Supplementary Materials

I. NEST SURVEY METHODS

I.1 Data for Analysis

Comparison of results from the two surveys eras was complicated by the fact that the primary data on nest group encounter rate from Tutin & Fernandez's (1984, hereafter T&F) 1981-83 study is now lost. All that remains for most of the 24 sample zones are two tables holding separate estimates of abundance and density for gorillas and chimpanzees in each zone. The abundance table gives estimates for each zone based on two different procedures: one based on a transect sample of about 20km and a second extrapolation based on the relationship between ape density and habitat type in the intensively studied (675.8km of line transects) Belinga region in northeast Gabon (Table IV, T&F). The second table (Table V) gives a density estimate for "suitable ape habitat" in each zone based on what the authors felt was the better of the two abundance estimates (which is noted in Table IV). We preferred to you use only transect estimates so we recalculated density (d_i) for each zone in which the extrapolated density was reported by T&F. We did this by multiplying the extrapolated density (Table V) for each zone i by the ratio of the transect abundance (a_{ci}) to extrapolated abundance (d_{ei}) for that zone,

$$\widetilde{d}_i = d_i \frac{a_{ii}}{a_{ei}}.$$

We performed this operation separately for gorillas and chimpanzees then added gorilla and chimp densities to arrive at an ape density for each zone. To convert ape density into ape nest group encounter rate we exploited the fact that gorilla and chimp nest group encounter rates for the intensively studied Belinga region were published in T&F (combined encounter rate =1.3 nest groups/km). Thus, we estimated the ape nest group encounter rate for each zone i as

$$\frac{n_i}{km} = 1.3 \frac{d_i}{d_B},$$

where \tilde{d}_{B} is the estimated transect density for the Belinga zone.

We pooled gorilla and chimps because of the complexities of making species identifications on sleeping nests, which are built by adults of both species each night. When T&F performed their ape surveys in the early 1980's prevailing practice was to assume that all nests in trees belonged to chimps and all nests in on the ground belonged to gorillas. Subsequent studies have shown that gorillas often build nests in trees and that gorilla tree nests are extremely difficult to discriminate from chimp nests (Tutin et al., 1995). A substantial proportion of nest groups classified as chimpanzee by T&F were probably gorilla nest groups. Establishing what proportion of tree nests were misidentified is virtually impossible, as the proportion of gorilla nests built in trees varies greatly as a function of factors such as rainfall and habit type. Because of this problem, we pooled gorilla and chimp nest group into a single class (ape nest groups).

We analyzed nest groups rather than individual nests, in part, because the early and recent surveys used different definitions for calculating nest group size. T&F counted only nests visible from the transect line as belonging to a nest group while the recent surveys included nests that were not visible from the transect line. We lacked information that would allow us to correct for this underestimation of true nest group size by T&F. Therefore, in comparing the two eras we used nest group encounter rate rather than individual nest encounter rate.

We analyzed nest group encounter rate rather than nest group density because most of the data from the recent epoch was collected using the "recce" method. When combined with line transects, recces can provide data for density estimation (Walsh & White, 1999; Beyers, et al., 2001). Unfortunately, about half of the recent data came from surveys in the Minkébé region in which no associated line transects were performed. Rather than throw out the large amount of data collected in this critical region we chose to use nest group encounter rate (nest groups/km) as the dependent variable in our analyses. To estimate encounter rate at a given site we used encounter rate data from both recces and line transects, as past studies of both elephant dung (Walsh & White, 1999) and ape nest groups (Hall et al., 1998) have shown a correlation between recce encounter rates and encounter rates on nearby line transects. This correlation also

held for the 30 sampling sites in our recent surveys that had both recces and transects (ape nest groups: $R^2 = 0.48$; p= 0.000023; elephant dung $R^2 = 0.39$, p=0.000025; unless otherwise noted all test results are for coefficient of determination for Peason correlation). Ape nest group encounter rates on transects and recces were not significantly different for the 30 sites with both recces and transects (paired t test, t=1.52, two tailed p=0.16). Therefore, when calculating the nest group encounter rate for each site we simply summed the number of nest groups encountered on recces and transects and divided by the combined length of recces and transects.

