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Power to the people: Analysis of occupancy models informed by local knowledge

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Abstract

Power analyses help to improve the cost-effectiveness of monitoring strategies for wildlife populations, but rarely account for variation in detection probability, affecting the power of data to detect trends in occupancy. We explore the power of occupancy models informed by two locally-informed methods (interviews and daily diaries) to detect changes in occupancy for 14 mammal species hunted for wild meat within a community forest in Cameroon. This is the first study to use the formula developed by to compare power between locally-informed methods and camera traps, and identify the monitoring strategies best suited to different species. Comparable effort is required between the three methods to detect 50% as 80% change in occupancy, except where occupancy is less than 0.13 (diary data), 0.03 (camera), or 0.6 (interviews). Overall, where occupancy <0.54, 200 sites and four repeat visits were required to detect at least a 30% change in occupancy. Achieving power to detect any level of change useful for conservation planning is often not viable for projects with small budgets and for species with very low detection rates. However, some species of conservation importance (e.g., gorilla, chimpanzee) are better detected and as such could be monitored using data collected in collaboration with local communities.

KEYWORDS

Africa, bushmeat, camera traps, detection, interdisciplinary, local ecological knowledge, monitoring, occupancy analysis, power analysis, tropical forests

1 | INTRODUCTION

Growing threats to biodiversity in the tropics require effective monitoring that balances scientific rigor with practical feasibility (Rist et al., 2010). However, threat assessments are often limited by a lack of robust data, and the consequences of different survey designs and sampling strategies for the precision of these assessments are often overlooked. As such, conservation resources may be misspent on monitoring programmes with poor statistical power to detect a desired level of change (Robinson et al., 2018) or wasted on unnecessary additional surveys when statistical power to detect change is already achieved. This is a particular issue for small-to-medium-sized non-governmental organizations who often carry out monitoring in and around protected areas,

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or those working in less developed countries, where limited conservation resources may be even more constrained.

Power analysis have long been used to improve the cost-effectiveness of monitoring strategies for wildlife populations (McDonald-Madden et al., 2010). Power analyses can inform the design of occupancy studies (Field et al., 2005) and can be used in occupancy studies to determine the number of sites and surveys required to detect a given change with enough power (Rist et al., 2009). This is especially helpful for the early stages of monitoring planning (Barata et al., 2017; Guillera-Arroita & Lahoz-Monfort, 2012). However, they rarely accounted for variation in detection probability, which could substantially affect the power of data to detect trends based on occupancy models (MacKenzie, 2005). To address this issue, Guillera-Arroita and Lahoz-Monfort (2012) developed and tested a formula for power analysis which accounts for both occupancy and detection probabilities. Studies have since found this approach to be effective in assessing the power of different occupancy study designs (Barata et al., 2017; Johnson et al., 2019).

In their comparison of occupancy, Guillera-Arroita and Lahoz-Monfort (2012) relate effect size to differences in occupancy between groups. It is commonly understood that estimating the magnitude of an effect, or effect size (e.g., difference in occupancy) using confidence intervals (e.g., evaluating precision) conveys more information than the outcome of a significance test, whereby a hypothesis is supported or rejected based on sample data. However, precision is gained by increasing the sample size by increasing the number of sites or sampling occasions (Barata et al., 2017). Power analysis is widely recognized as a useful tool to help determine the optimal survey design (c.f. Guillera-Arroita & Lahoz-Monfort, 2012). It allows us to determine whether a given study design will allow for statistically significant results when the actual effect size is biologically significant (e.g., a statistically significant effect that impacts health or survival) (Guillera-Arroita & Lahoz-Monfort, 2012).

Evaluating the power of monitoring to detect change in species populations is especially pertinent for mammal species in tropical forest habitats, where monitoring presents a unique set of challenges (Bowkett et al., 2006). Camera traps are frequently used in forest environments (e.g., Beaudrot et al., 2019; Rich et al., 2017), especially for monitoring shy or secretive species (Rowcliffe & Carbone, 2008). However, camera trapping is also relatively expensive and time consuming, a problem exacerbated by limited budgets (Lyra-Jorge et al., 2008). Monitoring programmes are increasingly drawing on local ecological knowledge (LEK) for monitoring such challenging habitats. For example, presence-absence social surveys (e.g., whereby species presence or absence data are collected through interviews, or daily diaries) can be combined with occupancy modeling to produce potentially robust and rapid estimates of occupancy across large spatial scales that cannot be achieved using conventional methods, while also accounting for heterogeneity in occupancy and detection (Brittain, 2018; Mohd-Azlan et al., 2013; Service et al., 2014; Turvey et al., 2013). Despite the increasing involvement of local communities in monitoring, this is the first published study to compare the power to detect change between locally two informed methods and camera traps, and to identify the monitoring strategies best suited to different species, to ensure that monitoring is both effective and efficient.

