Estimation of adult male Asian elephants (*Elephas maximus indicus*) population size in Nagarahole-Bandipur National Parks using capture-recapture methods

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Declaration

I declare that the thesis entitled "Estimation of adult male Asian elephant (*Elephas maximus indicus*) population size in Nagarahole-Bandipur National Parks using capture-recapture methods" comprises research work done by me under the guidance of Dr. M.D. Madhusudan and co-guidance of Dr. K. Ullas Karanth and Mr. N. Samba Kumar. The work is original and has not been done earlier by anyone else. Part of this work, which is related to or similar to work done by other researchers, has been referred to in this thesis at appropriate places. The results presented in this thesis have not been submitted previously to this or any other University for an M.Sc. or any other degree.

Signature of the Guide
(Dr. M.D. Madhusudan)

Signature of the Candidate
(Varun Rshav Goswami)

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Certificate

I declare that this thesis entitled "Estimation of adult male Asian elephant (*Elephas maximus indicus*) population size in Nagarahole-Bandipur National Parks using capture-recapture methods" comprises research work carried out by Varun Rshav Goswami at the Centre for Wildlife Studies under my guidance and the co-guidance of Dr. K. Ullas Karanth and Mr. N. Samba Kumar during the period 2005-2006 for the Degree of Master of Science in Wildlife Biology & Conservation of the Manipal Academy of Higher Education (MAHE). The results presented in this thesis have not been submitted previously to this or any other University for M.Sc. or any other degree.

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SUMMARY

Robust estimates of population size as well as associated demographic parameters like movement and survival rates are important from a conservation perspective of the threatened sex of Asian elephants, the adult male. Such estimates can play a pivotal role in understanding population dynamics and long term monitoring of populations, the survival of which are threatened by ivory poaching and habitat degradation.

Individual identification has been recognized as an important component in counting and monitoring threatened populations. The application of these to elephant biology could potentially open up many avenues of research including estimating population size and demographic parameters reliably. Given that it is possible to identify individual elephants from variations in tusk, ear and tail patterns, the appropriateness of photographic-capture-recapture to estimate adult male abundances was tested. Models associated with this technique allow reliable estimation of many of the parameters of interest and could therefore be the answer to understanding populations of a long-lived, wide ranging animal such as the Asian elephant.

The study was conducted in Nagarahole National Park and Bandipur Tiger Reserve from February to May, 2006. During this period, photo-identification data of adult male elephants were collected and these were used to estimate abundance. Additionally, proportions of age-sex categories obtained from group composition data were used in combination with the adult male abundance estimates to obtain estimates of total elephant population size.

The adult male population size was estimated to be 134 ± 14.20 (SE) and total elephant abundance 991 ± 32.75 for a sampled area of 176 km^2. The adult sex ratio was found to be 1 male to 4.33 females. The results suggest that photographic capture-recapture techniques are appropriate to reliably estimate abundance of adult males and could potentially be used to estimate other demographic parameters of interest. Moreover, both the population estimates and the adult sex ratio suggest that this population of elephants in Nagarahole and Bandipur has the potential to remain, as has been already recognized earlier, a strong hold for Asian elephants over the long run. Thus appropriate conservation support needs to be provided to maintain it in this state.

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CONTENTS

INTRODUCTION

Adult male Asian elephants differing from females by exhibiting large home ranges (Williams 2002), moving long distances in search for possible mates and potentially connecting different populations also suffer higher death rates (Sukumar 2003). Amongst other factors, poaching for ivory which, is one of the two major threats to the species (Sukumar 2003; Blake and Hedges 2004) is a major cause for such a trend. Assessment of the impact of ivory poaching can only be initiated when robust estimates of population size are available for a region (Walsh & White 1999). From a conservation perspective, it is thus critical that reliable estimates of population size and demographic parameters like movement and survival rates are available. Combining these estimates could facilitate a long-term monitoring program to assess population trends.

Individual identification has been recognized as an important component in counting and monitoring threatened populations (McGregor & Peake 1998). In addition to population estimation individual identification could potentially play an important role in estimating vital rates like movement and survival, and trace carcasses of poached animals to a photographic archive of adult males. In doing so, individual identification would provide an easier and cheaper option to answering many questions that can currently be answer only through methods like radio-telemetry.

A workable method needs be designed to allow identification and subsequent estimation of the population size of adult bulls. Against this background, capture-recapture techniques that are proven to be powerful tools in analyzing and estimating various demographic parameters and have over the years undergone great development and refinement (Williams et al. 2002), were selected to achieve the aim of this study. Adult male elephants can be identified by looking at their tusk patterns which can be supplemented by variations in the ears, tail and bodily scars (Douglas-Hamilton 1975, Moss 1996, Moss 2001, Sukumar 1989, Desai pers comm., Maisels pers comm.).These characters were used in the form of a combinatorial key, which in combination with clear photographs allowed unambiguous identification of adult male elephants.

Identities generated by a supervised method of classification were used to estimate the abundance of adult bulls under a capture-recapture framework. In addition, group composition data were collected and age-sex proportions of elephants from these data were used in conjunction with abundance estimates of adult males to estimate total population size. The final objective was to estimate density using the abundance estimates. These density estimates were then compared to density estimates from line transect data from the same area.

The thesis is comprised of two independent research papers. The first involves developing a protocol for reliable identification of adult male elephants from field data, and is titled:

Use of photographs and a combinatorial key for individual identification of adult male Asian elephants (*Elephas maximus)* in Nagarahole-Bandipur National Parks

This follows the format of the journal *Animal Conservation.*

The second paper involves estimating abundance of adult bulls using the photo-identification data and subsequently, total population size using this estimate and age-sex proportions. It is titled:

Estimation of adult male Asian elephant (*Elephas maximus indicus)* population size in Nagarahole-Bandipur National Park using capture-recapture methods

This follows the journal format of *Journal of Applied Ecology*

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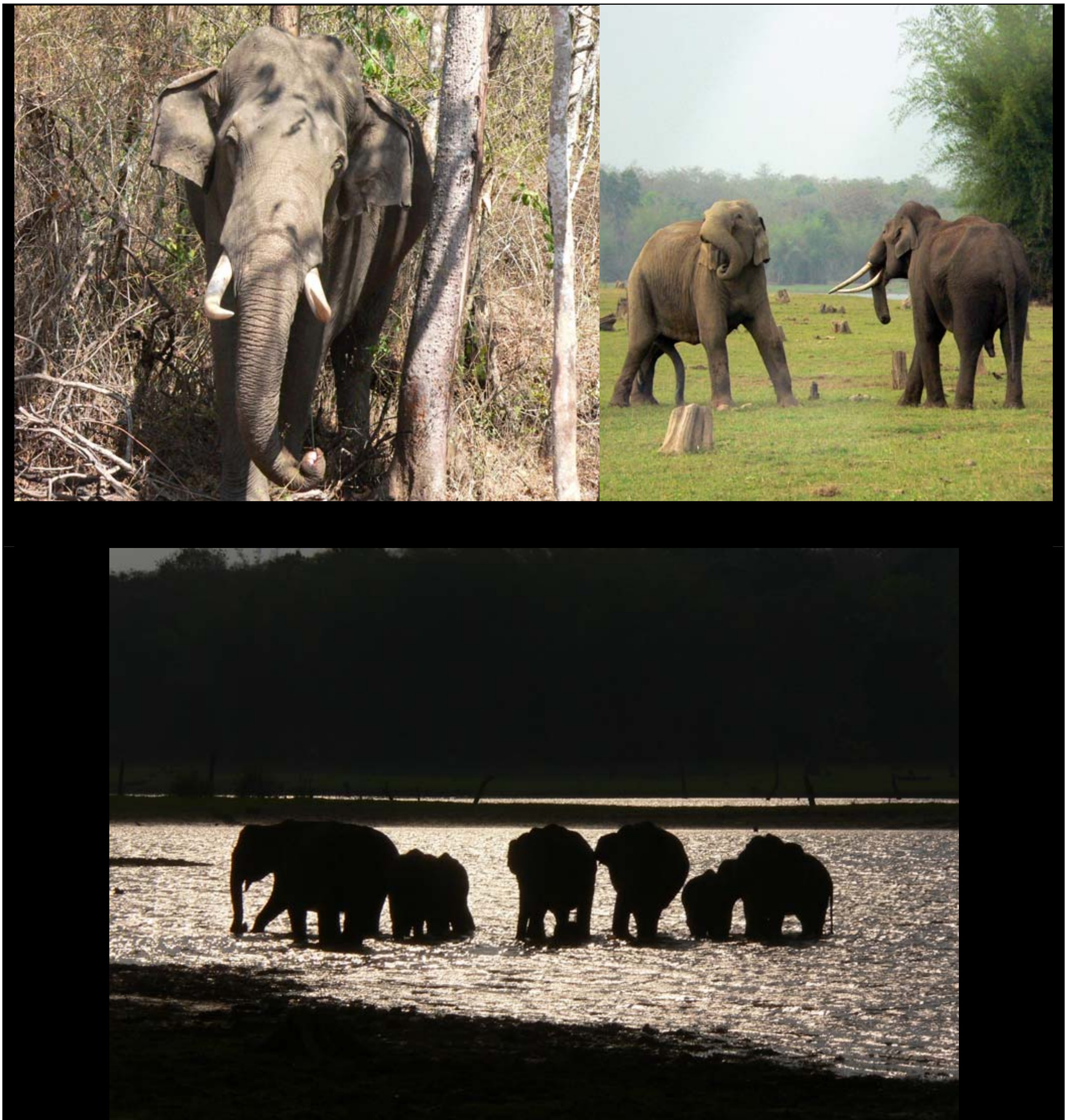
The Study Animal…



Use of photographs and a combinatorial key for individual identification of adult male Asian elephants (*Elephas maximus)* in Nagarahole-Bandipur National Parks

Abstract

Identification of individuals in free-ranging populations of wild species makes it possible to understand their ecology and behavior in powerful ways that can also assist in their conservation. For the threatened Asian elephant, although individuals have been identified using a combination of morphological characters ranging from variations in tusk, ear and tail patterns to differences in height and age, there are no clear protocols by which this can be done, nor are there assessments of the efficacy of identification methods. The aim of this study was to address this gap which, was achieved by taking clear photographs of adult bulls supported by field descriptions in the form of a combinatorial key and sketches using a template. These characters were entered into a database and when used in conjunction with photographs in a supervised manner gave distinct identities. The number of sightings recorded was 135 and these yielded 78 distinct individuals on the basis of 62 variables. Attempts were made to confirm these subjective identifications using more objective methods based on similarity measures. Hierarchical cluster analysis was selected for unsupervised classification and it resulted in clustering similar animals in a manner that allowed 70 distinct individuals to be identified from the clusters. This was fairly consistent with the supervised method that yielded 68 individuals for the same subset of the data. This field trial has established that it is possible to integrate such individual identity exercises with systematic sampling frameworks, to obtain not only information on population ecology and demography, but could also help in determining movement rates, all of which hold direct relevance to conservation.

Keywords: category; character; classification; hierarchical clustering; sightings

Introduction

Individual identification of elusive, rare and endangered animals is important to address vital issues related to the ecology, behavior, and conservation of the species. From counting and monitoring threatened populations, or ascertaining life history patterns, to understanding differences between animals within a population in terms of behavioral strategies, reproductive success and differential habitat use (McGregor & Peake, 1998), ascertaining identities play an important role in conservation biology. Differences between individual animals can be so great that often it becomes difficult to assume that the conservation value of individuals in a population are equal; on the contrary individuals should be considered different from a conservation perspective unless proven otherwise (McGregor & Peake, 1998).