I.2 Spatial Modeling

T&F's surveys in the 1980's were distributed fairly systematically across Gabon, with each sampling site chosen to be representative of some larger region. Our recent surveys were also spread across Gabon, but within a given region they focused on areas we expected to have uncharacteristically high large mammal densities: existing or potential protected areas, many of which have recently been declared National Parks (Rep. Gabonnaise, 2002). Our sampling design guaranteed that the difference between samples means in the two eras would be strongly biased towards underestimating the magnitude of ape decline. This problem we addressed by employing a spatial modeling approach in which the functional relationship between nest group encounter rate and important environmental predictors was first estimated, then used to interpolate a national encounter rate surface for each sampling era. The magnitude of ape decline was then estimated in terms of the national mean interpolated encounter rates for the two eras (i.e. the recent mean divided by the early 1980's mean).

The local and regional scale non-randomness of our surveys also limited which environmental variables could be used to predict nest group encounter rate. At many sites our sampling did not to span the regional gradient in the value of environmental covariates that have been shown to influence the distribution of apes (T&F; Walsh et al., 2000) or other mammals (Michelmore et al., 1994; Walsh et al., 2000). Initial attempts at modeling local variation in nest group encounter as a function of factors such as secondary forest density or distance from roads or villages, therefore, produced some bizarre results. We subsequently confined our

analyses to environmental factors that varied on a large spatial scale. Thus, care should be taken not to overinterpret local scale structure in our interpolated surfaces for ape nest group encounter rate. These surfaces are probably represent the national trend fairly well, but may very inaccurate on a local or regional scale.

The two large-scale variables we analyzed were distance from the nearest of Gabon's four major population centers (in order of declining population size: Libreville, Port Gentil, Franceville-Moanda, and Oyem) and distance from the nearest of the three human Ebola outbreaks that occurred before our surveys were conducted. A very large proportion of Gabon's population lives in these four metropolitan areas (probably about 80%) so that the distance from these areas provides a good first order approximation of market hunting pressure. The distance from human Ebola outbreaks provides the most reasonable proxy for actual data on ape infections, which are extremely sparse. However, the spatial distribution of human outbreaks may greatly underestimate the distribution in apes because much of ape range in northern and northeastern is sparsely populated by human so that the probability of detecting ape carcasses is low.

We considered three different functional forms for relating nest group encounter rate to distance to major cities (c) and distance to ebola outbreaks (h), with both distances measured in degrees (at the Equator, one degree equals about 110km). The first model we considered was the linear model

$$\frac{n}{km} = \alpha cO + \beta cR + \gamma hR + \delta,$$

where α , β , γ , and δ are constants and *O* and *R* are dummy variables, with *R* assuming a value of 1 for the recent era and 0 for the early 1980's. O followed the opposite pattern so that the Ebola term (γhR) only operated on the recent data. The second model was a power law

$$\frac{n}{km} = (c^{\alpha}O + c^{\beta}R + h^{\gamma}R)\delta$$

and the third a logistic model (not shown). For each functional form, we considered models in which each era could assume a different value of the constant δ , for example in the power law case

$$\frac{n}{km} = (c^{\alpha}O + c^{\beta}R + h^{\gamma}R)(\delta_1O + \delta_2R).$$

The various models were fitted using the principle of maximum likelihood assuming normally distributed errors. The maximum likelihood fitting produced parameters estimates that were identical to those derived from least squares but allowed the use of Akaike's information criterion (AIC) to select a best (most parsimonious) model (Burnham & Anderson, 1998). One sampling site, the Moukalaba Reserve (now the Moukalaba-Doudou National Park) in southwestern Gabon, was excluded from the estimation process as an outlier. This site had a nest group encounter rate more than twice as high as the next highest site in either era. Including Moukalaba with the other 89 sampling sites increased the negative of the natural logarithm of the likelihood by 87% (Sum of Squares increased by 88%).