We use the Guillera-Arroita and Lahoz-Monfort (2012) formula to explore the power of occupancy models informed by camera traps, seasonal interviews, and daily diary data to detect change in occupancy between two monitoring seasons for 14 different mammal species commonly hunted for wild meat within a case study community forest adjacent to the Dja Faunal Reserve in Cameroon, under different survey designs and budgetary scenarios. We address three key objectives: (1) Determine the power to detect differences in occupancy of multiple species using local knowledge or camera traps; (2) Assess how number of sites and number of replicate visits affect the power to detect differences in occupancy from both sampling methods; and (3) Determine an optimal survey design and method that takes into account each species occupancy and detection.

2 | METHODS

The Dja Faunal Reserve (hereon called The Reserve) was founded in 1950 and covers 5260km^2, situated between the southern and eastern regions of Cameroon (Figure 1). The region experiences high temperatures and four distinct seasons: a long dry season from December to May, a light wet season from June–July, a short dry season from August–September, and a heavy wet season from October to November. The mean annual rainfall is c.1570 mm, with <100 mm falling during the dry months. The Reserve is home to 107 mammal species, several of which are threatened (Diendhiou & Diawara, 2015), including the endangered forest elephant (*Loxodonta cyclotis*) and the critically endangered western lowland gorilla (*Gorilla gorilla gorilla*). Despite its global importance for biodiversity, the state of conservation within the reserve is precarious, with the reserve now on the world heritage sites in danger list. Despite monitoring efforts within the reserve, little monitoring work has been carried out in the surrounding community forests, which may also be home to

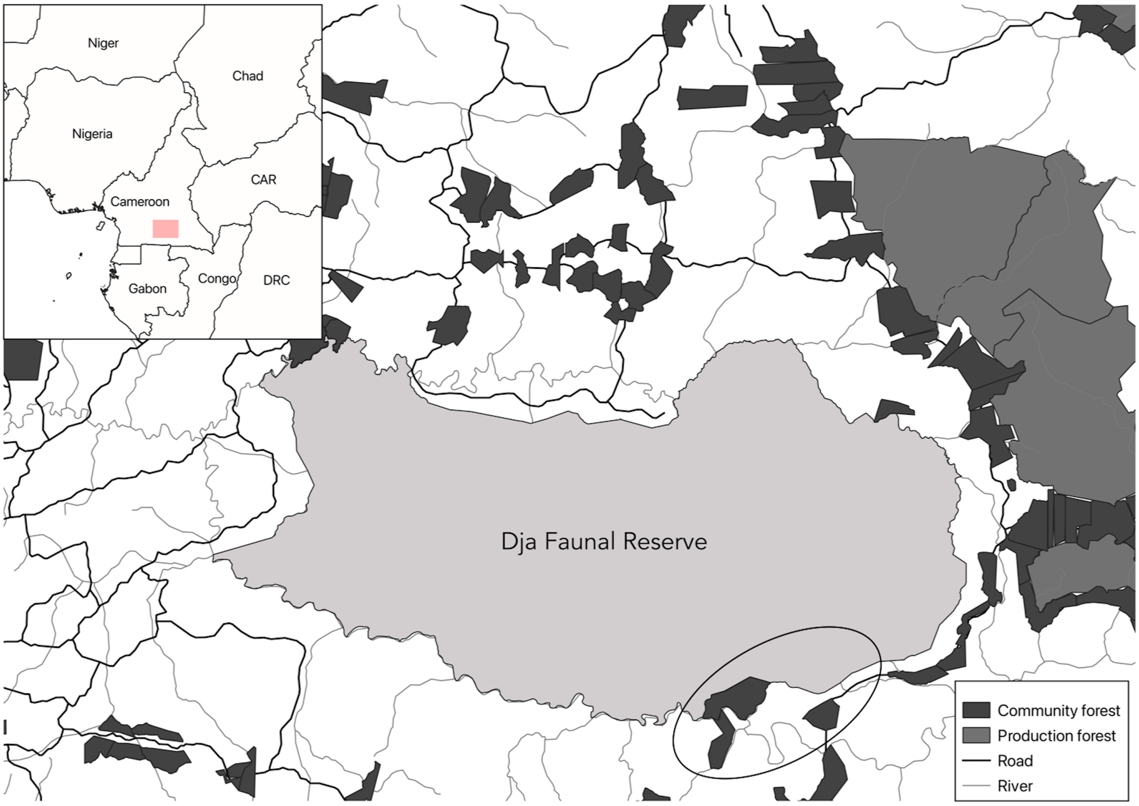

FIGURE 1 Location of the Dja faunal reserve and approximate location of the study village in southeastern Cameroon, with surrounding production and community forests

species of conservation importance. Monitoring efforts and knowledge of the forests are hindered by the dense forest habitat and low capacity for monitoring. As such, monitoring efforts here need to ensure that they are cost-effective, but also that they have the power to detect change, so as not to waste valuable and limited resources.