Identification in the field can be done by either artificially marking animals or by recognizing individuals from natural markings (Terry & McGregor, 2002). Artificial marking can be done using many different methods and these have been applied to a whole host of different taxa. These include the use of genetic markers to track marine turtles (Bowen, 1995); toe nail clipping of birds (St.Louis, Barlow, & Sweerts, 1989); satellite tagging (Lutcavage et al., 1999) of fish; and the use of fur dyes to mark small mammals (Blumstein et al., 2004). The use of natural markings to distinguish between individuals has also been varied in the type of marking used and the taxa studied. Amongst others the use of such markings have been used for the identification of chimpanzees from facial characteristics (van Lawick Goodall, 1971); African wild dogs from coat markings (Creel & Creel, 1995); tigers from strip patterns (Karanth, 1995; Karanth & Nichols, 1998) and from pugmarks (Riordan, 1998; Sharma, Jhala,

& Sawarkar, 2005); mountain lions (Smallwood & Fitzhugh, 1993) and black rhinos (Jewell, Alibhai, & Law, 2001) from their tracks; acoustic signals of corncrakes (Terry & McGregor, 2002) European bee-eaters (Lessells, Rowe, & McGregor, 1995), and Amazonian manatees (Sousa-Lima, Paglia, & Da Fonseca, 2002); Apennine brown bear with the help of DNA from hair samples (Lorenzini et al., 2004); and the use of pattern recognition software to identify cheetahs (Kelly, 2001) and whale sharks (Arzoumanian, Holmberg, & Norman, 2005) from spot patterns.

A charismatic large mammal of tropical Asia, the Asian elephant is increasingly being threatened by anthropogenic pressures. With home ranges larger than 400 km^2 (Williams, 2002), this wide ranging animal known to use traditional migratory routes, is greatly threatened both by the loss and degradation of its habitat (Blake & Hedges, 2004; Sukumar, 2003). Ivory poaching, too, is a serious threat to this species, However, unlike African elephants, only the male Asian elephant has tusks and are selectively targeted by ivory poachers (Blake & Hedges, 2004; Sukumar, 2003).

Elephants are known to have fluid social systems with high levels of complexity in acoustic communication, social interactions, behavior and associations between individuals within or across herds (McComb et al., 2000; McComb et al., 2001; McComb et al., 2003; Poole et al., 1988). Understanding of such behavioral aspects including relationships and associations amongst individuals, and individual specific acoustic and visual signals need the identification of individual elephants. In addition, exploring issues like the patterns of occurrence of musth and relation of secondary sexual characters to health status can also be bolstered by individual identification. From an ecological perspective, identifying individual elephants is important to understand and monitor demography using fluxes in population sizes and adult sex ratios, and recruitment, survival and mortality rates as indicators (Moss, 1996).

Movement and habitat utilization patterns can show temporal and spatial variations and the identification of solitary individuals as well as complete herds are essential to understand the dynamics of these patterns (Sukumar, 1989).

Elephants can be identified by variations in the ears, tail and body scars and in the case of adult males these features are supplemented by using tusk shape and size as additional distinguishing features (Douglas-Hamilton, 1975; Moss, 1996; Moss, 2001; Sukumar, 1989). Though individual identification of elephants has been carried out fairly extensively in Africa to monitor populations over a long term (Douglas-Hamilton, 1975; Moss, 1996; Moss, 2001), similar rigorous field protocols to individually identify Asian elephants do not exist in a formal manner. Keeping in mind the threat faced by adult male Asian elephants due to selective poaching pressures, it is essential that such protocols be developed for reliable field identification of male Asian elephants. When combined with the sampling frameworks of capture-recapture (Otis et al., 1978), individual identification of the Asian elephants through photo-documentation could also be extended to derive robust estimates of tusker numbers. More practically, such photo-documentation could also allow the tracing of a poached animal to a known identity, and over long time-frames allow the estimation of poaching related mortality rates in males. Thus, reliable individual identification has the potential to be an important and essential component of elephant monitoring programs. Moreover, movement patterns of known individuals could provide an insight on potential areas that could be ear-marked as elephant corridors or reserves.

Authors, who recognize the potential for individual identification, rarely do this systematically. Part of the reason is that the process of identification is often very highly subjective and dependent heavily on field skills of the researcher. While this is certainly important, there is also need to identify the morphological features on which data need to be collected and to establish unambiguous protocols of using these data to identify individuals in a way that reduces subjectivity.

The concept of similarity between and within sites in terms of species composition or abundance is inherent to many methods of analyses that try to explain biological communities. Multivariate techniques of such analyses are based on similarity coefficients calculated between a pair of samples which can be used to facilitate classification or clustering of mutually similar groups such that distance between such pairs reflect their relative dissimilarity of species composition (Clarke & Warwick, 1994). Hierarchical cluster analysis is one such technique that allow the segregation of data into similar clusters and prove to be a particularly appropriate representation in cases where the samples are expected to divide into well-defined groups (Clarke & Warwick, 1994).

The main objective of this study was to develop and perfect rigorous field protocols to allow reliable photo-identification of individual adult male Asian elephants. This was done by taking clear photographs of adult bulls and these were used in conjunction with a combinatorial key of distinguishing features to establish identities. This supervised method of comparing photographs and characteristics entered in a database was used to confirm identities. Hierarchichal cluster analysis was used to evaluate the supervised system of classification.

Materials and methods

Study area

Nagarahole National Park and Bandipur Tiger Reserve are a part of the Niligiri Biosphere Reserve and also a part of the Nilgiri-Eastern Ghats Elephant Reserve under the Government's Project Elephant. This contiguous stretch of forest separated by the Kabini reservoir is known to support the densest congregation of Asian elephants anywhere in the world with density estimates ranging from about 1.9 elephants per sq. km (Karanth & Sunquist, 1992) to about 3 elephants per sq. km. (Madhusudan & Karanth, 2002). Vegetation cover can be quite thick in some areas and observing or photographing elephants is not always easy. At the same time, the period from March to the beginning of May coincides with peak elephant activity near the Kabini reservoir where they congregate in large numbers. As a result animals can be approached quite close thereby facilitating photography and making clear observations of various characters. In addition, the extensive road networks and the high density of water holes also help in encountering a large number of elephants across the study area.

Field methods

A suite of different characters have been used albeit anecdotally in previous studies to identify elephants. Moss (1996; 2001) for instance, used notches, tears, bumps, holes and vein patterns on the ears, and by tusk and body configuration. Additionally, scars and deformities were also used. Young calves were identified by associating with known mothers. Douglas-Hamilton (1975) and Sukumar (1989) used similar features as described above in addition to degree of fold in the upper ear. In addition to these characters, other researchers have used variations in tail length and brush type (Desai pers comm..; Maisels pers comm…). Most features used by these elephant biologists were incorporated as classification features. Venation in the ear was not used even though its considered equivalent to finger prints in humans (Moss, 1996) primarily because noting differences in venation for Asian elephants found in denser forests and with smaller ears would have been difficult. However, in addition to the features mentioned, shape of the ear lobe which could be defined as either “L”, “U” or “V” can be useful to differentiate individuals (Desai pers comm..) and was thus used.

To fulfill the objectives of the study, clear photographs of adult males were required to allow unambiguous identification of individuals. This was achieved with the help of a Panasonic FZ20 5.0 mega pixel digital camera with 12X zoom. Maximization of the probability of elephant encounters was achieved by driving along roads and sitting next to waterholes in a systematic fashion. Whenever an adult bull was encountered photographs of the following types were taken to the extent possible - (a) a frontal shot of the tusks (with the head down - when the animal is not alarmed); (b) a side body or profile shot for both flanks to ascertain tusk angle, tail length, that helped in identifying the body structure; (c) a clear side shot of both ears or, a frontal shot of the ears when the animal is alarmed and holding its ears out in a threat gesture; (d) a close-up shot of the tail to recognize the brush type. These photographs were accompanied by making schematic diagrams using a template and complemented by filling up a combinatorial key containing all features used to establish identities (Table 1). A pair of 8x40 binoculars aided this exercise. Every sighting of an animal was treated as a fresh encounter and a complete description of the individual was made each time

In the context of this study, a “character” was defined as the criterion used to differentiate between individuals while “categories” are the different possible values a character could have (Table 1). Moreover, the categories themselves were clearly defined. For instance, the character tusk arrangement was divided into three categories namely, convergent, where the tusks curve inwards, parallel to each other, or splayed, where the tusks are oriented outwards. Similarly, if the fold at the top of the ear is L-shaped, it means that the fold forms a 90° angle with the rest of the ear, and a U-shaped fold is defined as the top of the ear folding in a manner such that it forms an inverted "U" with the rest of the ear. Ear lobes were distinguished in a similar manner as being "V" shaped when the margins of the lobe form an acute angle, "L" shaped when the margins are perpendicular to each other, and "U" shaped when they are rounded. These categorical features used in the key were also accompanied by descriptive fields that included a sighting description that could potentially give cues related to specific behavior shown by an individual; overall description that included descriptions of body condition, any specific character that was distinctive for the individual, and whether the animal was in musth – a rut like condition in adult male elephants where the animal goes through a period of intense aggression towards other males and shows sexual proclivity towards females in estrous (Sukumar, 2003); tusk description; ear description; tail description; descriptions of the location of a tumour or scar if present.

Table 1 Categorical features used to establish identities

Character	Categories
Age class in years	< 15 / 15 - 20 / 20 - 25 / 25 - 30 / 30 - 35 / 35 - 40 / 40 >
Shoulder height in feet	< 7 / 7 – 9 / > 9
Presence of tusks	Absent / Both / Right only / Left only
Tusk arrangement	Parallel / Convergent / Splayed
Tusk angle*	Straight ahead / Intermediate / Downward pointing
Tusk length in feet*	> 3 / 2 - 3 / 1 - 2 / < 1
Tusk thickness*	Thick / Normal / Slender
Ear fold*	Absent / L-shaped / U-shaped
Ear lobe shape*	L-angular / V-acute / U-rounded
Ear tear*	Yes / No
Ear hole*	Yes / No
Tail length	Below ankle / Below knee and above ankle / Below penis sheath and above knee / Stump (above penile sheath)
Brush type	Absent / Inside only / Outside only / Both-discontinuous / Both-continuous
Presence of tumours	Yes / No
Presence of scars	Yes / No

* Entered separately for left and right

A – Parallel tusks, left ear hole, top right ear missing (peculiarity), V shaped ear lobe
C – Splayed tusks, left ear tear
E – Intermediate angle, brush hair absent

B – Convergent, thick tusks, downward pointing
D – Left tusk < 1 ft, right 1-2 ft, L shaped ear lobe
F – Complete brush, tail below penis sheath and above knee

Figure 1 Some characters used to differentiate between adult male Asian elephants in Nagarhole-Bandipur National Parks, India.

Identification methods

All encounters that yielded in usable photographs were entered chronologically into a database created specifically for this purpose in FileMaker Pro Advanced 8.0v1 following a format similar to the combinatorial key. The software allows queries to be run with the use of filters and thereby helps to narrow down comparisons to only individuals with similar characters for the purpose of identification.