AIC consistently favored models with all three major effects (i.e. separate distance from city effects for the early and recent samples and a distance from Ebola outbreak effect for the recent samples) over models in which one or more of the major effects was omitted. AIC chose the power law model as the best model, with a common intercept constant δ for the two eras. The estimated parameter values were α =0.86, β =1.16, γ =0.34, δ =1.66. Adding separate constants for the two eras did not significantly improve model fit (Likelihood Ratio Test, X^2 =0.62, df=1). This result is consistent with the notion of a "characteristic" density for healthy ape populations that is typical of both eras. Rather than uniformly reducing all populations from this characteristic density, market hunting and ebola appear to have acted more like an advancing wave, decimating populations along the wave front but having relatively light impacts on populations beyond the front.

A national surface for ape nest group encounter rate was estimated by cutting Gabon into a 30arc second (approximately 1km²) grid based on the TREES Project vegetation classification for Central Africa (http://www.gvm.sai.jrc.it/Forest/Africa/carto.htm). All cells in the classification identified as primary or secondary forest (about 84% of the surface area of Gabon) were assumed to be suitable for apes. Because a comparable vegetation classification for the early 1980's was not available, we assumed that both sampling epochs enjoyed the same distribution of suitable habitat. Using this relatively recent estimate of suitable

habitat represents a further source of conservatism in our estimate of the magnitude of ape decline, because it tends to underestimate the amount of ape habitat available during the early 1980's surveys and overestimate the amount available during the recent surveys. In addition, much deforestation in Gabon occurs at a spatial scale below 1km. Therefore, the 1km vegetation classification we used probably tends to underestimate the amount of habitat degradation in Gabon, much of which has occurred over the last two decades: after the 1987 opening of the transnational railroad and the 1994 currency devaluation. Furthermore, conversion from primary to secondary forest over the last two decades has probably diminished habitat quality for chimpanzees, which rely heavily on primary forest fruit trees. All of these factors further contribute to the tendency for our procedure to underestimate the magnitude of ape decline.

I.3 Nest Group Size

Our recent surveys suggest that, since the early 1980's, Ebola may have caused a substantial decrease in the size of nest groups. A linear regression of ape nest group size versus distance to the nearest of the first three human Ebola outbreak sites (Minkouka, Mayibout, or Booué) showed that nest group size far away from human outbreak sites was 50% higher (n=1,143nest groups, p=0.0002) than nearby human outbreaks

Nest/Group = 2.02 + 0.23*Distance to Ebola Outbreak,

where distance was again measured in degrees. The sampling site furthest away from the nearest human outbreak was the Mayumba Reserve (now Mayumba National Park) in extreme southwest Gabon, which was 4.27degrees from the Booué outbreak. Because the raw data from T&F's survey have been lost, we could not use them to evaluate whether this gradient in nest group size already existed in 1982. However, clues in the paper published by T&F suggest that it probably did not. About 86% of sampling (675.8km of 782.8km of transects) in the initial phase of their survey took place in the Belinga region in the northeast. In that initial phase, T&F reported mean nest group sizes of 4.0nests for gorillas (540nests in 136nest groups) and 1.8nests for chimpanzees (1,606nests in 896 groups), giving a mean ape nest group size of 2.1nests. However, this figure includes only nests visible from the transect line and, therefore, substantially underestimates nest group size. This underestimation may have been particularly serious for gorilla groups,

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which sleep in substantially larger groups than chimpanzees but often build ground nests that cannot been seen from even a few meters away. Unfortunately, we lacked any data with which to establish exactly how much group size was underestimated by T&F. But the nest visibility data presented in Tables II & III of T&F give some sense of the magnitude of underestimation. These tables show that the number of nest groups detected decreased strongly with increasing distance from the transect line, with anywhere from 8-35% fewer gorilla and chimpanzee nests detected at higher distances from the transect line than detected from 0-2.5m (the "0" class covers 0-2.5m while other classes cover 5m intervals). This observation is potentially meaningful because much of the decrease may have been associated with the failure to count all nests within detected groups rather than the failure to detect groups at all.

