

Using seismic sensors to detect elephants and other large mammals: a potential census technique

JASON D. WOOD, CAITLIN E. O'CONNELL-RODWELL and
SIMON L. KLEMPERER

Department of Geophysics, Stanford University, Stanford, CA 94305–2215, USA

Summary

1. Large mammal populations are difficult to census and monitor in remote areas. In particular, elephant populations in Central Africa are difficult to census due to dense forest, making aerial surveys impractical. Conservation management would be improved by a census technique that was accurate and precise, did not require large efforts in the field, and could record numbers of animals over a period of time.
2. We report a new detection technique that relies on sensing the footfalls of large mammals. A single geophone was used to record the footfalls of elephants and other large mammal species at a waterhole in Etosha National Park, Namibia.
3. Temporal patterning of footfalls is evident for some species, but this pattern is lost when there is more than one individual present.
4. We were able to discriminate between species using the spectral content of their footfalls with an 82% accuracy rate.
5. An estimate of the energy created by passing elephants (the area under the amplitude envelope) can be used to estimate the number of elephants passing the geophone. Our best regression line explained 55% of the variance in the data. This could be improved upon by using an array of geophones.
6. *Synthesis and applications.* This technique, when calibrated to specific sites, could be used to census elephants and other large terrestrial species that are difficult to count. It could also be used to monitor the temporal use of restricted resources, such as remote waterholes, by large terrestrial species.

Key-words: geophone, *Loxodonta africana*, *Loxodonta cyclotis*

Journal of Applied Ecology (2005) **42**, 587–594

doi: 10.1111/j.1365-2664.2005.01044.x

Introduction

Recent genetic evidence suggests that there may be two species of African elephant, the savanna elephant *Loxodonta africana* Blumenbach and forest elephant *Loxodonta cyclotis* Matschie (Roca *et al.* 2001). Aerial census techniques are used to estimate population numbers in open habitats frequented by the savanna elephant, but this is not possible for forest elephant populations because of the dense tree canopy that covers much of their habitat. Instead, biologists and conservation managers have used a technique that

involves counting elephant dung balls along line transects (Barnes *et al.* 1997; Barnes & Dunn 2002). This technique requires a great deal of time and effort because a line transect must be cut through the forest (Walsh & White 1999). The final estimate can have large standard errors because this indirect method also requires an estimate of production and decomposition rates for dung balls. Each of these estimated rates have associated errors that add to the error of the final estimate (Plumptre 2000). Due to this and other limitations (political instability, lack of infrastructure, etc.: see Walsh *et al.* 2001), the estimates of elephant numbers in Central Africa are less reliable than those in East and Southern Africa (Blanc *et al.* 2003). Plumptre (2000) argued that it is unlikely that indirect methods would be able to detect a 30–50% change in population

size from one survey to the next, based on population estimates in Africa thus far. However, the dung counting technique has seen many improvements since it was first applied to estimating elephant numbers (Wing & Buss 1970; Jachmann & Bell 1979; Walsh & White 1999; Barnes & Dunn 2002; Laing *et al.* 2003), and further improvements may continue. In some instances (such as small or declining populations), it has been argued that dung counts may be more appropriate than aerial surveys (Barnes 2001). However, conservation management would be improved by more accurate methods for monitoring and estimating the size of elephant populations or other large mammals in Central Africa, as these populations are relatively small and threatened by poaching activities. Indeed, the importance of improved techniques to estimate population size is borne out by the frequency with which they are reported as Methodological Insights in this journal (e.g. Ruetter, Stahl & Albaret 2003; Frantz *et al.* 2004; Webbon, Baker & Harris 2004). Others have investigated alternatives to counting elephant dung, such as acoustic arrays (Payne, Thompson & Kramer 2003) and infrared detectors (Prinzivalli 1992). To date, none have explored the potential use of seismic sensors (geophones) to estimate elephant numbers. This technique has the potential to census large mammal species, or to monitor the use of specific sites (such as waterholes or salt licks) over long periods of time. The information collected by the seismic sensors could be linked to a satellite and downloaded by managers remotely.

US government defence contractors developed geophone sensor systems that were deployed by the US military during the Vietnam War to detect troop and vehicle movements (Ullrich 1996), and subsequently several patents have been filed for geophone intruder detection systems (Lee 1973; Hawk *et al.* 1976). The Wyoming Cooperative Fish and Wildlife Research Unit also evaluated a geophone and infrared sensor system that was successful at detecting mule deer about to cross a highway (Gordon *et al.* 2001). Of most relevance to the present project, Seneviratne & Rossel (2001) modified a US Army surplus miniature seismic detector system to detect crop raiding Asian elephants *Elephas maximus* Linnaeus in Sri Lanka. They managed to detect approaching elephants with their system, but it was abandoned as an option for elephant management because of high initial cost and because some elephants started to dig up the geophones and destroy them.