Hundreds of villages are located around the periphery of the reserve and inhabitants rely predominantly on farming, hunting, and fishing for their food security and livelihoods (Bobo et al., 2015). Data collection were conducted within the community forest and with inhabitants of one such village, selected as a case study, located close to the south-eastern boundary of the Reserve.

2.1 | Data collection

2.1.1 | Camera traps

From August–November 2017, 30 Bushnell Aggressor cameras were placed within the 32 km^2 community forest in a systematic grid set 1 km apart, one camera within each 1 km^2 site. The cameras were checked every 60 days, when data were also downloaded from the memory cards and the batteries were changed. Cameras were placed to capture a gradient of distance from each village out towards the reserve and adjacent land uses but remaining within the limits of the community forest where local people had the right to hunt and access. The cameras were placed 30–45 cm off the ground, angled horizontally. No attractants were used. To avoid sunlight interfering with the cameras, they were set facing north or south (Bruce et al., 2018). Tall grass and foliage that could have caused an obstruction were cleared from in front of the cameras. The placement of two cameras close to the road had to be adjusted as they would have been within a hunting camp, but the 1 km spacing was not substantially compromised.

Suitable places to position the cameras were chosen within 100 m of each grid point, that were close to frequently used animal trails (Amin et al., 2015) or possible feeding spots. Once a suitable place was identified, the cameras were attached to trees located about 4 m from the trails.

Because we wanted to compare the power of camera traps, interviews, and diaries to detect changes in occupancy, it was important for the spatial extent and scale of monitoring to be consistent across methods. As such, we determined that gathering presence–absence data at a 1 km^2 site resolution would allow the most informative comparison. Since the home ranges of the larger species in our study area are typically larger than 1 km^2, we interpreted occupancy as the proportion of sites used by a species (MacKenzie et al., 2006; Tudge et al., 2022).

Locally informed methods

Data from both the interviews and hunter diaries detailed below were opportunistic. Participants were not "monitors"; they did not collect data systematically or survey the forest in a systematic way. Responder knowledge was checked prior to participation, by showing a series of photos of locally present and absent species and asking respondents to identify them. Only data from respondents who provided the correct name of the species present in the area, and identified those that were absent from the area, either in French or in the local language, were included in the analysis.

2.1.2 | Semi-structured seasonal interviews

Semi-structured interviews comprising questions about the presence–absence of each target mammal species in specified locations were designed and administered to village inhabitants once a season (four times a year) over the course of 1 year (from May 2017–July 2018). Each interview was carried out by two researchers, one to ask the questions and maintain a flow of conversation with the respondent, and the other to take notes and, with permission, record the interview allowing for more in- depth responses to be recorded later. As people in villages regularly travel away for work or study, we were unable to employ a stratified random sample approach, as a representative sample of each demographic variable selected for use in this study was not always available. Further, despite our efforts to interview the same respondents each season, this was not always possible. Therefore, a targeted non-probability sampling strategy was employed, interviewing all willing adults within the village, at least one adult per household. To prevent double counting, we only included data from people in the same household if they frequented different parts of the community forest (e.g., if someone regularly goes to their field, or to the river, while another hunts).

2.1.3 | Daily diaries

Diaries are a method that are gaining popularity, often used in studies to gather self-reported data on hunting patterns (Rist et al., 2009; van Vliet et al., 2015) or wild meat consumption (Broegaard et al., 2017; Kumpel et al., 2010). Ten hunters were trained to keep image-based daily diaries from May 2017–April 2018, providing information on the species they detected, where the species was detected and the date of detection (following Rist et al., 2010). The daily diaries gathered the same information as the seasonal semi-structured interview, but only required a tick or cross in columns with corresponding images. The respondents, while not reflective of the whole village, were reflective of the hunting community. A range of ages, livelihoods ethnicities, and demographics were included where possible, to ensure the sample is as representative as possible and the patterns of hunting reflect broader trends in hunting across the villages. Hunters were selected from different households and different parts of the village, to ensure spatial representation of offtake. Hunters that hunt together were not selected, to prevent duplication of records. Hunter follows were conducted opportunistically, following Rist et al. (2009) to ensure that the species sighting data was being entered correctly.

