have potential application in wildlife conservation, particularly in developing countries. Although our method was not expensive and could be implemented by an individual working alone, acquisition of sample sizes adequate to yield analyses with high discriminatory power was problematic. Investigators planning to use this technique are cautioned to obtain large (preferably >5) numbers of tracks per track set, preferably on similar substrates. Because manual and electronic methods lead to identical groupings, manual measurements are acceptable for use by investigators lacking sophisticated spatial analysis software. The method requires only a camera and accessory equipment. If investigators obtain adequate samples on appropriate substrates, this technique may be of value to researchers attempting to enumerate mountain lions at a landscape-level during a limited period of time.

Occasionally trackers and researchers need to measure tracks in the field manually . For example, trackers often attempt to make quick decisions about the identity of a particular mountain lion, based on a paw print in the soil or snow. Certain track measurements when analyzed in a univariate context, have greater power to discriminate between individual mountain lions (Table 2). Measurements such as heel width, a variable commonly used by mountain lion trackers to identify a particular animal, appear to have little discriminatory value compared to the area of each toe and outer toe spread and hence, should be used with great caution (Fig. 1).

The application of this technique to species in other parts of the world can be used to address research questions of a general nature, such as how many individuals are in an area, or presence and absence data, where funds are limited and large areas need to be surveyed under a limited amount of time. Future studies will allow investigators to evaluate how well this technique works across species, such as mountain lions, snow leopards, jaguars, sloth bears, giant pandas, and other rare species. Developing track transects (e.g. Smallwood, 1994) that are regularly inventoried and properly distributed may provide a viable method of monitoring these uncommon species over time.

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Appendix
Description of statistical technique, Fisher's Discriminant Analysis, used for this study

Fisher's approach has several advantages for separating populations for visual inspection or graphical descriptive purposes (Johnson and Wichern, 1988). Suppose that there are k track sets with n_i tracks for the ith track set, $i=1,...,k$. Assume that $\mathbf{X}_{ij}$ is the vector of linear and area measurements for the jth track in the ith track set. Set:

$$\bar{X}_i = \frac{1}{n_i}\sum_{j=1}^{n_i} X_{ij},\ \ \bar{X} = \frac{1}{n_i}\sum_{i=1}^{k}\sum_{j=1}^{n_i} X_{ij}$$

where $n=n_1+...+n_k$ is the total number of observed tracks. The between group and within group sum of products (SSP) are defined by:

$$B = \sum_{i=1}^{k} n_i(\bar{X}_i - \bar{X})(\bar{X}_i - \bar{X})^t = \text{between group SSP}$$

$$W = \sum_{i=1}^{k}\sum_{j=1}^{n_i}(X_{ij} - \bar{X}_i)(X_{ij} - \bar{X}_i)^t = \text{within group SSP}$$

Let: $\hat{\lambda}_1 \geqslant \hat{\lambda}_2 \geqslant ...$ be the eigenvalues of WB^{-1} with the corresponding eigenvectors $\hat{\boldsymbol{e}}_1, \hat{\boldsymbol{e}}_2$... The eigenvectors are rescaled so that $\hat{\boldsymbol{e}}_i^t\ S\ \hat{\boldsymbol{e}}_i = 1$, where:

$$S = \left[\frac{1}{n-k}\right]W$$

and $\hat{\boldsymbol{e}}_1^t\boldsymbol{x}$ is the first discriminant, $\hat{\boldsymbol{e}}_2^t\boldsymbol{x}$ is the second discriminant etc.

If μ_1, μ_2 etc. are the true mean vector of linear and area measurements for track-sets 1, 2, etc., then it can be shown that for each track set j:

$$\sqrt{n_i}(\hat{\boldsymbol{e}}_t\boldsymbol{x}_j - \hat{\boldsymbol{e}}_i^t\boldsymbol{u}_j),\quad i = 1, ..., k$$

are approximately independent N (0,1) variables. We plotted the first discriminant against the second discriminant for the sample track set means along with 95% confidence ellipsoids. In this graphical representation, each track set is represented by a point (centers of the ellipse) in a plane and if two track sets are from two different mountain lions, the points representing them in the graph should be far apart. The 95% confidence ellipsoids are sensitive to the number of tracks per track set and become considerably smaller (in width and height) when additional tracks are added to the analysis.

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