Classification and subsequent identification of individuals using a supervised method involved a systematic step by step approach of elimination. The first step was to check if tusks were present or absent for the individual being considered. If tusks were absent, a search for all individuals without tusks was carried out without using any other filter. This was done since the total number of tuskless adult male elephants (makhanas) encountered was low and so the number of sightings across which comparisons had to be made was small. On the other hand if tusks were present, a search was carried out on all tuskers using filters for categories that have a higher likelihood of being unambiguously classified. For instance, classification of tusk arrangement as convergent, parallel or splayed is more definitive than tusk length since individuals with tusk length of about 2 feet could have been classified as having a tusk length of 1-2 feet or 2-3 feet. This was important so as to ensure that similar but differently classified sightings of individuals did not get missed out on application of a more specific filter. Once all individuals with the same definitive category (e.g. convergent tusks) were checked to correct for the possibility of similar looking individuals being classified differently e.g. tusk length falling under two different heads, the second step was to apply a more specific filter/s. For instance a query was run on all individuals with convergent tusks to segregate animals that possessed thick tusks that were greater than 3 feet in length and ear folds that were U-shaped. The third step involved applying filters for very specific or distinguishing attributes like tears or holes in either ear on the narrowed down pool of sightings of individuals. The last step involved a visual comparison of the even smaller pool containing sightings of animals that matched each other for most broad categories and possessed the distinguishing attributes (e.g. hole in the left ear) searched for in the penultimate step. If an individual was confirmed to be an individual seen earlier, it was assigned the same individual ID as the former.

To evaluate the likelihood that this method of supervised classification has resulted in misclassification of two different individuals with an identical set of characters as one, it was important to calculate the maximum probability of two such individuals occurring in a natural population. To achieve this, it was necessary to first calculate the maximum probability (p_{max}) of any one individual showing any 1 combination. This was calculated by first looking at frequency distributions of all categories for a character and thereafter tabulating the percentage of the category observed in the maximum number of sightings. For instance, for the character tail length, the maximum number of sightings contained individuals with the tail below the knee and above the ankle (68.4%) followed by tail below the ankle (24.1%), below the penile sheath (the point where it curves between the legs) and above the knee joint (6.3%) and above the penis sheath (1.3%). In this case therefore, the category tail below the knee and above the ankle occurring in 68.4% of the total sightings was tabulated. This was done for 19 out of the 22 characters since the other 3 did not have a meaningful representation in the sighting records e.g., for the character “presence of tusks” there were 6 sightings of tuskless individuals and the remaining all had both tusks. For these 19 characters, the probability of the most frequent category for a character was calculated. Using the most frequently occurring character viz., absence of hole in the right ear (88.6%), and moving downwards in rank, the data was checked for the combination of characters that was most common. Since the different characters were found to be dependent on each other (shown by a chi-square test for all possible pairs of characters) a step-by-step conditional probability was applied to these characters. In case such a character resulted in a lower number of sightings when conditional on the other most frequent characters higher in rank, then the respective category for this character was replaced by the category that gave the maximum number of sightings. By this process, p_{max} that described the maximum likelihood of any one individual showing a given combination of these 19 characters was estimated. The squared value of this probability gave the maximum probability of any 2 individuals showing the exact same combination.

Individual identification using an unsupervised method has been used for a suite of different taxa using many different statistical approaches. For animals with unique pelage patterns that may be cumbersome to visually compare if data sets are large, pattern recognition software have been developed to allow an automated computer aided matching of photographs. Kelly (2001) used such a method to analyze 10,000 photographs of cheetahs (*Acinonyx jubatus*) to establish individual identity. When individuals of a species are identified based on their footprints, discriminant function analysis has been a very widely used tool. Amongst others, this method has been used for identifying individual tigers (*Panthera tigris*) from their pugmarks (Sharma et al. 2005), black rhinos (*Diceros bicornis*) from their spoor (Jewell et al. 2001) and mountain lions (*Felis concolor*) from their tracks (Smallwood and Fitzhugh 1993).

In this study, hierarchical cluster analysis with average linkage between clusters was used to compare and contrast the supervised classification of individuals. To be able to meaningfully carry out both analyses, all categories for each character were converted into a binary scale. Therefore each category could have a "1" if present or a "0" if absent for each sighting. In addition, to ensure that there was no error due to missing data, only the sightings that were complete for all 19 categories mentioned above were used. These analyses approaches were preceded by the construction of a Euclidean distance triangular similarity matrix for the data set. In the context of the presence-absence data the Euclidean distance between samples j and k could be defined as per Clark and Warwick, 1994:

$$d_{jk} = \sqrt{\left[\sum_{i=1}^{p} (y_{ij} - y_{ik})^2 \right]}$$

From this it follows that samples that are more dissimilar will have a larger Euclidean distance between them. This matrix formed the basis for the rank based hierarchical cluster analysis.

Results

There were a total of 172 adult male elephant encounters and out of these 31 encounters resulted in unsatisfactory sightings where data on characters or pictures of individuals could not be obtained. Among the remaining 141 sighting records, six sighting records did not have clear pictures and unambiguous descriptions and were therefore left out of the analysis. Using the supervised method, all 135 sighting records were assigned to specific individuals and the total number of distinct individuals was found to be 78 including three tuskless individuals or *makhanas*. However, some of these sighting records had certain categories that were missing.

Therefore for the purpose of comparison with the unsupervised method, only sighting records with complete description were used in the analysis. The number of such sighting record was 107 out of which 68 sightings were identified as distinct individuals. The maximum likelihood of any one individual showing a combination of the 19 selected characters, p_{max} was found to be 0.084 and the maximum probability of any 2 individuals showing the exact same combination $(p_{max})^2$ was 0.007.

Hierarchical cluster analysis clustered the data in a manner that resulted in 70 different individuals as compared to 68 individuals obtained from the supervised method. Out of these 70, two sightings were actually recaptures as distinguished by supervised means but were found to cluster away from other sightings of the same individual. In the reduced subset of 107 sighting records used to compare the two methods, there were 20 individual identities that had two or more sightings. Hierarchical clustering also identified 20 such clusters, a result that was identical to the supervised method. A dendrogram plot showing average linkage between groups for ranks of similarities is given in Figure 1. Despite the encouraging results obtained from hierarchical classification, supervised classification was chosen as the appropriate method to establish identities.

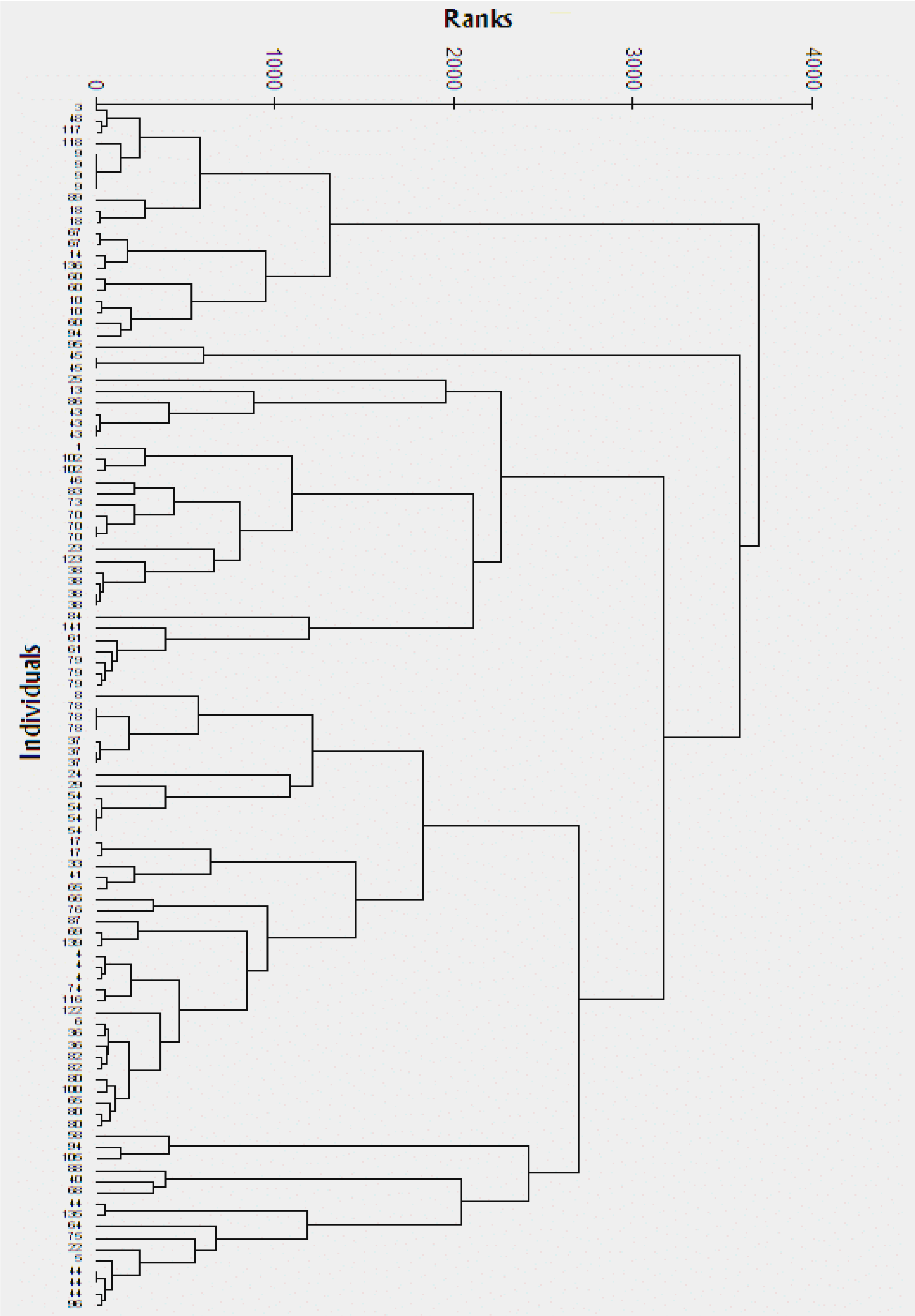


Figure 2 Dendrogram showing clusters made up by different sightings for an individual based on rank similarities.

Discussion

Supervised classification

Supervised identification and classification was found to be a somewhat subjective yet reasonable method for the purpose of establishing a rigorous protocol that allows identification of individual adult male elephants from field data. Despite some amount of subjectivity involved in identifying individuals from the suite of characters, this method appears to be reliable and finds support in the fact that previous studies on elephants have relied on many of the characters described hare to identify animals in the field (Douglas-Hamilton, 1975; Moss, 1996; Moss, 2001; Sukumar, 1989). For instance, Moss (2001) monitored the demography of an elephant population in Amboseli, Kenya for a period of 27 years during which, she used the subjective method described above to identify 480 to 1087 animals. The essentials of course are clear photographs that can be colluded with a combinatorial key. The added advantage of such a method over automated processes is that it allows the investigator to distinguish elephants with peculiar or distinct characters. For instance, one of the individuals identified in this study had its right ear torn in such a manner that the top of the ear was completely missing. This individual could be easily recognized even from afar. An automated process would not allow such an outlier to be categorized or recognized.

The characters of age and height classification were thought to have a fair degree of subjectivity attached to it and hence were not used to distinguish between individuals under the supervised method. Height classification for instance, is difficult to measure in the field though techniques like estimating height from the diameter of the foot, (Moss, 1996) have been previously used. Efforts can be made to improve classification of such subjective characters in future studies. It is reasonable to assume that some of the variations seen in identification could be due to these subjective classifications. But it is equally likely that these variations have surfaced due to the fact that unambiguous classification requires good sighting encounters, and because former sighting records were not modified on the basis of a later, more conclusive sighting of the same individual.