2.1.4 | Mapping of species detections

A simple map of the village and surrounding forest was made, combining GPS points of key village landmarks and GIS data on major roads and land uses. Subsequently, participatory mapping exercises with mixed gender and age groups were held to identify paths, rivers, and key landmarks, which helped participants accurately recall where species were detected (Corbett, 2009). Features were ground-truthed with GPS, resulting in a map that was both representative of areas of local importance and spatially accurate. To facilitate comparison of estimates of occupancy between methods, the spatial sampling units used for the interviews and daily diaries reflected the same 1 km^2 grid used for the camera trapping. This was achieved by placing a 1 km^2 grid over the research team's copy of the map, so that they could allocate grid references to the detections recorded in the semi-structured interviews during the interviews. Species detections from both interviews and diaries were mapped onto the participatory map and the corresponding 1 km^2 site reference recorded. The hunters taking part in the daily diary exercise were involved in the design of the participatory map, were all familiar with the features shown and able to record where they had detected each species. If they were uncertain, they were able to speak to our key contact, who provided support to the hunters while the research teams were not in the village. The key contact was selected to help because they were instrumental in the process of zoning the community forest when it was created, had lived in the village their whole life and was highly experienced at reading and interpreting maps and grid references.

2.1.5 | Ethics

Free, prior informed consent was obtained by all respondents involved in this study. To ensure personal anonymity, identification numbers were allocated to each participant and used on all datasheets. Village location was not recorded to ensure anonymity at the community level (St. John et al., 2016). The research was approved by Oxford University's Central University Research Ethics Committee (CUREC).

2.2 | Data analysis

2.2.1 | Species selection

Target species were identified during a scoping trip in February 2016. We focused on species people saw regularly and those considered to be of conservation interest, such as rare or threatened species. We used mammals only in this analysis, as they are the group of animals most important for wild meat hunting. See Supporting Information S1 for further details on the rationale behind species selection in this study.

2.2.2 | Camera trap data processing

Species identification was aided by Kingdon (2015) and carried out by our research team staff (SJT), with support from SB and MR. Where identification was possible, images were given a species tag in ExifPro 2.1, and the metadata were exported to Excel (Microsoft Office 2016 version).

2.2.3 | Sampling and environmental covariates

Four sociodemographic covariates hypothesized to influence the ability of respondents to detect (p) the species when using interviews and diaries were included (age, gender, frequency of visits, and time spent in the forest per visit), in addition to six environmental covariates hypothesized to help to explain variation in ψ (occupancy) for all methods. These included habitat type (e.g., semi-deciduous or riparian forest) and slope, distance (km) of each detection from the reserve, roads and from rivers, as well as distance from village. For camera traps, these variables were also used instead of the sociodemographic covariates as detection covariates (p), with the addition of slope. We used the Euclidean distance tool in QGIS 3.0.2 to extract distances (QGIS Development Team, 2018), and Pearson tests for correlation between environmental covariates, none of which were highly correlated (e.g., >0.7). Covariates were standardized before modeling to aid comparisons and model convergence (Reilly et al., 2017). See Supporting Information S2 for hypotheses for variable inclusion.

2.2.4 | Occupancy analysis

A subset of data from the hunter diaries, seasonal interviews, and camera traps were extracted to facilitate comparison over a period of two seasons (short dry season, August–September, and wet season, October–November, 2017). From this subset of data, species detection histories were created by arranging the data into presence–absence (1/0) during repeat visits to a site. For camera traps, the sampling occasion was set at five days, as a compromise between model stability and ensuring an adequate number of repeat visits to each site. Following Martínez-Marti (2011), individuals were treated as effective repeat spatial and temporal surveys for the interview and diary data, respectively. Single species, single-season occupancy models (MacKenzie et al., 2002), were performed using the "occu" function in package "unmarked" (Fiske & Chandler, 2011) in R version 3.4.2 (R Core Team, 2017).