The present study outlines the development of a seismic detection technique for elephants and other large mammals that is based on the detection of the vibrations caused by footfalls. We begin with an investigation of the spectral differences between species and then consider their temporal differences. Based on these initial findings we develop a technique that differentiates between species. Finally, we investigate methods for determining the number of animals creating the seismic signal.

Materials and methods

SEISMIC RECORDINGS

Seismic recordings were made at Mushara waterhole, Etosha National Park, Namibia, in June 2002, using a single 4.5 Hz vertical geophone (Mark Products, Texas, USA) buried 1 m from a major path leading to the waterhole, at a depth of 15 cm. A preamplifier (MM1, Sound Devices, Wisconsin, USA) was used to increase the recording gain, a sound card (VX pocket version 2, Digigram, Monbonnot, France) converted the signal from analogue to digital, which was then recorded on a Dell Inspiron laptop using Cool Edit Pro (version 1.2, Syntrillium, Arizona, USA) at a sampling rate of 44.1 kHz. During recordings notes were taken on species, group size and basic spatial data. Data were collected 86 m from the geophone in an observation tower.

Fifty-seven recordings were made of the footfalls of animals as they passed near the geophone, as well as recordings of the background seismic noise (elephant bulls = 31, elephant herds = 12, gemsbok *Oryx gazella* = 6, giraffe *Giraffa camelopardalis* = 3, human *Homo sapiens* = 1, kudu *Tragelaphus strepsiceros* = 1, lion *Panthera leo* = 1, seismic noise = 2). Recordings ranged in length from 40 to 738 s, with an average length of 275 s. For analytical purposes, these recordings were down-sampled to a sampling rate of 200 Hz, after being passed through an anti-aliasing filter with an eighth-order low-pass Chebyshev Type I filter with a cut-off frequency of 80 Hz. This was carried out to facilitate subsequent processing, because most of the signal generated by animal footfalls is below 80 Hz. An example of a recording of a single bull elephant is shown in Fig. S1 (see Fig. S1 in Supplementary material). Clearly visible is the temporal patterning of the footfalls, with a large amplitude event (a front foot striking the ground) every ~1.5 s, preceded by a smaller amplitude event (a rear foot striking the ground). This temporal pattern is obscured in recordings of a herd of elephants. Figure 1 illustrates the distinction between an elephant footfall and footfalls of smaller, lighter species: the elephant footfall is clearly longer and contains more energy (although these plots were chosen to depict individual footfalls with roughly the same peak amplitude so that their duration and shape could be more easily compared).

SPECTRAL DIFFERENCES BETWEEN SPECIES

We investigated the difference in the spectral components of all the species recorded, except kudu, as a recording of sufficient quality to identify individual footfalls was not available for that species. By viewing the time-series (which depicts the change in amplitude of a recording over time – see Fig. S2 in Supplementary material for an example of a time-series) of a single recording for each species in Cool Edit Pro, we

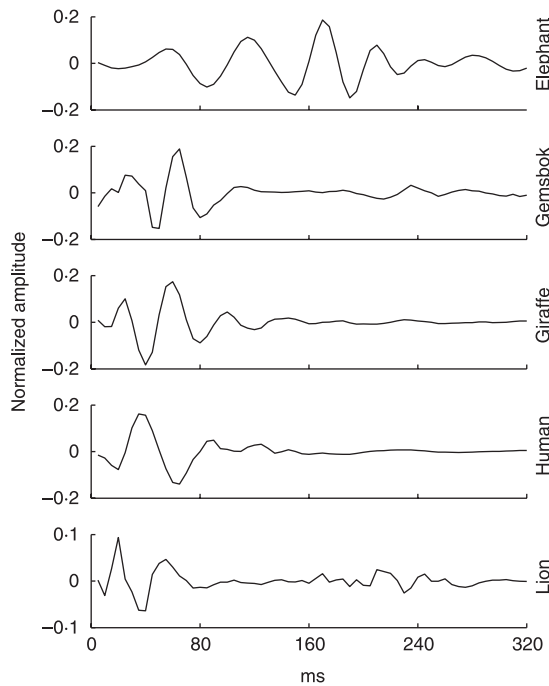


Fig. 1. Time-series of a single footfall for five species to illustrate the variation between species. The frequency of the wavelets are similar, but the duration of the elephant wavelet (front footfall) is longer. Sampling rate = 200 Hz. Amplitude normalized by maximum dynamic range of recording equipment.

extracted 20 individual footfalls per species, each with a length of 64 samples (equivalent to 320 ms). Due to the amplitude difference between front and rear footfalls in elephants we only used front footfalls for that species (the larger amplitude events).