The database and the combinatorial key

As explained earlier, the database had sighting records of the same individual with a few minor differences in certain categories of characters. These differences can be explained by the fact that descriptions for a sighting were not modified on the basis of a later, more conclusive sighting of the same individual (even if the identity of the animal was known for certain). This allowed for some variations amongst entries of the same individual on different occasions and was thought to be useful because firstly, it makes room for human error in classification; secondly, an error could result due to constraints of an unsatisfactory sighting; thirdly, it accounts for variations occurring purely out of chance, and lastly, it accounts allows for the argument that despite these variations in classification, one is able to determine identities unambiguously. Additionally, the combinatorial key used proved to be quite advantageous since it allowed for unambiguous identification despite some degree of misclassification or variations in classification. If instead a dichotomous key were to have been used, a single error in classification would have resulted in a completely wrong identity being assigned to a sighting record. Moreover, dichotomous keys assume nestedness of the characters used for classification, which is not true in this case

Unsupervised classification

Hierarchical clustering techniques had promising results. The number of distinct individuals that could be segregated from the cluster analysis data was found to be very similar to the supervised method. The 2 sightings that were additionally distinguished as being distinct by the unsupervised method were found to be inconsistent with other sighting record of the same individual in terms of characters. For instance, one of the sightings coinciding with individual 44 was found to be clustered quite far from the other three sightings. This was because that sighting was classified as having an intermediate tusk angle as compared to the other three that were classified as having downward pointing tusks. This was due to the lack of clear photographs that showed the tusk angle clearly. Similarly the other sighting coinciding with individual 60, was different from the others since it was classified as having a hole in the right ear while the others were classified as not having such a hole. This arose because the sighting that was an aberration was actually a much closer encounter and allowed to observe the minute hole that was not visible for the other sightings. This highlights the limitation of an unsupervised automated method to distinguish between sightings of very similar looking animals separated by a difference in a single categorical value. The other major handicap was the fact that including sighting records with some amount of missing data would have changed the complexion of such a process. Thus a fairly large part of the data had to be omitted from the cluster analyses. However, despite these handicaps, hierarchical clustering can be used quite effectively to narrow down the pool of sighting records that need to be compared to establish final identities and hence a very useful method to identify individuals when used in combination with the supervised method.

Classification and regression trees are highly suited for the analysis of complex ecological data as they can deal with non-linear relationships, high-order interactions and missing values (De'Ath and Fabricus 2000). The algorithm for this method uses combinations of explanatory variables that may be categorical and/or numeric to repeatedly split the data into more homogeneous groups and thereby explain the variation of a single response variable (De'Ath and Fabricus 2000, Krishnaswamy et al. 2004). Thus these methods could potentially be useful to automate the process of identification to some extent. Riordan (1998) compared a neural-network based, the Kohonen self-organizing map (SOM) and a Bayesian method, AutoClass, for successful classification of footprints from captive tigers and snow leopards, and concluded that AutoClass proved to be more successful at discriminating animals from both species into individual classes. These methods were thought to be less appropriate for the purpose of this study because the Kohonen self organizing map requires prior knowledge of the animals being classified and though such a requirement may not be a compulsion for AutoClass, it is likely to be important (Riordan 1998). Despite this caveat in the context of such a study, it might still be worthwhile to attempt these methods to test to what degree, precision may be improved by an automated process.

Pattern recognition software could also be used to automate some of the processes involved in establishing identities. For instance, such software could be used to decipher characters like the presence or absence of tears and holes in the ears. The disadvantages of using such software would mainly hinge on two main factors – firstly, the software would require absolutely clear photographs which may not always be available for a sighting, and secondly, photographic angles would need to be standardized as differences in photographic angles could bring about great variations in the similarity coefficient computed by the software (Kelly, 2001). In addition to software, there also is potential to corroborate this method with other methods (like use of DNA from the gut epithelium) to further strengthen the database of known individuals in a population or area.

Applicability and scope

Despite the scope for improvement of precision, this study has shown that this method of classification and identification with the help of photographs and a combinatorial key is reliable and applicable to field situations for the Asian elephant and could prove useful for other species with distinguishable variations in morphological characters. There is ample room for improvement and ideally what is required is a hybrid technique, where partly automated procedures can help filter large datasets from which close-calls can be made manually. This last step could be aided by circumstantial information such as behavior, location or association to make the final decision on individual identity.

In conclusion, one might add that the integration of individual identities established using the protocol reported here with a capture recapture sampling framework could effectively yield robust estimates of population size. Extending this over space (movement rates) and time (survival) would allow estimation of extremely important parameters that are currently extremely difficult and expensive to achieve.

Acknowldegements

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Estimation of adult male Asian elephant (*Elephas maximus indicus)* population size in Nagarahole-Bandipur National Park using capture-recapture methods

Summary

1. Asian elephant populations are threatened by habitat loss and degradation. The adult male is differentially faced by additional threats of poaching for ivory and conflict with humans. To understand the biology behind the predisposition of adult bulls to conflict and to assess impacts of poaching robust estimates of population size and vital rates like movement and survival rates are essential.

2. Discriminating power between individuals has been recognized as an important component in counting and monitoring animals. Individual identification of adult male Asian elephants can potentially open many avenues for research which have been difficult to achieve previously and could be the means to attaining the goal of obtaining robust estimates of abundance as well as demographic parameters.

3. In this study, photographic capture-recapture techniques were used to estimate the abundance of adult bulls in a globally important population from south India. This estimate was combined with age-sex proportions obtained from group composition data to estimate total elephant abundance.

4. The abundance of adult males in the population was found to be 134 ± 14.20 (SE) and the proportion of the total population that these occupy was 0.14 ± 0.008. The total elephant abundance as derived from these estimates was 991 ± 32.75.

5. The methods also find application in estimation of densities, as well as movement and survival rates. Density estimation yielded and estimate of 0.19 ± 0.021 km^{-2} for adult bulls and 1.38 ± 0.048 km^{-2} for all elephants. This was found to be lower than line transect estimates of 2.18 ± 0.502 km^{-2} for the same area.

6. *Synthesis and applications.* The results of this study indicate that photographic capture-recapture sampling techniques used in combination with open population models can give robust estimates of abundance. They further support earlier findings that these methods are a useful tool to understand the demography of species that can be identified through natural markings. Such estimates of demographic parameters could play a pivotal role in understanding the dynamics of a population over a long term and to monitor factors threatening the species.

Key-words: abundance, bulls, demography, density, group composition, superpopulation

Introduction

The endangered megaherbivore *Elephas maximus* or the Asian elephant has many threats to contend with during its struggle for survival in an ever-increasing human dominance of the landscape. In India, these can be mainly narrowed down to habitat degradation and poaching for ivory (Blake & Hedges 2004; Sukumar 2003). The threat from poachers however, is selective with adult males, the tusk-bearing sex getting preferentially targeted. From the perspective of conserving the species, the impact of ivory poaching needs to be assessed and this is only possible when robust estimates of population size are available (Walsh & White 1999).

The adult bull is a wide ranging animal with home ranges that are larger than 400 km^2 (Williams 2002). By moving long distances in search for possible mates, bulls can potentially connect different populations. However, they also are more prone to encountering humans and come into conflict. A lower survivorship of males

(Sukumar 2003) can be caused by many factors and conflict with humans is one of them. Such conflicts often arise due to a high risk-high gain strategy adopted by males to maximize nutritional benefits from raiding crops (Sukumar & Gadgil 1988). The benefit of a larger body size however, comes with the cost of an additional metabolic price that makes males more susceptible to nutritional stress and diseases (Sukumar 2003). Males also are at higher risks of injury or mortality due to competition with other males and while emigrating from natal families (Sukumar 2003). These issues bring to light the necessity to estimate demographic parameters such as rates of movement, and survival and these when combined with robust estimates of population size, can allow long term monitoring of populations.

Identification of individuals has been recognized as an important component in counting and monitoring threatened populations (McGregor & Peake 1998). Individual identification in the context of elephant research has the potential to open up avenues for estimating parameters that are difficult to estimate currently. In addition to its applicability to population estimation, individual identification could be applied to estimate various demographic parameters of interest. Such parameters have been estimated through long term monitoring of identified individuals in Africa (Moss 2001) and there is scope to apply them to adult males here. Moreover, individual identification has potential to be a very useful tool to managing adult male populations. An archive of adult bulls collected over a relatively long period could be used to trace carcasses of poached bulls to identities in the database. This can be used in combination with rates of survival to assess mortality due to poaching in the light of natural mortality amongst bulls. Similarly if the identities of rogue bulls or males that are especially inclined to raiding crops are known, management interventions towards removing such problem animals become easier.

Currently, demographic parameters can be understood only with the help of methods like radio telemetry. These methods are limited by small sample sizes in addition to the high expenses involved. Sexing individuals in the field is often challenging due to problems of observability. Thus using current approaches of elephant population estimation to estimate male numbers might be difficult though not impossible. Ideally therefore, an alternative method that can reliably estimate population sizes and demographic parameters is needed. Individual identification could provide the means for such a method even more so because of the fact that adult male Asian elephants are readily identifiable using a suite of different characteristics (Sukumar 1989).

Capture-recapture techniques are powerful tools in analyzing and estimating various demographic parameters and over the years they have undergone great development and refinement (Williams, Nichols & Conroy 2002). These techniques are useful to understand many biological systems and can be used to estimate demographic parameters with the help of 'marked individuals' from a sampled population. For studies conducted over a short duration, capture-recapture models assuming geographic and demographic closure can give robust estimates of population size (Otis et al. 1978). On the other hand, if the study period extends over a larger time scale or if the sampled area is too small to accommodate the normal ranging and movement patterns of the study animal then it becomes difficult to assume closure. Under such circumstances, the population is considered open to gains and losses and the basic model that allows abundance estimation of such populations is the Jolly-Seber model (Pollock et al. 1990). Another potential approach is the "superpopulation" model of Schwarz and Arnason (1996), which is an alternative parameterization of the basic Jolly-Seber model and involves estimation of the abundance of a superpopulation that serves as a source of animals that move into the sampled area and get captured during the period of the study.

In India, pioneering studies have been done to estimate tiger numbers under a capture-recapture framework using the natural pattern of stripes on tigers to identify and 'mark' individuals (Karanth 1995; Karanth, Kumar & Nichols 2002; Karanth & Nichols 1998; Karanth et al. 2004). Adult male elephants can also be identified in a similar fashion by looking at their tusk patterns and this can be supplemented by variations in the ears, tail and bodily scars (Douglas-Hamilton 1975; Moss 1996; Moss 2001; Sukumar 1989). Williams (2002) has used these features in combination with radio collars on some of the animals to mark and re-identify individuals to estimate the adult male population in Rajaji National Park, India under a mark re-sight framework (White, Tutin & Fernandez 1993). Being the first study of its kind on Asian elephants, this study has laid the foundation for the use of mark-recapture techniques for Asian elephants and in the long run such techniques may prove to be a scientifically rigorous and efficient method to find reliable answers to questions related to the demography of a long-lived animal like the elephant.