The only other data with which to test for the existence of a national group size gradient in the early 1980's are from a study conducted by one of us (LJTW) at the Lope Reserve (now National Park) from 1989 to 1991. These data also suggest that a gradient did not exist in the early 1980's. Lope is located in the center of the country only 50km (0.45degrees) from the site of the 1996 Booué Ebola outbreak. In this study, mean nest group size was 2.37nests for chimpanzees (218 nest groups) and 5.24nests for gorillas (69 nest groups), for a combined mean ape nest group size of 3.1nests (all nests were counted not just those visible from the transect line). This figure is very close to the mean ape nest group size of

3.0nests/group = 2.03 + 0.23*4.27degrees

predicted by the regression analysis of our recent data for the sample site furthest from human Ebola outbreak sites (i.e. Mayumba National Park). It is also similar to the raw data means of 2.8nests/group for both Mayumba (n=76nest groups) and the Gamba Complex (including what are now Moukalaba-Doudou and Loango National Parks, n=866nest groups). Therefore, we incorporated an effect of declining nest group size into our overall estimate of ape decline by assuming a homogeneous, nationwide nest group size of 3.0nests/group for the early 1980's. This was implemented by multiplying each cell in the interpolated, nationwide nest group encounter rate surface by 3.0. Each cell in the surface representing the recent

surveys was multiplied by a quantity determined by the above regression equation (given the distance of that cell to the nearest human Ebola outbreak). This converted the two ape nest group encounter rate surfaces into ape nest encounter rate surfaces. The magnitude of ape decline was then calculated as before (i.e. as 1 - the ratio of interpolated means for the two eras).

I.4 Confidence Limits

Confidence limits on the estimates were obtained using non-parametric bootstrapping. For each bootstrap replicate, the data within each era were sampled with replacement. Parameter values for the best model were then estimated, national encounter rate surfaces for each era interpolated, and mean encounter rates compared. Uncertainty in the estimated mean nest group size decline was incorporated by separately bootstrapping group size data and re-estimating the relationship between nest group size and the distance from human ebola outbreaks. The bootstrap nest group encounter rate decline predicted for each cell in the national grid was then multiplied by the bootstrap estimated group size for that cell. A total of 10,000 replicates were performed for each estimate (i.e. with or without the group size effect). The 95% confidence limits reported in the text are respectively the 251st and 9,750th largest proportional declines in mean nest group or nest encounter rate.

I.5 Potential Sources of Bias

I.5.A Spatial trends in detection probability

In principle, our finding of a reduction in nest group encounter rate could be a spurious result of a decrease in the probability of nest group detection. The loss of the original data and the differences between eras in field methodology preclude a direct test of detection probability homogeneity between eras. However, two lines of evidence suggest that the observed decline in encounter rate is not a consequence of changes in detection probability but of real changes in ape density. First, the perpendicular distance of detected nest groups from transect midlines (a good index of detection probability) showed no sign of correlation with either distance from major cities (n= 252 nest groups, $R^2 = 0.00001$, p= 0.95) or distance from human Ebola outbreaks (n= 252 nest groups, $R^2 = 0.000126$, p= 0.86). Thus, the observed effects of distance from cities and Ebola outbreaks, which are form the basis for our decline estimates, were not caused by spatial trends in nest group detection probability. Second, the two eras did not show significantly different asymptotic nest group encounter rates (the constant δ), as one would expect if detection probability for the two eras differed by some constant. Given that the two eras differed neither in the spatial trend in detection probability nor in the asymptotic encounter rate, it does not seem likely that the observed decline in encounter rate between eras was the consequence of some spurious effect of detection probability change.

I.5.B Spatial trends in recce-transect encounter rate ratio

Much of our data came from recce surveys. If nest group encounter rates on recces were systematically lower than transect encounter rates, this would tend to reduce our combined encounter rate estimate for the recent era. However, test results reported above suggest that recce and transect encounter rates were not significantly different. Furthermore, the ratio of recce and transect encounter rates was not correlated with either the distance from major cities (n=31, R²=0.000004, p=0.99) or the distance from human Ebola outbreaks (n=31, R²=0.059, p=0.19).