The footfalls were imported into Matlab (version 6.5, The MathWorks, Massachusetts, USA) where a power spectrum plot was created for each, using a Fast-Fourier Transform (FFT) size of 256, and a Hanning window. An FFT converts a signal which is recorded in the time domain into the frequency domain, which allows one to analyse or view the frequency (or spectral) content of a recording by plotting frequency vs. amplitude (see Fig. 2 for an example of a power spectrum plot). The FFT size and sampling rate affect the spectral resolution of a power spectrum (spectral resolution = sampling rate/FFT size). We chose an FFT rate of 256 to gain a fine spectral resolution (0.78 Hz). The 20 power spectra were then summed to obtain a representative power spectrum for each species. In addition, the power spectrum of each footfall was correlated with the power spectrum of every other footfall in order to compare the shape of each power spectrum. The correlation coefficients were then used as the dependent variable in an analysis of variance (ANOVA), to test if there was a difference between comparisons (all correlation coefficients were generated in Matlab while all statistical tests were run in Minitab 13, Minitab Inc., Pennsylvania, USA). We were most interested in the comparison of elephants to themselves

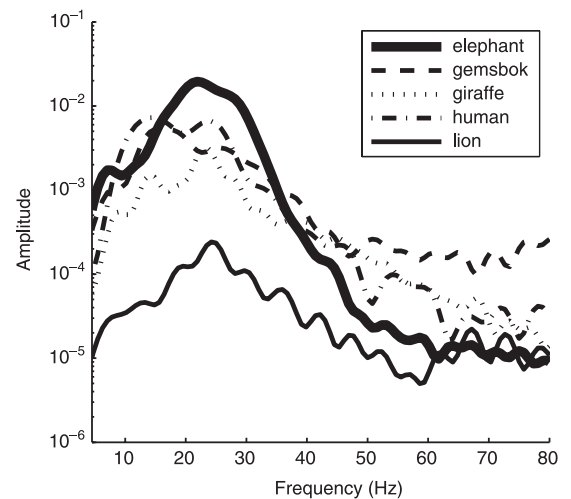


Fig. 2. Representative power spectrum plots for the footfalls of five species created by summing 20 footfalls for each species (using a 256-sample FFT, Hanning window), showing the spectral difference between species. Frequency range 4.5 Hz (the resonant frequency of the geophone) to 80 Hz (the cut-off frequency for the anti-aliasing filter).

and to other species, therefore we included only the correlations of elephant footfalls to other elephant footfalls, and elephant footfalls to the footfalls of other species (elephant vs. elephant $n = 190$, elephant vs. other species $n = 400$ for each species).

TEMPORAL DIFFERENCES BETWEEN SPECIES

Although the temporal patterning begins to break down when there is more than one individual present, we none the less explored temporal patterns in the recordings. Each footfall generates a short wave train (multiple cycles of energy, Fig. 1), so we attempted to identify individual footfalls, or 'beats', by smoothing the time-series. A Hilbert transform was used to create an amplitude envelope for each recording. This transform has no effect on the amplitude of a signal, but shifts the signal by 90° . To generate the amplitude envelope the following equation was used:

$$\text{amplitude envelope} = \sqrt{r^2 + i^2} \quad \text{eqn 1}$$

where r is the original signal and i is the Hilbert transformed signal. A Matlab script was written to extract the time between 'beats' and the duration of 'beats' (Fig. S2). Using the amplitude envelope we extracted the time between 'beats' by identifying peaks that had an amplitude greater than 5% of the maximum amplitude in that recording and greater than 2% of the maximum dynamic range (the maximum range from the smallest to the largest ground motion that can be recorded by the equipment). This helped to control for differences in amplitude due to distance of the animals from the geophone during recording and ensured that recordings with too low an amplitude (probable

background noise) were not included; the 2% and 5% values were chosen by visual inspection of the records. In addition we set temporal thresholds when determining the 'beats' by using only peaks that were more than 0.125 s and less than 2 s apart in order to exclude peaks that were not due to footsteps and to calculate time between peaks only when animals were moving; again, these times were chosen by visual inspection of the data. If a 'beat' was not encountered within 2 s of the previous 'beat' it was assumed that the animal/s had momentarily stopped moving and therefore that this particular time between 'beats' was not indicative of their temporal pattern due to walking. We also extracted information on duration of 'beats' from the amplitude envelope, by selecting peaks with an amplitude greater than 5% of the maximum amplitude of that particular recording and greater than 2% of the maximum dynamic range, and including any peaks within the duration of a 'beat' that were less than 0.125 s apart.