This study was aimed at obtaining robust estimates of adult male numbers under capture-recapture framework and using this to obtain total elephant abundance. This was achieved by firstly, developing field techniques and sampling designs that were appropriate for photographic capture-recapture of elephants and to evaluate what capture-recapture models were best suited to estimate adult male Asian elephant population size given the field conditions; secondly, estimating the abundance of adult bulls from the photo-identification data using capture-recapture models and using this estimate of adult male abundance to estimate total population size; and lastly, extending these abundance estimates to estimate densities of adult males and of all elephants. The estimate of overall density was then compared with estimates from line transect data for the same area. The implications of the results are discussed.

Materials and methods

STUDY AREA

Nagarahole National Park spanning 644 km^2 (11˚50'-12˚15'N Lat. and 76˚0'-76˚15'E Long.) and Bandipur Tiger Reserve covering an area of 880 km^2 (11˚57'-11˚35' N Lat. and 76˚12'-76˚51'E Long.) are located in the state of Karnataka in southern India. This contiguous stretch of forest separated by the Kabini reservoir is part of the Niligiri Biosphere Reserve and also a part of the Niligiri-Eastern Ghats Elephant Reserve under the Government of India's Project Elephant. Moist and dry deciduous forests are the dominant vegetation types with stretches of teak dominated forests being fairly common in Nagarahole. Rainfall patterns show a distinct seasonality with a dry season between November and May, and a wet season lasting from June to September (Madhusudan 2004). Within these parks an area of 176 km^2 on either side of the Kabini reservoir (Fig. 1) was selected as the study area.

SELECTION OF STUDY AREA

The contiguous stretch of forest that comprises both parks is known to support the densest congregation of Asian elephants anywhere in the world with density estimates ranging from about 1.9 elephants km^{-2} (Karanth & Sunquist 1992) to about 3 elephants km^{-2}. (Madhusudan & Karanth 2002). During the dry season the backwaters of the Kabini reservoir start receding and expose a fertile stretch of land rich in grassy forage (Madhusudan 2004). Complemented by a permanent water source (the Kabini reservoir) this fertile plain within the study area during a period of general scarcity in the landscape is ideal for herbivores like the Asian elephant. Consequently, during March-May peak elephant activity occurs near the Kabini reservoir where they congregate in large numbers (Madhusudan 2004). The road network in both parks is fairly extensive (~0.9 km/km^2) and the density of waterholes is high (~0.1 km^{-2}). These two factors allowed for the study area to be covered quite intensively and thereby maximized the likelihood of encountering elephants. Though in some areas the dense vegetation made the task of observing elephants more difficult, the above mentioned factors in combination with the seasonal congregation of elephants during the dry months provided a good opportunity to observe elephants closely and photograph the adult males in the population in a systematic fashion.

FIELD METHODS

Equipment

A Panasonic FZ-20 digital camera with 12X optical zoom and 5.0 mega pixel resolution was used to photograph the adult male Asian elephants. In addition, an 8 x 40 binocular set was used to make visual observations. Locations of elephants were taken using a Garmin 12XL GPS unit.

Sampling (design and implementation)

The total study area spanned 176 km^2 on either side of the Kabini reservoir with 117.8 km^2 in Bandipur Tiger Reserve and 58.2 km^2 in Nagarahole National Park (Fig. 1). The entire area was covered by driving across a predetermined road network and waiting near 5 different waterholes distributed across the study area. Covering the entire study area in a manner that ensured that there were no 'holes' was one of the important considerations in study design. In the context of capture-recapture studies, 'holes' are portions within the study area that are large enough to be able to contain the movements of the study animal during the sampling period and within which any such animal has a zero probability of capture (Karanth & Nichols 1998).

The targeted road length to be traversed in Bandipur during each sampling occasion was 170.7 km, For logistic purposes this was divided into 3 routes such that each route included driving a fixed circuit in the morning and driving to and from a waterhole in the late afternoon-evening. Similarly, the targeted road length in Nagarahole was 90.5 km and this was divided into 2 routes, each associated with a waterhole. Selection of the waterhole to be sampled while covering a given route was based on the following two criteria: a) the waterhole was known to have water throughout the period of the study (February-May); b) elephant activity was known to be high around the waterhole. The study area has a relatively large number of waterholes (Fig. 2) and though only 5 waterholes were sampled in terms of spending 1.5-2 hours next to each, most of the others were crossed while driving the different routes and elephant encounters near these were also recorded.

Each road segment within a route was given a unique name and defined as a trap line such that the exact location of a capture was known to come from a specific trap line (Karanth & Nichols 1998) (figure 2). Effort was also recorded in terms of the time spent on each of the 5 routes and this included spending 1.5-2 hours at each of the 5 waterholes, recording group composition data for all herds encountered, and observing and photographing adult bulls. Each route was completed in a day and therefore, each sampling occasion requiring 5 days of sampling involved driving the 5 different routes and waiting near 5 different waterholes.

Details of morphological characters and protocols used for individual identification have been given elsewhere (Paper I). Finally, each encounter with its associated set of photographs was given a unique sighting ID and the geographic location of the sighting was marked with the help of a GPS.

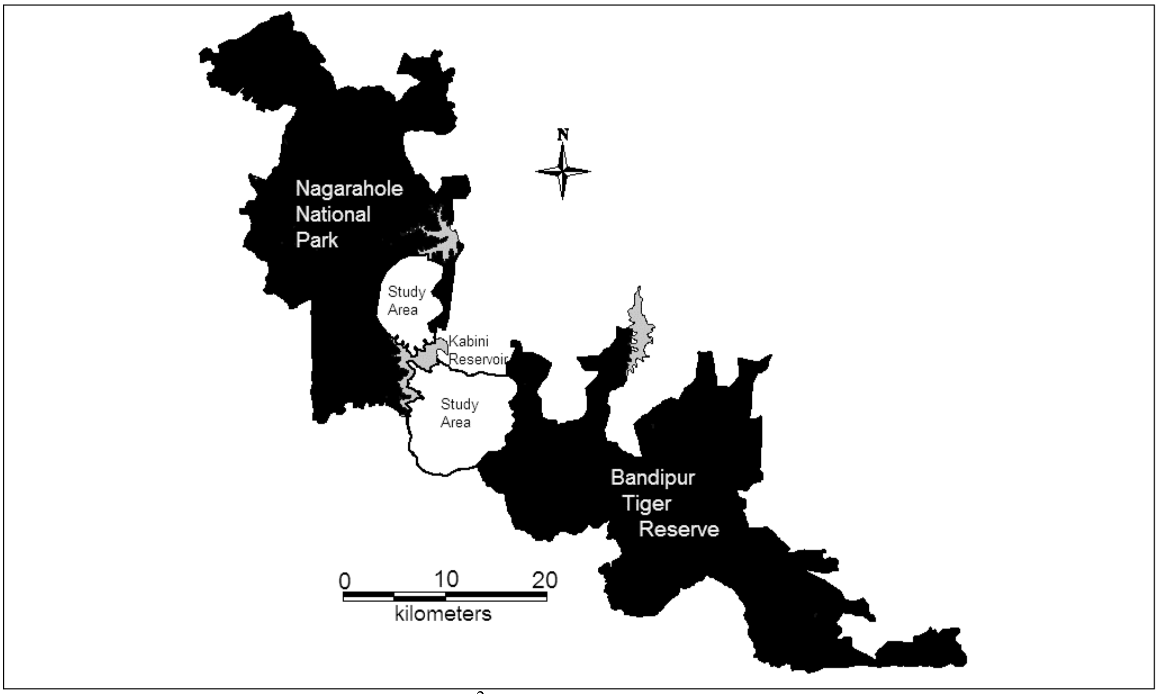
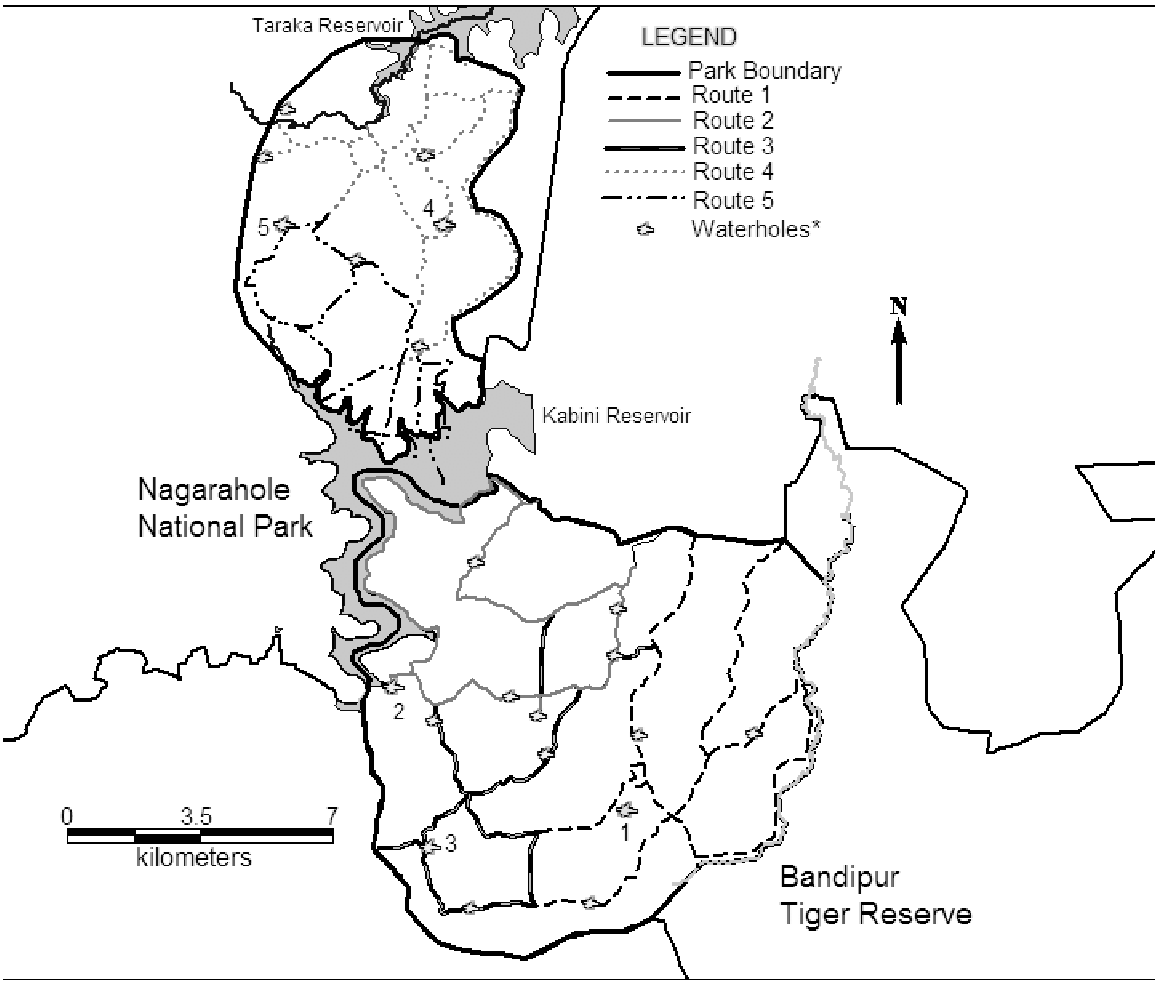


Fig. 1. Location of the study area of 176 km^2 (white) on either side of the Kabini reservoir occupying 58.2 km^2 within Nagarahole National Park (top black) and 117.8 km^2 within Bandipur Tiger Reserve (bottom black).