I.5.C Temporal trends in decay time

It is possible that nest group decay times were generally shorter during the recent era than during T&F's surveys, so that decreases in nest encounter rate were not due to actual decreases in nest group density. However, if this were true then one would expect a different asymptotic nest group encounter rate (δ) in the two eras, which was not observed. It also stretches credulity to expect that decreases in nest group decay time during the recent era would be closely correlated with distance from major cities or distance from Ebola outbreaks. The four major urban centers considered are spread across Gabon and distance from them does not correlate with any obvious environmental gradient (e.g. coastal-continental or altitudinal) that might be related to factors (e.g. rainfall) that influence nest decay time. A similar argument applies for Ebola outbreak sites.

I.6 Recovery Time Projections

In order to project chimpanzee population growth rates we used a life table analysis. For reproductive parameters (age at first reproduction, age at last reproduction, and annual birth probability) we used estimates from Kaplan et al. (2000). For annual mortality probability we used pooled estimates from the six best studied wild populations of chimpanzees (Hill et al., 2001). Unfortunately, these estimates produced a negative population growth rate. Therefore, in order to approximate a healthy wild population growing without density dependent constraint, we substituted annual mortality rate estimates from captive populations (Hill et al., 2001). This should provide an optimistic population projection, as wild chimpanzees should rarely survive as well as captive chimps. We then iterated the life table until it reached an approximately stable age distribution (after about 100years). Population growth rate was then estimated as the proportional difference between successive years in the abundance of chimps summed across all age classes. The estimated annual growth rate was 1.65%.

No long term demographic data exist for wild western gorillas. The only available data on wild gorillas comes from mountain gorillas in the Virunga mountains. Previous analyses have suggested an annual growth rate as high as 3% for mountain gorillas, although this rate is not likely to be sustainable over large areas or time periods (Steklis & Gerald Steklis, 2001). Nonetheless, in order to make optimistic projections about gorilla recovery time we assumed a 3% annual growth rate.

In order to project into the future, we first converted the annual growth rates into instantaneous growth rates by taking the natural logarithm (r=0.0163). We then asked how many years (t) it would take the ape encounter rate interploated in each 1km^2 cell of the national surface for the recent surveys (N₁) to return to its early 1980's value N₀, given exponential growth

$$N_0 = N_1 e^{rt},$$

or

$$t = \ln(\frac{N_0}{N_1}) / r.$$

I.7 Sustainable Yield

We used the population growth rates derived from the life table analysis to estimate sustainable yield for chimpanzees. We assumed that chimpanzees lived at a fairly high density of 2/km² and were hunted randomly with respect to age. To estimate mean body weight, we multiplied age specific body weight (from Hamada & Udono, 2000) by the proportion of the stable age distribution in each age class, then summed the product across all weaned age classes (>4years). This gave a mean body weight of 46.3kg for weaned individuals: probably higher than for wild populations as body weight were from captive individuals. Thus, in order to maintain at equilibrium a population otherwise growing exponentially at 1.6%, hunting would have to be confined to about 0.032individuals/km²/ per year. Given that the amount of meat obtained from a carcass is about 60% of live weight (Noss, 1998), this suggests a sustainable meat yield of about 0.9kg/year. It should be emphasized that this estimate is based on optimistic assumptions about population growth rates and body weight. Actual sustainable yields would probably be much lower.

I.8 Additional References

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BUSHMEAT SURVEY METHODS

II.1 Market survey

The data on which the results reported in the text are based were drawn from an ongoing survey of the bushmeat markets of Gabon. Sales of bushmeat were recorded at 11 markets in Gabon between January 2000 and July 2002. In each market a researcher recorded only sales, rather than animals on display. For each sale of bushmeat, data was recorded on the species, age (Adult or Juvenile), sex, the part of the animal sold (whole, leg, head etc) and price paid (in CFA). In markets where it was impossible for a single researcher to observe all bushmeat sales (due to either the rapidity of sales or the layout of the market), the markets were divided into zones and the different parts of the markets either: 1) observed by two different researchers (Oloumi and Mont Bouet markets in Libreville) or 2) observed by the same researcher on alternate days (in Franceville). The dataset used for this analysis included surveys on between 21 and 426 days per market, giving a total of 80,528 bushmeat sales of which 7,686 (9.5%) were of whole animals.