DIFFERENTIATING SPECIES

In order to determine if spectral differences could be used to differentiate between species, a Matlab script was written that generated consecutive power spectra for each recording. This script extracted the first 128 samples (640 ms), followed by the next 128 samples, and so on until it reached the end of that particular time-series. Each 128 sample segment was used to generate a power spectrum (FFT: 256, Hanning window). The Fourier transform works most efficiently when the FFT size is a power of 2. We chose an FFT size of 256 (2^8) for fine frequency resolution and chose 128 (2^7) sample length for our script so that each segment would be shorter than the duration between footfalls. Each of these power spectra was correlated with the representative power spectrum for an elephant (see below; see Fig. 2). In order to obtain a measure of high correlation over a period of time, the number of correlation coefficients greater than 0.8 (the mean correlation coefficient for the spectral comparison of elephant footfalls to other elephant footfalls was 0.78, SE: 0.01 see below) were counted over 100 consecutive correlations (equivalent to 64 s of recording). For each of the 57 recordings the highest count of correlation coefficients over 100 correlations was used as the dependent variable in a discriminant analysis (for the three recordings less than 64 s, the count across the length of the recording was used). For this analysis, each recording was grouped as elephant ($N = 43$), or other ($N = 14$).

DETERMINING NUMBER OF INDIVIDUALS

Using the group size noted for each recording (which varied from one to 23 elephants), we tried to develop a method to predict group size without that information. We used two methods: (1) calculating the number of peaks per second and (2) calculating the area under the amplitude envelope of the signal.

Peaks per second

Each time-series was filtered with a 23rd-order Butterworth band-pass filter with the corner frequencies at 10 and 40 Hz. This was conducted to exclude frequencies outside the band pass, as most of the energy of the footfalls fell within this band pass range (Fig. 2). The Hilbert transform was then used to calculate the amplitude envelope from which the number of peaks over a given threshold was calculated. We used 5, 10, 15, and 20% of the maximum amplitude as threshold values. In addition the peaks had to be greater than 2% of the maximum dynamic range. Sections of recordings that were used for the rate calculation were more than 2 s in duration. Separate sections were assigned to a time-series if there were any gaps between peaks greater than 5 s. This was performed so that large periods without peaks were not included in the rate calculation. The value from the section with the highest peak per second rate from each file was then regressed against the number of animals in that file.

Area of amplitude envelope

For this analysis we used the same band-pass filter and amplitude envelope as we did for the peaks per second analysis. In addition a 5 s segment of background noise was identified for each recording and the area under this part of the amplitude envelope was calculated and then divided by 1000 (the number of samples from 5 s of recording with a 200 Hz sampling rate). This gave us a measure of the background noise level for each recording. We then calculated the area under the amplitude envelope for each recording and subtracted area due to noise to find the area due to the footfalls of elephants. This process was carried out in order to estimate the energy created by the elephant footsteps (more energy should result from more elephants). This can only be achieved by calculating the energy (the area under the amplitude envelope) in the recording while the elephants are present and subtracting from this the energy due to background noise in the ground. Background noise is usually dominated by wind, either coupling directly to the ground or through vegetation shaking, but may also include anthropogenic sources and even other seismic signals from animals (e.g. Günther, O'Connell-Rodwell & Klemperer 2004).

Results

SPECTRAL DIFFERENCES BETWEEN SPECIES

Power spectrum plots were generated for the five species (Fig. 2). All species have a peak around 25 Hz but the shape of the spectra are different, with the elephant spectrum having the most pronounced low-frequency component and one of the lower high-frequency components, yielding a very distinctive

low-to-high frequency ratio. $A_{25\text{Hz}}/A_{50\text{Hz}} \sim 1000$ for elephants, but ≤ 100 for the other measured species. There were significant differences in the shape comparison of elephant footfall spectra vs. the spectra of other elephant footfalls, and elephant footfalls vs. the footfalls of other species (ANOVA: $F_{4,1785} = 147.78$, $P = 0.000$). These differences were significant for each pairwise comparison (Tukey's multiple pairwise comparison, $P < 0.05$). The least squares means and their standard errors (in parentheses) were as follows: representative elephant footfall vs. elephant footfalls = 0.78 (0.01), representative elephant footfall vs. gemsbok footfalls = 0.49 (0.01), representative elephant footfall vs. giraffe footfalls = 0.67 (0.01), representative elephant footfall vs. human footfalls = 0.73 (0.01), representative elephant footfall vs. lion footfalls = 0.54 (0.01).

TEMPORAL DIFFERENCES BETWEEN SPECIES

We were successful in extracting the duration of beats and the time between beats, but when we plotted the mean duration of beats vs. the mean time between beats (see Fig. S3 in Supplementary material) neither measure gave any insight into differentiating between species, although duration of beat did give some indication of group size. Mean time between beats may not be a good measure for the temporal patterning of elephant footfalls because of the syncopated pattern of elephant gaits (Fig. S1).

DIFFERENTIATING SPECIES

In general, the correlation coefficients for the comparison of the representative elephant power spectrum to the power spectra from elephant recordings were higher than the coefficients resulting from the comparison to the power spectra of recordings of other species, or background noise. The mean highest count over 100 correlations for elephant recordings was 86.49 (SD = 9.75), while the equivalent figure for other species and background noise was 57.0 (SD = 25.36). The discriminant analysis differentiated successfully between elephant footsteps and the footsteps of other species, on average, 82% of the time (Table 1).