Group composition data were collected each time a herd of elephants was encountered. It involved observing and counting all visible animals in the herd, classifying them as adult male, adult female, juvenile and young. Classification was based on Karanth & Sunquist (1992). Since vegetation cover could be quite dense in some areas, the counts of different age-sex classes of the groups were regarded as minimum counts. In a case where it was known that other individuals existed in the herd but were not visible for correct classification, the group was recorded but the classification was labeled as incomplete. These data were not used at the analysis stage. Each sighting was given a group ID and GPS locations were taken.

The study was carried out from mid February to beginning of May and this total sampling period was partitioned into 10 sampling occasions each involving 5 days of effort. Due to climatic and logistical constraints, the effort in terms of time spent and distance covered during each sampling occasion was not identical. Details of the sampling effort are given in Table 1.



* Numbered waterholes were sampled

Fig.2. Enlarged map of the study area showing: (a) The 5 sampling routes encompassing all roads whose segments were defined as individual trap lines. (b) All waterholes including the ones sampled (numbered).

ANALYTICAL METHODS

Identification of adult male elephants

Classification and subsequent identification of animals was done using a supervised method that involved a step by step process of elimination such that it facilitated final visual comparisons only for similar looking animals. FileMaker Pro Advanced 8.0v1 was used to create a database of all the sighting records. Details of the exact protocol used for the application of such filters and how identification of individuals was finally achieved has been presented elsewhere (Paper I). Examples of unambiguous identification (Ids are presented in Fig. 3.

Capture-recapture techniques and abundance estimation

In the context of this study, marking was defined as methods used to identify individual adult males with the help of features described earlier. 'Capture' involved the successful identification of all individuals recorded and photographed. In samples subsequent to the first, previously identified adult bulls were recorded as recaptures and new individuals were assigned an identity. By such a cumulative process, a capture history was constructed such that each entry assumed a value of "1" if the animal was encountered and photographed on that occasion or a value of "0" if it was not successfully photographed on the same occasion. A probabilistic model describing the sequence of events producing each capture history was developed using this matrix often described as

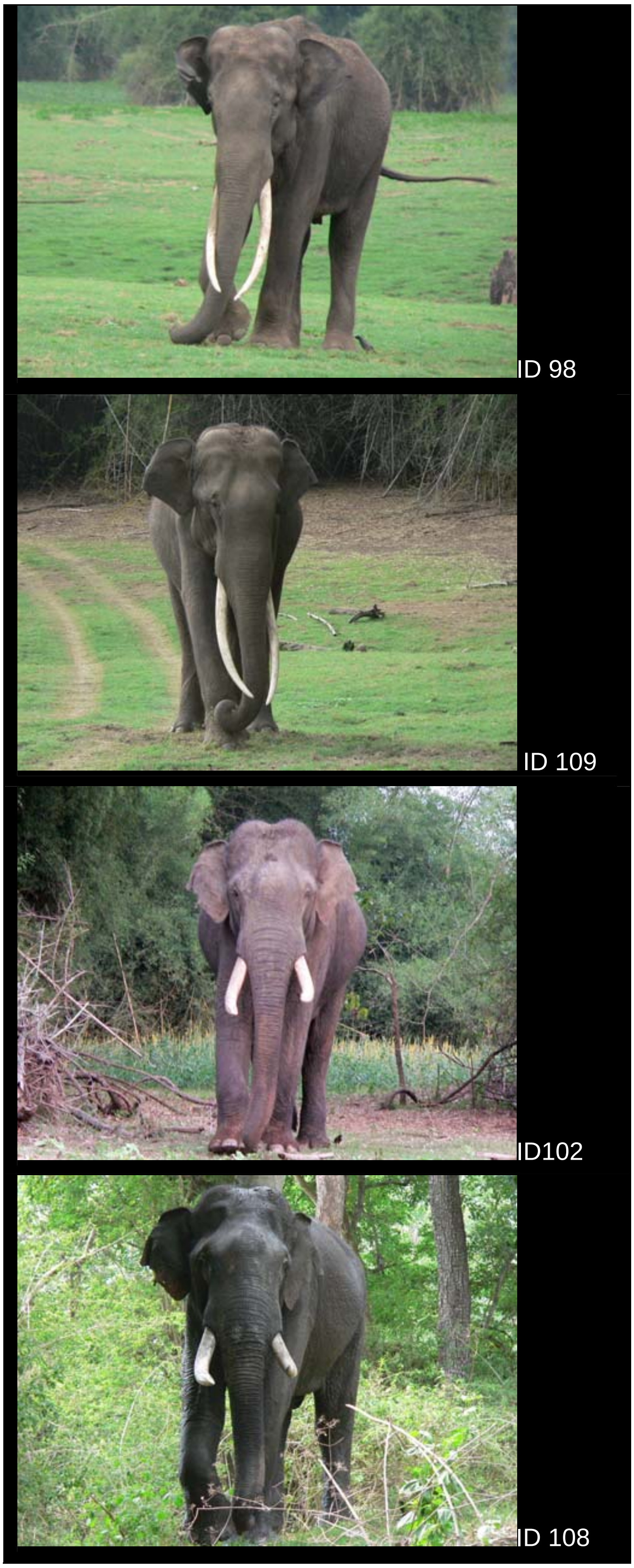


Fig. 3. Examples of unambiguous identification of adult male individuals using photographic capture-recapture in Nagarhole-Bandipur National Parks, 2006.

the “X matrix” (Otis et al. 1978) and this was then used to derive estimators of adult male Asian elephant population size.

Given the relatively short period of this study, the likelihood of the demographic closure assumption being violated was low. However, it was difficult to assume geographic closure given that the Asian elephant is a wide ranging animal and an adult bull can have home ranges that are larger than 400 km^2 (Williams 2002). Since the likelihood of animals moving in and out of the study area was relatively high, Schwarz and Arnason’s (1996) “superpopulation” approach was used. This likelihood based approach focuses on estimating a new parameter, N, that denotes the size of a “superpopulation” that serves as a source of individuals for the population of interest (Schwarz & Arnason 1996; Williams, Nichols & Conroy 2002). Using this approach:

$$N = \sum_{i=0}^{K-1} B_i$$

is the total number of animals available for capture at anytime during the study with B_i being the number of new animals in the population at sampling occasion $i + 1$ that were not present in the population at occasion i (Schwarz & Arnason 1996; Williams, Nichols & Conroy 2002). In the initial sample all individuals are new with respect to sampling, i.e., $B_0 = N_1$ and after which, the random variables B_i are modeled with a multinomial distribution such that members of the super population are assumed to enter the sampled population according to entry parameters β_i (Williams, Nichols & Conroy 2002). Therefore, besides estimating the usual open population parameters of φ_i, probability of an animal surviving between sample time i and $i + 1$ given that it was alive at time i, and p_i, probability of capture at sample time i, the modeling for this approach requires estimation of a new parameter β_i, which is the probability of entry of new individuals at sampling occasion *i*. Under this model, capture probabilities cannot be estimated for the first sampling occasion and the constraint that entry parameters β_i sum to 1 leaves K – 1 of these parameters to be estimated, such that under the full, time-specific superpopulation model a total of 3K – 3 of these parameters can be estimated (Schwarz & Arnason 1996; Williams, Nichols & Conroy 2002).

Four parameters were modeled under the Schwarz and Arnason (1996) superpopulation approach. These included apparent survival (φ) denoted as "phi", recapture probability (p), probability of entry (β) denoted as "pent" and initial population size (N). These parameters were modeled such that: phi, p and pent could be constant over all sampling occasions, denoted as phi(.), p(.) and pent(.) respectively; or could vary with time, denoted as phi(t), p(t) and pent(t) respectively. Since the parameter N represents initial population size, it has only one value and therefore was not modeled as being constant or time specific. Sometimes a parameter may be confounded by one of the other parameters and this can be checked by holding the given parameter constant. (White & Burnham 1999). The apparent survival parameter phi was held constant for some models, denoted as phi(1).

The closure statistic that program CAPTURE computes from the capture history was used to test for closure and analysis of the data to arrive at estimates of the superpopulation size, N, and other parameters of interest under the Schwarz and Arnason model (1996) was done using the POPAN model type in program MARK (White & Burnham 1999). Model selection was done using AIC_c.

The estimate of the superpopulation size of adult male Asian elephants was used in combination with group composition data collected to estimate the total elephant population size in the superpopulation ($\hat{N}_t$). To achieve this, a cumulative count of all individuals recorded under the various classification categories viz., adult male, adult female, sub-adult male, sub-adult female and young, were made. These counts were used to calculate the ratio of adult males to the rest of the population averaged over the 10sampling occasions. This ratio, and the actual estimate of adult males in the superpopulation, was used to calculate the total elephant population size in the superpopulation. The variance of the total elephant abundance ($\hat{N}_t$) was estimated using the relationship between $\hat{N}^*$, $\hat{N}_t$ and the proportion of adult males in the population (P_{AM}), which may be defined as

$$\hat{N}_t = \hat{N}^* / P_{AM} \quad (1)$$

since $\hat{N}^*$ and P_{AM} are independent of each other, the variance of $\hat{N}_t$ was estimated using

$$\mathrm{var}(\hat{N}_t) = (\hat{N}^*/P_{AM})^2 \, [\mathrm{var}(\hat{N}^*)/(\hat{N}^*)^2 + \mathrm{var}(P_{AM})/P_{AM}^2] \quad (2)$$

Elephant density estimation

For density estimation, the study area of 176 km^2 required a buffer strip to be added since it has been recognized that the area from which animals are trapped is not equal to the area defined when it is assumed that the outer boundary is made up by the perimeter trap sites (Otis et al. 1978). This addition of a boundary strip helped to account for the additional area from which animals of the superpopulation moved into the sampled area and were "captured". The approach of "mean maximum distance moved" which has been applied to estimate the density of tigers (Karanth & Nichols 1998; Karanth et al. 2004), was modified in order to estimate effective area sampled over the study period. Because the area over which our sampling was distributed was considerably smaller than home range sizes known for adult male Asian elephants, the mean maximum distance moved during this study was thought to underestimate the area that bulls potentially used, and hence positively bias density estimates. Therefore, the mean maximum distance moved by bulls was estimated as the radius of a circle whose area equaled the average annual home range size of 5 bulls obtained from radiotelemetry studies (Bhaskaran et al. 1995; Williams 2002). Estimations of mean home range size and its variance, and the boundary strip width and its associated variance were made as per Karanth & Nichols (1998).

The sampled area (A) was computed by mapping all the roads sampled and joining the ends of the road segments near the study area boundary to form the perimeter. Addition of the boundary strip width (W) to the sampled area (A) gave the effective sampled area, $\hat{A}(W)$ (Fig. 3). On addition of (W) if the polygon formed extended into areas that were considered to be non-elephant habitat, then these areas were deducted to compute the final effective sampled area. Density of all elephants as well as adult bulls only were estimated using

$$\hat{D} = \hat{N} / \hat{A}(W)$$

$$\text{var}(\hat{D}) = \hat{D}^2[\text{var}(\hat{A}(W))/[A(W)]^2 + \text{var}(\hat{N})/\hat{N}^2] \qquad (4)$$

Var($\hat{A}(W)$) was estimated using the approach followed by Karanth & Nichols (1998) while the variance of the abundance estimate of adult males ($\hat{N}^*$) was obtained from the output in MARK.

Line transect data of elephants collected in 2005 from the same geographical area (Karanth unpublished data) were analyzed using program DISTANCE (Buckland et al. 2001) to estimate elephant density. Model selection in DISTANCE followed protocols suggested by Buckland et al 2001.