It was impossible to weigh the parts of animals that were sold, so prices per unit mass were calculated using average body weights taken from Kingdon (1997). We used only data from the sale of whole adult animals to avoid the problem of estimating weights of variably-sized body parts or of juveniles. Data on 42 species were included in the analysis.

II.1.A Prices of alternatives

Prices of alternative meats, poultry and fish were recorded monthly in a sample of shops in each town. Prices were highly constant over time. Alternative meats were sold by the kilogram so price per unit mass was recorded directly.

II.1B Transport times

Overland transport times from Libreville to towns on the TransGabonais railroad were calculated based on the railway's timetable. For towns not on the railroad estimates of 50kmh⁻¹ on tarmac roads and 40kmh⁻¹ on unsurfaced roads were used to calculate journey time from the nearest station on the TransGabonais.

II.1.C Statistical tests

The relationships between price per unit mass and body weight and price and travel time form Libreville were examined using linear regressions performed using Minitab's GLM function; significance of fit was assessed using an F-test. All variables were log₁₀ transformed to meet the assumption of homogeneity of variance.

II.2 Household consumption survey

We visited 518 households once each between January and April 2001 and asked about 1) their consumption of meat over the previous three days, 2) household income in the previous month, and 3) household assets measured by a basket of goods using a standardised questionnaire. This gave a total of 1,793 consumption-days. No reliable sampling frame was available so respondents were chosen haphazardly by 1) selecting random starting points in the city and selecting a random direction in which to proceed, 2) counting every 6th house along the road or path in this direction and 3) tossing a coin to decide whether to include it or continue for another 6 houses. Interviews were normally with both the male and

female heads of the household at the same time. Consumption was defined as any meat or fish that was purchased, hunted, caught or otherwise obtained by the household on a given day.

II.3 Urban interviews

We carried out a total of 98 interviews in Libreville between May and July 2002 focusing on how households made decisions about which meats to consume. Households were selected according to the same protocol as for the consumption survey. Interviews were then conducted with either the male or female head the selected households (N = 56 women, 42 men). Interviews began with questions about the frequency with which different meats were eaten. This was followed by questions exploring the roles of 1) economic factors (price and availability), 2) personal preferences, 3) health issues and 4) taboos and other cultural or religious restrictions in determining the frequency of consumption of different types of meat.

II.4 Village interviews

The results reported here are based on 40 focus group discussions that we conducted in 8 villages in Ogooué-Lolo Province of central Gabon in July 2002 (N = 25 male and 15 female group discussions with a total of 124 subjects). They were carried out at the end of a period of 15 months during which one of us (MS) lived in the villages, learnt the basics of the local language and built up trust with the informants. The discussions took place with between 2 and 8 respondents at a time, divided into groups of the same sex and approximately equal ages. The participants were drawn from a sample of households that had previously been selected randomly for a related quantitative survey.

Discussions with male informants focused on 1) the importance of hunting relative to other livelihood options and 2) changes in hunting practices and the abundance of game animals over the last 20 years. Questions about hunting practices focused on changes in the number of hunters (local and external), changes in hunting methods, changed in the mix of species hunted and changes in the area hunted. Discussions with women also focused on the relative importance of hunting compared to other livelihood options and changes in hunting practices and in addition addressed the current and past nutritional importance of bushmeat in comparison to other meats. The 'starter' questions used to promote debate were standardized for all groups, but the order in which they were posed differed so as to allow free flow of the discussion.

Discussions with young people were mostly carried out in French and those with older people in Pouvi, the local language, or a mixture of Pouvi and French. All 'starter' questions had previously been translated into Pouvi so as to ensure standardization between groups. All discussion were recorded and later transcribed and translated into French.