Table 1. Classification results from discriminant analysis using the highest count of correlation coefficients > 0.8 across 100 correlations

Classified Group	True group	
	Elephant	Other
Elephant	40	4
Other	3	10
Total N	43	14
N correct	40	10
Proportion	0.93	0.71
Average proportion correct	0.82	

Table 2. Regression analyses for peaks per second at various amplitude levels vs. number of elephants in group

Amplitude threshold*	Summary statistic	P -value	R^2
5%	$F_{1,38} = 25.6$	0.000	40.3%
10%	$F_{1,38} = 18.4$	0.000	32.7%
15%	$F_{1,38} = 21.4$	0.000	36.0%
20%	$F_{1,38} = 24.0$	0.000	38.7%

*Percentage of maximum amplitude.

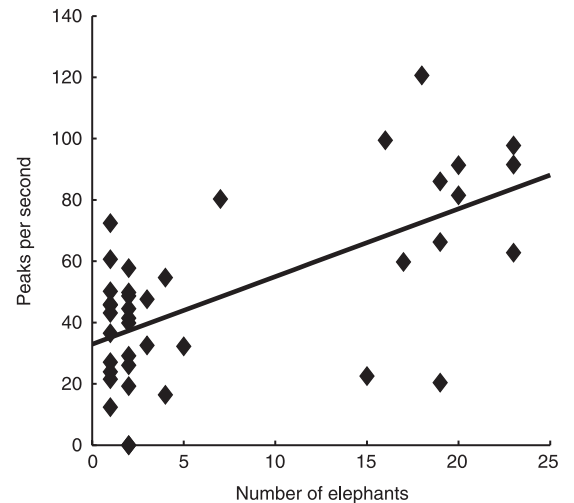


Fig. 3. Plot of peaks per second vs. number of animals using the 5% amplitude threshold and the fitted regression line that explains 40% of the variance in the data (regression line: $Y = 32.9 + 2.2X$).

The misclassified data were three recordings of single elephants, two recordings of giraffe and two of gemsbok. Our false positives represent 29% of our non-elephant large-mammal population (although our number of useful recordings is still small), but our false negatives comprise only 7% of our total number of elephant recordings (Table 1).

DETERMINING NUMBER OF INDIVIDUALS

Estimates of the number of individuals were run on the 40 elephant recordings that were categorized as being elephants by the discriminant analysis.

Peaks per second

While the regression line for all amplitude levels was significant, the 5% amplitude level explained the largest amount of variance in the data (see Table 2). Figure 3 shows the regression line for the 5% amplitude level. Only 40% of the variance in the data is explained by this line. Much of the variance in peaks per second is due probably to the distance at which the elephants passed the geophone and the configuration in which they passed (i.e. in single file, a single cluster or several

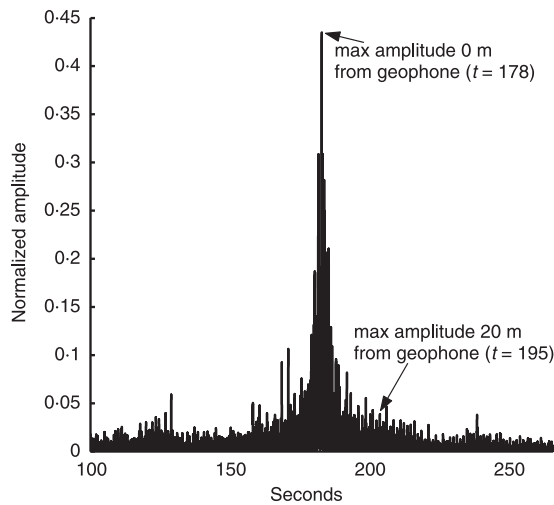


Fig. 4. Amplitude envelope of a single bull elephant that passed directly over the geophone. Based on the estimated speed of 1.2 m s^{-1} for this individual we can use the amplitude envelope to estimate the amplitude this individual created at 20 m.

smaller clusters). We used an amplitude selection criterion based on a percentage of the maximum amplitude of that recording to control for much of the variation due to distance from the geophone. However, we expected less variation between the peaks per second recorded for single elephants. Our results suggest that we have not identified an effective way of controlling the variance in peaks per second due to distance differences, or that peaks per second is not an appropriate measure to use.