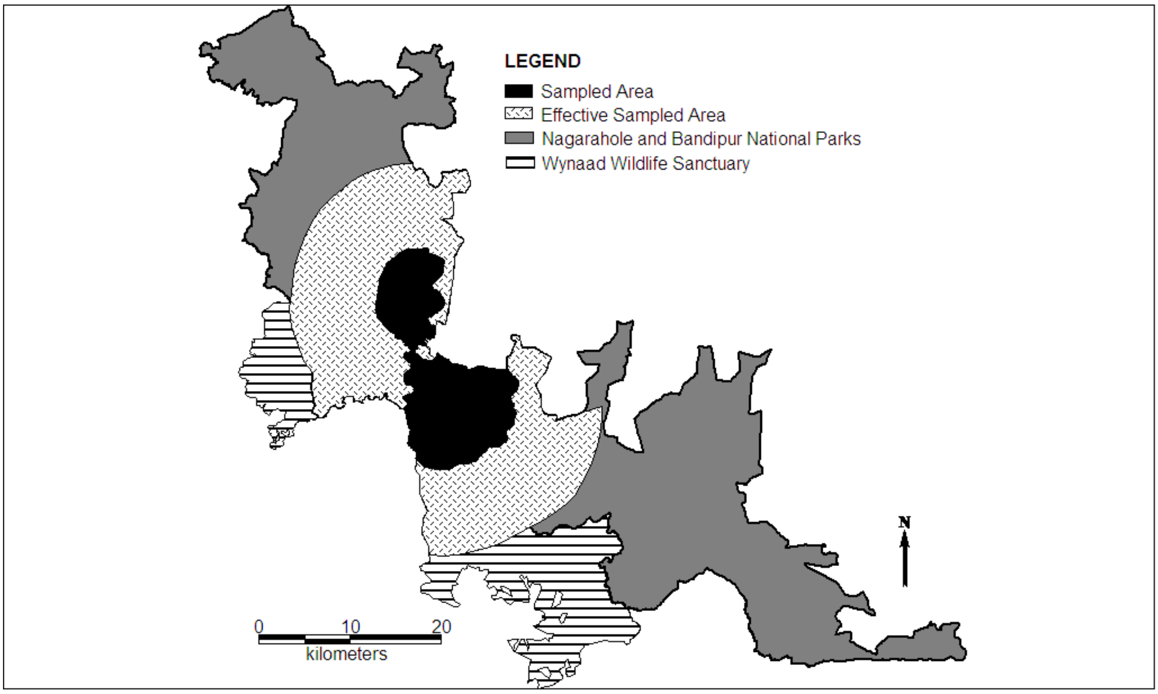


Fig. 4. Effective sampled area, A(W), encompassing the actual sampled area (A), and the boundary strip width (W), used for estimating elephant density of the superpopulation occupying a portion of Nagarahole and Bandipur National Parks, India.

Results

SAMPLING EFFORT

A total distance of 2697 km was covered along all roads that made up the trap lines over a period of 80 days and the total time spent driving, photographing and waiting near waterholes was 293 hours (Table 1). During this period a total of 2421 pictures were taken out of which 746 were used for individual identification.

Sample	Start Date	End Date	Distance covered (km)				Time spent (hours)			
			BP	NH	Total	Cumulative	BP	NH	Total	Cumulative
1	17/02/2006	25/05/2006	175	98	273	273	19	12	31	31
2	26/02/2006	04/03/2006	181	99	280	553	18.75	12	30.75	61.75
3	06/03/2006	11/03/2006	189	98	287	840	18.75	12	30.75	92.5
4	12/03/2006	17/03/2006	188	98	286	1126	18.75	12	30.75	123.25
5	20/03/2006	24/03/2006	184	99	283	1409	19	11	30	153.25
6	25/03/2006	29/03/2006	194	97	291	1700	22	11	33	186.25
7	04/04/2006	09/04/2006	160	91	251	1951	19.5	10	29.5	215.75
8	16/04/2006	19/04/2006	170	74	244	2195	18.25	7	25.25	241
9	25/04/2006	01/05/2006	165	93	258	2453	17.5	9	26.5	267.5
10	02/05/2006	08/05/2006	155	89	244	2697	15.5	10	25.5	293

Table 1. Sampling effort expended between February-May 2006 for estimating adult male elephant abundance in Bandipur (BP) and Nagarahole (NH), India

IDENTIFICATION OF INDIVIDUAL ADULT MALE ELEPHANTS

A total of 172 adult male elephants were encountered, of which, 135 sightings resulted in unambiguous identities derived from clear photographs. Using a supervised method of classification and subsequent identification, the total number of unique animals (M_{t+1}) was found to be 78 including 3 “makhanas” or tuskless adult male elephants. The capture history matrix of these 78 individuals is given in Appendix 1.

POPULATION ESTIMATION - THE SUPERPOPULATION APPROACH

The sampled population was found to be open to gains and losses with the statistical test for population closure in program CAPTURE not supporting the hypothesis that the population is closed during the period of the study ($z = -3.249$, $P = 0.00058$). The “recaptures only” model set in program MARK was also used to test the closure assumption and this supported the hypothesis that the population was open during the study period ($\varphi \neq 1$). Model selection criteria in MARK under the POPAN model type identified the model {phi(.),p(.),pent(.),N(.)} with constant survival probability (phi), capture probability (p), entry probability (pent), and initial population size (N) to be the most appropriate model with an AICc value of 345.977 (Table 2).

The parameters estimated under the {phi(.),p(.),pent(.),N(.)} were survival probability ($\hat{\varphi}$ = 0.86 with standard error SÊ($\hat{\varphi}$) = 0.041), capture probability ($\hat{p}$ = 0.26, SÊ($\hat{p}$) = 0.043), probability of entry ($\hat{\beta}$ = 0.09, SÊ($\hat{\beta}$) = 0.007) and initial population size ($\hat{N}$ = 126.38, SÊ($\hat{N}$) = 12.832). The corresponding final estimates of the derived parameters of recruitment ($\hat{B}$) and the population size of the superpopulation ($\hat{N}^*$) were $\hat{B}$= 12, SÊ($\hat{B}$) = 1.687 and $\hat{N}^*$= 134, SÊ($\hat{N}^*$) = 14.20 with 95% confidence interval (CI) ranging from 106 to 162.

Model Description	AICc	Delta AICc	AICc Weight	Model Likelihood	No. of Parameters
{phi(.),p(.),pent(.),N}	345.977	0.00	0.77270	1.0000	4
{phi(.),p(t),pent(.),N}	348.692	2.72	0.19874	0.2572	13
{phi(.),p(.),pent(t),N}	353.062	7.09	0.02236	0.0289	12
{phi(1),p(.),pent(.),N}	356.748	10.77	0.00354	0.0046	3
{phi(t),p(.),pent(.),N}	357.419	11.44	0.00253	0.0033	12
{phi(.),p(t),pent(t),N}	364.129	18.15	0.00009	0.0001	21
{phi(t),p(.),pent(t),N}	365.309	19.33	0.00005	0.0001	19
{phi(1),p(t),pent(t),N}	380.029	34.05	0.00000	0.0000	20
{phi(t),p(t),pent(t),N}	385.134	39.16	0.00000	0.0000	29

Table 2. Model selection statistics for open population analysis using the POPAN model type on elephant capture-recapture data from Nagarahole-Bandipur National Parks, India, 2006.

GROUP COMPOSITIONS

The total number of elephants encountered during the period of the study was 1306 and this included 172 adult males, 744 adult females, 57 sub-adult males, 143 sub-adult females, and 190 young. The mean proportion of the total population for adult males was 0.14 ± 0.008 (S.E.), adult females was 0.58 ± 0.010, sub-adult males was 0.04 ± 0.008, sub-adult females was 0.10 ± 0.007 and young was 0.15 ± 0.007. Additionally, the adult sex ratio of males to females was found to be 1:4.33. Using the estimate of the abundance of adult males in the superpopulation, $\hat{N}^*$ = 134 ± 14.20, and the mean proportion of adult makes in the population, the estimate of the total elephant population size of the superpopulation, $\hat{N}_t$ was calculated as 991 ± 32.75 with 857 ± 30.52 non adult male individuals including 571 ± 19.79 adult females, 40 ± 1.50 sub-adult males, 102 ± 3.78 sub-adult females and 145 ± 4.98 young.

DENSITY ESTIMATES

Estimates of density using different approaches to calculating the boundary strip width are given in Table 4. The estimates obtained by using annual home range sizes was selected and compared to density estimates from line transect data for the same area. These estimates from DISTANCE were found to be 2.18 ± 0.502 km^{-2}.

Source	Home range type	Mean home range size (km^2)	Boundary strip width (km)		Effective sampled area (km^2)	Adult male density (no. km^{-2})		Elephant density (no. km^{-2})	
			$\overline{\hat{W}}$	SE ($\overline{\hat{W}}$)		$\hat{D}*$	SE ($\hat{D}*$)	$\hat{D}$	SE ($\hat{D}$)
This study	Mean[a] maximum distance moved	NA	1.98	1.29	292.5	0.46	0.076	3.39	0.077
Secondary data	Annual[b]	286.98	9.44	1.30	716.6	1.38	0.048	0.19	0.021
Secondary data	Seasonal[c]	138.87	6.35	1.75	526.4	1.88	0.036	0.25	0.033

a. Estimated from the capture-recapture data of this study
b. Estimated by averaging across home range sizes from two previous radio telemetry studies (Bhaskaran 1995, Williams 2002)
c. Estimated from home range sizes in Williams (2002).

Table 3. Density estimates of elephants from Nagarahole-Bandipur National Parks obtained by using annual and seasonal home range estimates as well as mean maximum distance moved by adult bulls during the study.

Discussion

PHOTOGRAPHIC CAPTURE-RECAPTURE OF ELEPHANTS: APPLICABILITY AND RELIABILITY

The results of this study show that the photographic capture-recapture techniques can generate robust estimates of adult male Asian elephant numbers. Karanth and Nichols (1998) suggest that photographic capture-recapture is a practical and reasonable approach to estimating the abundance of tiger numbers. There is no reason to believe that this is not true for elephants as well. Moreover, this study adds to the evidence from earlier findings (Karanth et al. 2004; Kawanishi & Sunquist 2004; Silver et al. 2004; Wallace et al. 2003; Wegge, Pokheral & Jnawali 2004) that photographic capture-recapture techniques can reliably estimate population sizes of animal species that can be identified from photographs on the basis of natural markings.

The applicability of this novel approach to population estimation of adult males opens up many avenues for elephant research. Given that variations in ear and tail patterns were used in combination with tusk patterns, there is potential to apply the same method to additionally identify other segments of an elephant population. Open population models like the superpopulation approach (Schwarz & Arnason 1996) are important for abundance estimation of a wide ranging animal like the Asian elephant and these applied to studies conducted over a long term can give meaningful estimates of additional population parameters such as survival, mortality, recruitment and dispersal rates (Karanth & Nichols 1998) which are not easily available for elephants (Sukumar 2003). Estimates of these different demographic parameters obtained from photographic capture-recapture have been used to understand the population dynamics of tigers (Karanth et al. in press) and can be applied to elephants whose population dynamics can be understood only when a similar long-term demographic profile is available (Sukumar 2003).