Area of amplitude envelope

In addition to background noise, the area under the amplitude envelope (the estimate of the amount of energy created by the elephants) is also affected by the distance at which the animals pass the geophone. This is evident when viewing the amplitude envelope in Fig. 4. This figure was generated from a recording of a single bull elephant that passed directly over the geophone. The section of the amplitude envelope that is shown is the length of the recording in which the footfalls were visible above the background noise. Based on five location measurements of this elephant as it approached the waterhole and the distance and duration between these locations, we estimated its speed at 1.2 m s^{-1} (see Wood 2003 for details). Given that the duration of the recording in which footfalls are visible is 166 s, the radius of detection is roughly 100 m. With a calculated speed of 1.2 m s^{-1} , we can use Fig. 4 to estimate the maximum amplitude for an elephant that passed 20 m from the geophone. As indicated on the figure, this is considerably lower ($\sim 20 \text{ dB}$) than when the elephant passed directly over the geophone.

In addition, the duration of time over which the footfalls were detectable for the more distant elephant

Table 3. Regression analyses for area under the amplitude envelope vs. number of elephants in group. Various corrections were attempted to deal with the variance due to the elephants passing the geophone at different distances

Dependent variable	Summary statistic	P-value	R^2
Area	$F_{1,38} = 15.3$	0.000	28.7%
Area/maximum	$F_{1,38} = 16.3$	0.000	30.0%
Area/ $\sqrt{\text{maximum}}$	$F_{1,38} = 47.5$	0.000	55.6%
Area/maximum/duration	$F_{1,38} = 11.4$	0.002	23.0%
Area/ $\sqrt{\text{maximum}}$ /duration	$F_{1,38} = 24.0$	0.000	38.8%

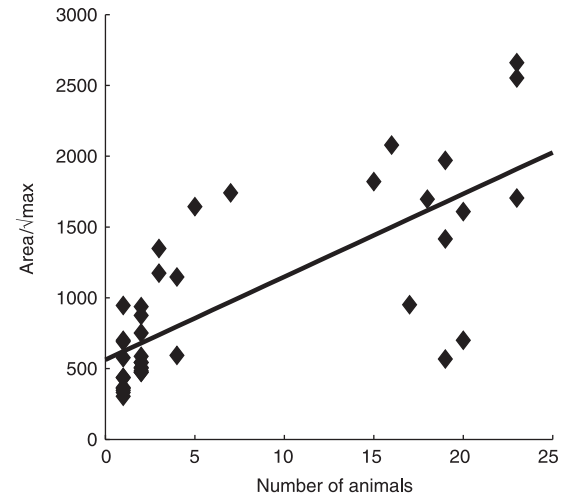


Fig. 5. Plot of $\text{area}/\sqrt{\text{maximum}}$ vs. number of animals and the fitted regression line that explains 55% of the variance in the data (regression line: $Y = 562.8 + 58.5X$).

would be shorter. This is easy to conceptualize if one thinks of a detection circle around the geophone. The further the elephants pass from the geophone, the less time they will be within the detection circle. The amplitude envelope created by elephants passing further from the geophone will also have less of a pronounced peak at its maximum, as demonstrated in Fig. 4. If the animals in question passed 20 m from the geophone its maximum amplitude would not be much higher than the rest of the recording. These issues (duration of time within detection radius and height of maximum amplitude relative to the rest of the amplitude envelope) will all affect the area under the amplitude envelope and therefore our estimate of the amount of energy created by the elephants. We tested different methods to control for this including area/maximum, area/ $\sqrt{\text{maximum}}$, area/maximum/duration, and area/ $\sqrt{\text{maximum}}$ /duration.

The results of the regression of these variables against the number of animals in the group are given in Table 3. The highest R^2 value was 55% using area/ $\sqrt{\text{maximum}}$ as the dependent variable. This regression (Fig. 5) is an improvement on the regression based on peaks per second (Fig. 3). There is less variation for one

to two animals relative to the herds in Fig. 5 than there is in Fig. 3. Therefore, at this stage, we recommend use of the measure $\text{area}/\sqrt{\text{maximum}}$, and the regression line shown in Fig. 5, to estimate the size of the herd in each recording.

Discussion

Counting the number of animals in a given area has long been a difficult issue for conservation managers, either because of the effort required (both physical and financial) or the quality of the final estimate. This is particularly true of elephant populations in Central Africa. While much progress has been made in refining current techniques, in certain circumstances it may be preferable to utilize alternative methods.

This study has shown that it is possible to differentiate the footfalls of different species (with ~82% accuracy) using a single geophone, and to count the number of elephants using a regression line that explains ~55% of the variance in the data. Given this level of precision, and that the resulting estimates will be unbiased, our technique should be immediately useful to managers. Our attempts to improve this technique have been impeded by the variation in our seismic recordings due to the distance at which the animals passed the single geophone. Some of the variation in the energy generated by herds (e.g. the lowest two points for herds of size 19 and 20 in Fig. 5), can be attributed to the fact that these recordings started only after the herd had passed the geophone. Had we managed to record them approaching and passing the geophone their measure of $\text{area}/\sqrt{\text{maximum}}$ would have been higher.

However, correcting the measure of area under the amplitude envelope (our measure of energy) by dividing it by the square root of the maximum amplitude does provide a reasonable estimate of elephant numbers. This is due probably to the fact that the area under the maximum amplitude is fairly localized (Fig. 4). The maximum amplitude has a small effect on the area under the rest of the curve, so dividing the area by the maximum amplitude over-corrects for variation due to the distance between the animal and geophone. While there is variation in the duration that the animals are within the detection radius of the geophone, due to distance between animal and geophone, this variation is on a much smaller scale (a factor of 2 or 3). Controlling for variation in duration by dividing by duration gives a less precise estimate, because the duration the animals are within the detection radius is confounded by the configuration of the individuals in the herd. If two identical herds of the same size passed the geophone on the same path, one in single file and the other in a cluster, the one in single file would have lower maximum amplitude but longer duration, while the clustered herd would have higher maximum amplitude and shorter duration. The area under the amplitude envelopes would be roughly the same, so that if one divides by the duration, the herd in single

file would be incorrectly estimated to have fewer individuals.

We intend to improve our current technique by utilizing an array of geophones which will allow us to use beam forming techniques, such as those used in hydrophone arrays (e.g. Clark & Ellison 2000), to track the movements of elephants past the array. This has two benefits: (1) using a model of the variation in the amplitude envelope due to distance from the geophones and the calculated distance to the elephants, we can control for variations in the signal and its amplitude due to the distance between the elephants and the sensor; and (2) calculations of the bearing and distance would allow us to use a point sampling technique to estimate population numbers (Greenwood 1996). In addition, using this technique in areas such as Central Africa, where elephant group size is smaller than in East or Southern Africa, should improve estimates of the number of animals passing the geophones.

Using a geophone array has additional advantages. Seismic equipment is designed for rugged field use, and independent arrays can be buried and left in the field to collect the data, for perhaps as long as a month (depending on the number of geophones, sampling rate, computer memory and power requirements). These arrays could be left for longer durations by changing the battery and downloading the data at regular intervals. By deploying several arrays in an area we should be able to estimate not only the numbers of individuals in that area, but also their spatiotemporal resource use. A seismic detection system may also be valuable for managers who need to monitor the use of a scarce resource by elephants or other species. For example, deploying an array at a waterhole in an arid region would allow the manager to monitor the use of this waterhole by different species over a long period of time.

This paper lays out the fundamentals for a seismic census and detection technique. Its successful application in the field will depend on software developed to automate signal processing, making the data accessible to managers. Another limiting factor is the distance over which elephant footfalls will travel. As indicated above, the detection radius for an elephant footfall is roughly 100 m in Etosha National Park. This will vary depending on the soil type where the geophone is deployed, but using 100 m as an estimate, an array of three geophones would cover between 0.06 and 0.09 km². A large number of arrays (up to 40) would be needed to decrease the sampling variance so that the estimate was valuable to managers. This is because of the relatively small area covered by each array and because elephant use of their habitat is not uniform. Despite these caveats, the real benefit of using a seismic system is that it can be left in place over long periods of time. This should enable managers and researchers to gather population data at a finer temporal scale than current census techniques, and to monitor the use of specific habitat features over time. By leaving the arrays

in place and downloading the data and changing batteries as needed, one could monitor an area for long enough to measure changes in abundance and use, not just on an annual scale but at seasonal scales. This technique has the potential to increase our understanding of the ecology of large mammal populations in a non-invasive way, and it can also provide crucial data for reserve planning and management.

Acknowledgements

We thank the Namibian Ministry of Wildlife and Tourism for their support of this project, Timothy Rodwell for technical support and Roland Günther for input on data analysis. We are grateful to Peter Walsh and an anonymous reviewer whose suggestions greatly improved this article. This project was funded by the US Fish and Wildlife Service, National Geographic and a Stanford University Bio-X research grant.

Supplementary material

The following supplementary material is available for this article online.

Fig. S1. Time series of a single bull elephant showing the distinct temporal pattern with low amplitude rear footfalls followed shortly by higher amplitude front footfalls.

Fig. S2. Time series from a single elephant showing the amplitude envelope and how the time between 'beats' and duration of 'beats' was calculated.

Fig. S3. Plot of mean duration of 'beats' vs. mean time between 'beats'.