Precision of the different parameter estimates can be improved by covering a larger area and at higher densities, such that more animals get captured. For instance, the sampling effort for this study involved sampling five different waterholes for 1.5 to 2 hours during each sampling occasion. Logistically it was not possible to cover more waterholes despite the sampled area having over twenty such sources of water for the animals. Sampling most of these water bodies as compared to a fraction of them would have helped maximize capture probabilities and improve precision. Furthermore, maximization of capture probability can be aided by the availability of a relatively 'silent' vehicle that allows elephants to be approached much closer.

ESTIMATING TOTAL ELEPHANT ABUNDACE AND DENSITY

Use of group composition data

If line transect estimates of elephant density are available for a region, then group composition data can be collected to estimate adult male numbers. This however, does not amount to the same as estimating the abundance of adult bulls directly. The primary reason for this lies in the fact that there are two sources of variance associated with line transect and group composition data that are likely to bias adult male abundance estimates. On the other hand, direct estimation of adult male numbers with only a single associated source of variance will tend to give more robust estimates. The reverse of this i.e., estimating total elephant abundance using estimates of adult male numbers and their proportion in the population, has been attempted here and the same sources of variance apply in this case as well. Estimation of adult male numbers is of primary importance due to its conservation implications and this objective however, was achieved with a fair degree of confidence. Though distance sampling methods could potentially achieve the same goal, especially in relatively open areas, they are unable to facilitate estimation of different demographic parameters that are essential for population monitoring of adult males as well as entire populations.

Adult sex ratio as obtained from the group composition data was found to be 1 male to 4.33 females. A simulation by Sukumar (2003) showed that under a potential growth rate of 2%, a population of 25-30 elephants would have a 99% probability of surviving for 100 years if the adult sex ratio is 1 male to 4 females. The study area is known to have the highest density of Asian elephants in the world and the estimated adult sex ratio coinciding with a total population size of 991 ± 32.75 suggests that the area has tremendous potential of continuing to be one of the most important hotspots for the Asian elephant in the future. This ratio also suggests that this population has been relatively doing better than other populations in South India most of which, have skewed ratios of 1:8 to 1:16 (Sukumar 2003).

Home ranges, the effective sampled area and densities

An abundance estimate on it own has little value when the objective is to focus across sites. Density estimations are important because it is an absolute measure that allows comparisons to be made across contexts. With the help of methods described in this paper, densities were estimated not just for adult males but for all elephants as well. These figures could therefore be directly compared to line transect estimates.

Mean maximum distances moved can be used to estimate the area from which animals were captured. However, if the area sampled is smaller than the normal ranging patterns of the study animal or if the period of the study is short, these may negatively bias area estimates. This was thought to be the case in this study. Under such circumstances, the possibility of using home range estimates from radio-telemetry studies exist and these can give more realistic estimates of density.

The assumption that the geometric shapes of the home range sizes obtained from radio-telemetry data (Bhaskaran et al. 1995; Williams 2002) are circles is likely to negatively bias the home range length positively bias density. However, given the fact that the study period was relatively short and that elephants were inclined to converge towards the Kabini reservoir, adult bulls are unlikely to have ranged as widely as was found in the radio telemetry studies. From such a perspective, the use of annual home ranges could have actually had the opposite effect of potentially over estimating the area and negatively biasing density estimates.

The use of these seasonal home range sizes could arguably be better suited to account for movement patterns of bulls during the period of this study. However, the assumption of the home ranges being circular in shape apply to these as well. This assumption is in fact, likely to have a greater effect with seasonal home ranges as compared to annual home ranges since the study animals are likely to range over an area that is similar to the former and an underestimate of this would undoubtedly overestimate density. Annual home ranges are likely to be much larger than the area covered by the adult bulls during the study period and therefore, an underestimate in this area is unlikely to positively bias density estimates to a great extent. These were used for density estimation since the area thus estimated was considered to be large enough to account for most animals that could potentially move into the study area and get captured. The density estimates obtained are conservative as the area in all likelihood has been over estimated and therefore, these should be considered as minimum density estimates of elephants for the area. This in addition to the fact that there were two sources of variance while estimating total population size, probably explains the reason why the line transect estimates of elephant density for the same area are higher.

ADULT MALE POPULATIONS AND IVORY POACHING

As has been emphasized earlier, ivory poaching is one of two major threats to the survival of Asian elephants. Besides directly depressing adult male numbers, ivory poaching imposes a cost from an evolutionary perspective as well. Adult bulls with longer tusks haven been found to have lower parasite loads (Watve & Sukumar 1997) and if these traits are heritable, then the selective poaching of parasite resistant adult males over several generations could have long-term implications for he population (Sukumar 2003).

Reliable estimates of adult bull population sizes are essential and will undoubtedly help to provide a basis on which conservation strategies against ivory poaching can be designed in addition to facilitating long-term monitoring of populations. However, the status of elephant populations can be understood and clearly evaluated only when information on both elephant abundance and rates of poaching are available (Walsh & White 1999). Therefore, as much as it is important to obtain robust estimates of population size and other demographic parameters of interest, effort needs to be made to establish workable methods that can establish and monitor rates of elephant poaching as well.

Currently there does not seem to be an alternative to collecting information on population trends to monitor elephant populations (Walsh & White 1999). Given this situation, it becomes extremely important that demographic parameters including population sizes are rigorously estimated over a long term such that these can be integrated into conservation practices for elephants based on modern adaptive approaches.

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Appendix 1.

Capture History Matrix																					
Ind ID	**#1**	**#2**	**#3**	**#4**	**#5**	**#6**	**#7**	**#8**	**#9**	**#10**	**Ind ID**	**#1**	**#2**	**#3**	**#4**	**#5**	**#6**	**#7**	**#8**	**#9**	**#10**
1	1	1	0	0	1	1	0	0	0	0	**61**	0	0	0	0	0	1	0	0	1	0
3	1	0	0	0	0	0	0	0	0	0	**64**	0	0	0	0	0	1	0	0	0	0
4	1	0	0	1	0	1	1	0	0	0	**65**	0	0	0	0	0	1	0	0	1	0
5	1	0	0	0	0	0	0	0	0	0	**66**	0	0	0	0	0	1	0	0	0	0
6	1	1	0	0	0	0	0	0	0	0	**67**	0	0	0	0	0	1	0	1	0	1
7	1	0	0	0	0	0	0	0	0	0	**68**	0	0	0	0	0	1	1	0	0	0
8	1	0	0	0	0	0	0	0	0	0	**69**	0	0	0	0	0	1	0	0	0	0
9	1	0	0	0	1	1	1	1	1	0	**70**	0	0	0	0	0	0	1	0	1	1
10	0	1	0	1	0	0	0	0	0	0	**73**	0	0	0	0	0	0	1	0	0	0
12	0	1	0	0	0	0	0	0	0	0	**74**	0	0	0	0	0	0	1	0	0	0
13	0	1	0	0	0	0	0	0	0	0	**75**	0	0	0	0	0	0	1	0	0	0
14	0	1	0	0	0	0	0	0	0	0	**76**	0	0	0	0	0	0	1	0	0	1
15	0	1	0	0	0	0	0	0	0	0	**78**	0	0	0	0	0	0	1	1	1	0
17	0	1	0	0	0	0	0	0	1	0	**79**	0	0	0	0	0	0	1	1	1	0
18	0	1	0	0	0	0	0	0	0	1	**80**	0	0	0	0	0	0	1	0	1	1
19	0	1	0	0	0	0	0	0	0	0	**82**	0	0	0	0	0	0	1	1	0	0
22	0	0	1	0	0	0	0	0	0	1	**83**	0	0	0	0	0	0	1	0	0	0
23	0	0	1	0	1	0	0	0	0	0	**84**	0	0	0	0	0	0	1	0	0	0
24	0	0	1	0	0	1	0	0	0	0	**86**	0	0	0	0	0	0	0	1	0	0
25	0	0	1	0	0	0	0	0	0	0	**87**	0	0	0	0	0	0	0	1	0	0
29	0	0	0	1	0	0	0	0	0	0	**88**	0	0	0	0	0	0	0	1	0	0
30	0	0	0	1	0	0	0	0	0	0	**89**	0	0	0	0	0	0	0	1	0	0
33	0	0	0	1	0	0	0	0	0	0	**94**	0	0	0	0	0	0	0	1	1	0
35	0	0	0	0	1	0	0	0	0	0	**95**	0	0	0	0	0	0	0	1	0	0
36	0	0	0	0	1	1	0	0	0	1	**96**	0	0	0	0	0	0	0	1	0	0
37	0	0	0	0	1	1	0	1	1	1	**100**	0	0	0	0	0	0	0	1	0	0
38	0	0	0	0	1	1	0	0	1	1	**102**	0	0	0	0	0	0	0	1	1	0
40	0	0	0	0	1	0	0	0	0	0	**105**	0	0	0	0	0	0	0	0	1	0
41	0	0	0	0	1	0	0	0	0	0	**116**	0	0	0	0	0	0	0	0	1	0
42	0	0	0	0	1	0	0	0	0	0	**117**	0	0	0	0	0	0	0	0	1	0
43	0	0	0	0	1	1	0	1	0	0	**118**	0	0	0	0	0	0	0	0	1	0
44	0	0	0	0	1	1	1	0	0	0	**122**	0	0	0	0	0	0	0	0	1	0
45	0	0	0	0	1	0	0	0	1	0	**123**	0	0	0	0	0	0	0	0	1	0
46	0	0	0	0	1	0	0	0	0	1	**125**	0	0	0	0	0	0	0	0	0	1
48	0	0	0	0	1	0	0	0	0	0	**135**	0	0	0	0	0	0	0	0	0	1
54	0	0	0	0	0	1	0	1	1	1	**136**	0	0	0	0	0	0	0	0	0	1
55	0	0	0	0	0	1	0	0	0	0	**137**	0	0	0	0	0	0	0	0	0	1
58	0	0	0	0	0	1	0	0	0	0	**139**	0	0	0	0	0	0	0	0	0	1
60	0	0	0	0	0	1	1	0	1	0	**141**	0	0	0	0	0	0	0	0	0	1

Table 1. Capture history of all adult male Asian elephants captured in Nagarahole National Park and Bandipur Tiger Reserve between February and March 2006.

CONCLUSION

The results suggest that the study was successful at developing a relatively rigorous protocol for individual identification of adult males in the light of field conditions. These methods for individual identification can be further improved and strengthened by automating some of the processes. However, as it stands now, it still is useful to establish identities with a fair degree of certainty. This is true despite some amount of subjectivity being inherent in the method.

Photographic capture-recapture techniques were found to generate robust estimates of adult male Asian elephant numbers. This was achieved by using the analytical approach of the superpopulation model (Schwarz & Arnason 1996) that allows estimation of population size for open populations. This highlights the applicability and need for such models to estimate the abundance of a wide ranging animal like the male Asian elephant. These models also allow estimation of demographic parameters such as rates of survival, recruitment, mortality and movement over a long term. Understand the dynamics of an elephant population over time and assessing impacts of threats such as poaching for ivory can thus be facilitated.

The study also found that photographic capture-recapture of adult males can be extended to estimate densities as well. Additionally, using the abundance estimate of adult males and proportions of age-sex categories obtained from group composition data the abundance and subsequently estimates for density of all elephants can be generated. Another important finding was that the adult sex ratio obtained from group composition suggested that the population was relatively healthy. This makes a case for the importance of the population as a genetic pool for elephants in the region and therein lies the need for conservation attention to be maintained in the area.