References

- Barnes, R.F.W. (2001) How reliable are dung counts for estimating elephant numbers? *African Journal of Ecology*, **39**, 1–9.
- Barnes, R.F.W., Beardsley, K., Michelmore, F., Barnes, K.L., Alers, M.P.T. & Blom, A. (1997) Estimating forest elephant numbers with dung counts and a geographic information system. *Journal of Wildlife Management*, **61**, 1384–1393.
- Barnes, R.F.W. & Dunn, A. (2002) Estimating forest elephant density in Sapu National Park (Liberia) with a rainfall model. *African Journal of Ecology*, **40**, 159–163.
- Blanc, J.J., Thouless, C.R., Hart, J.A., Dublin, H.T., Douglas-Hamilton, I., Craig, C.G. & Barnes, R.F.W. (2003) *African Elephant Status Report 2002: An update from the African Elephant Database*. IUCN/SSC African Elephant Specialist Group. IUCN, Gland, Switzerland and Cambridge, UK.
- Clark, C.W. & Ellison, W.T. (2000) Calibration and comparison of the acoustic location methods used during the spring migration of the bowhead whale, *Balaena mysticetus*, off Part Barrow, Alaska, 1984–93. *Journal of the Acoustical Society of America*, **107**, 3509–3517.
- Frantz, A.C., Schaul, M., Pope, L.C., Fack, F., Schley, L., Muller, C.P. & Roper, T.J. (2004) Estimating population

- size by genotyping remotely plucked hair: the Eurasian badger. *Journal of Applied Ecology*, **41**, 985–995.
- Gordon, K.M., Anderson, S.H., Gribble, B. & Johnson, M. (2001) *Evaluation of the FLASH (Flashing Light Animal Sensing Host) System in Nugget Canyon, Wyoming*. Report Number FHWA-WY-01/03F, PB2002101172. Wyoming Cooperative Fishery and Wildlife Research Unit, University of Wyoming, US Department of Transportation Federal Highway Administration, Laramie.
- Greenwood, J.J.D. (1996) Basic techniques. *Ecological Census Techniques: a Handbook* (ed. W. J. Sutherland), pp. 11–110. Cambridge University Press, Cambridge.
- Günther, R.H., O'Connell-Rodwell, C.E. & Klemperer, S.L. (2004) Seismic waves from elephant vocalizations: a possible communication mode? *Geophysical Research Letters*, **31**, L11602.
- Hawk, H.L., Hawley, J.G., Portlock, J.M. & Scheibner, J.E. (1976) *Seismic Intrusion Detector System*. US Patent 3 984 803 5 October 1976.
- Jachmann, H. & Bell, R.H.V. (1979) The assessment of elephant numbers and occupancy by means of droppings counts in the Kasungu National Park, Malawi. *African Journal of Ecology*, **17**, 231–239.
- Laing, S.E., Buckland, S.T., Burn, R.W., Lambie, D. & Amphlett, A. (2003) Dung and nest surveys: estimating decay rates. *Journal of Applied Ecology*, **40**, 1102–1111.
- Lee, R.D. (1973) *Intruder Detection System*. U.S. Patent 3 719 891 6 March 1973.
- Payne, K.B., Thompson, M. & Kramer, L. (2003) Elephant calling patterns as indicators of group size and composition: the basis for an acoustic monitoring system. *African Journal of Ecology*, **41**, 99–107.
- Plumptre, A.J. (2000) Monitoring mammal populations with line transect techniques in African forests. *Journal of Applied Ecology*, **37**, 356–368.
- Prinzivalli, R.A. (1992) Investigating the use of infrared detectors to count elephants in a forest environment. *African Journal of Ecology*, **30**, 346–348.
- Roca, A.L., Georgiadis, N., Pecon-Slattery, J. & O'Brien, S.J. (2001) Genetic evidence for two species of elephant in Africa. *Science*, **293**, 1473–1477.
- Ruette, S., Stahl, P. & Albaret, M. (2003) Applying distance-sampling methods to spotlight counts of red foxes. *Journal of Applied Ecology*, **40**, 32–43.
- Seneviratne, L. & Rossel, G. (2001) Living next door to a national park. *Sri Lanka Nature*, **2001**, 51–56.
- Ullrich, R. (1996) Building on and spinning off: Sandia National Lab's creation of sensors for Vietnam. Report no. SAND-96-2824C, CONF-9611112-1. *History of Science Society Meeting, 8 November 8 1996, Atlanta, Georgia*. US Department of Energy, Washington, DC.
- Walsh, P.D. & White, L.J.T. (1999) What it will take to monitor forest elephant populations? *Conservation Biology*, **13**, 1194–1202.
- Walsh, P.D., White, L.J.T., Mbina, C., Idiata, D., Mihindou, Y., Maisels, F. & Thibault, M. (2001) Estimates of forest elephant abundance: projecting the relationship between precision and effort. *Journal of Applied Ecology*, **38**, 217–228.
- Webbon, C.C., Baker, P.J. & Harris, S. (2004) Faecal density counts for monitoring changes in red fox numbers in rural Britain. *Journal of Applied Ecology*, **41**, 768–779.
- Wing, L.D. & Buss, I.O. (1970) Elephants and forests. *Wildlife Monographs*, **19**, 6–92.
- Wood, J.D. (2003) *Communication and spatial cohesion of the African elephant, Loxodonta africana*. PhD Thesis, University of California, Davis.

Received 14 June 2004; final copy received 16 February 2005
Editor: Steve Rushton