2.2.5 | Power analysis of occupancy models

Guillera-Arroita and Lahoz-Montfort's (2012) formula (Equation 1) was used to assess and compare the power of occupancy models under different survey design and budgetary scenarios. In all analyses, the significance threshold alpha (α) was set at 0.05 and the desired power was 0.8, in keeping with the standard in ecology.

$$\begin{aligned} G &= 1-\beta \\ &= \left\{1-\Phi\left(\frac{z_{\alpha/2}\sqrt{\sigma_1^2+\sigma_2^2}-(\psi_1-\psi_2)}{\sqrt{\sigma_1^2+\sigma_2^2}}\right)\right\} \\ &\quad +\Phi\left(\frac{-z_{\alpha/2}\sqrt{\sigma_1^2+\sigma_2^2}-(\psi_1-\psi_2)}{\sqrt{\sigma_1^2+\sigma_2^2}}\right) \end{aligned} \tag{1}$$

We first assessed the power to detect changes in the occupancy of each species between two seasons of 10%, 30%, 50%, and 80% growth and decline (relative proportional change $= R$, where $R < 0$ is a decline, $R > 0$ is growth), under our study design. Because the interviews and daily diaries data were opportunistic rather than systematic, the number of repeat samples, respondents and sites varied with each survey, so the median number of sites and repeat visits were used for analysis.

We then explored how statistical power to detect change varied with the number of sites and repeat visits. The number of 1 km^2 sites was halved, doubled, and tripled, holding the number of repeat surveys per site constant. The process was then repeated, holding the number of sites constant and changing the number of repeat visits. Finally, to explore the most robust and cost-effective monitoring strategy, we determined the minimum number of sites and repeat visits required to detect decline and growth in occupancy of 10%, 30%, 50%, and 80% with 80% power, and the costs of detecting 50% growth and decline in occupancy.

2.2.6 | Cost data and management strategies

The costs of achieving 80% power over a three-year monitoring period were calculated based on the approximate costs incurred during our data collection, as a proxy for the likely approximate level of effort that would be feasible for a small-to-medium-sized non-governmental organization's monitoring programme. Adapting the formula developed by Earle (2016), we calculated the total cost (C) in Great British Pounds (GBP) of a monitoring regime as:

$$C = Y^{*} S^{*} K^{*} a \tag{1}$$

where Y is the number of years the monitoring project will operate, S is the number of villages included in the monitoring, K is the number of repeat survey visits to the village per year, and a is the cost per repeat survey. The monitoring scenarios used are outlined in Supporting Information S3.

3 | RESULTS

3.1 | Summary

141 people participated in the seasonal interviews. Each 1 km^2 site was visited a mean of 106 times over 75 days (range = 42–139, median = 135). Ten hunters completed the hunter diaries over the same time and each 1 km^2 site was visited a mean of 3.93 times (range = 2–10, median = 2). Of the 30 cameras set, four malfunctioned or were damaged. In total, 26 cameras over 75 days resulted in a survey effort of 1950 camera trap days and 16,050 photos.

All 14 species occupancy models using the interview data converged, while for the diary data, the occupancy model for forest elephant did not converge due to a lack of detections. Seven of the 14 occupancy models for the camera traps converged (Figure 2). See Supporting Information S4 for a summary of all species occupancy models and directions of effects.

3.2 | Power to detect trends under the current study design

Changes in occupancy for certain species could only be detected using one monitoring method (Table 1). For example, 30% declines in forest elephant occupancy were detected with interviews, while hunter diaries only identified 50% changes in African golden cat occupancy. In contrast, changes in occupancy for several species were detected by all three monitoring methods, but with varying power to detect different proportional changes in occupancy. For example, all three methods detected 30% declines in brush-tailed porcupine and tree pangolin occupancy. In contrast, interviews and daily diaries allowed for 30% declines in blue duiker occupancy to be detected, while cameras could detect 50% declines in occupancy. Further, interviews could detect a 30% decline in yellow-backed duiker occupancy, while diaries and cameras can only detect declines of 50% and 80%, respectively. Interviews and diaries detected 30% declines in chimpanzee occupancy, while cameras detected 50% declines. Declines in occupancy of 30% for gorillas can be detected with interviews, but only 80% declines can be detected from diaries.

Only species with a probability of occupancy or detection >0.25 had 80% power to detect some level of change from the interview data (Table 1). Unlike the interview data, the seven species detected by the cameras had 80% power to detect some level of change, regardless of their probability of occurrence and detection. However, only declines of 80% could be detected by cameras for yellow-backed duiker and red river hog, both of which had a very small likelihood of detection ($p < .03$, Table 1). Eight of the 13 species observed in the diary data had a power to detect changes of 80–30%. Diary data gave the greatest power to detect changes in primate and pangolin occupancy, although this data type had little power to detect changes in ungulate species occupancy.

3.3 | Statistical power with varying numbers of repeat visits and sites

Achieving 80% power to detect change was rarely possible where occupancy or detection were already very low (e.g., African golden cat, Figure 3). Where occupancy was high and detection low, increasing the number of repeat visits substantially increased the ability to reach 80% power;

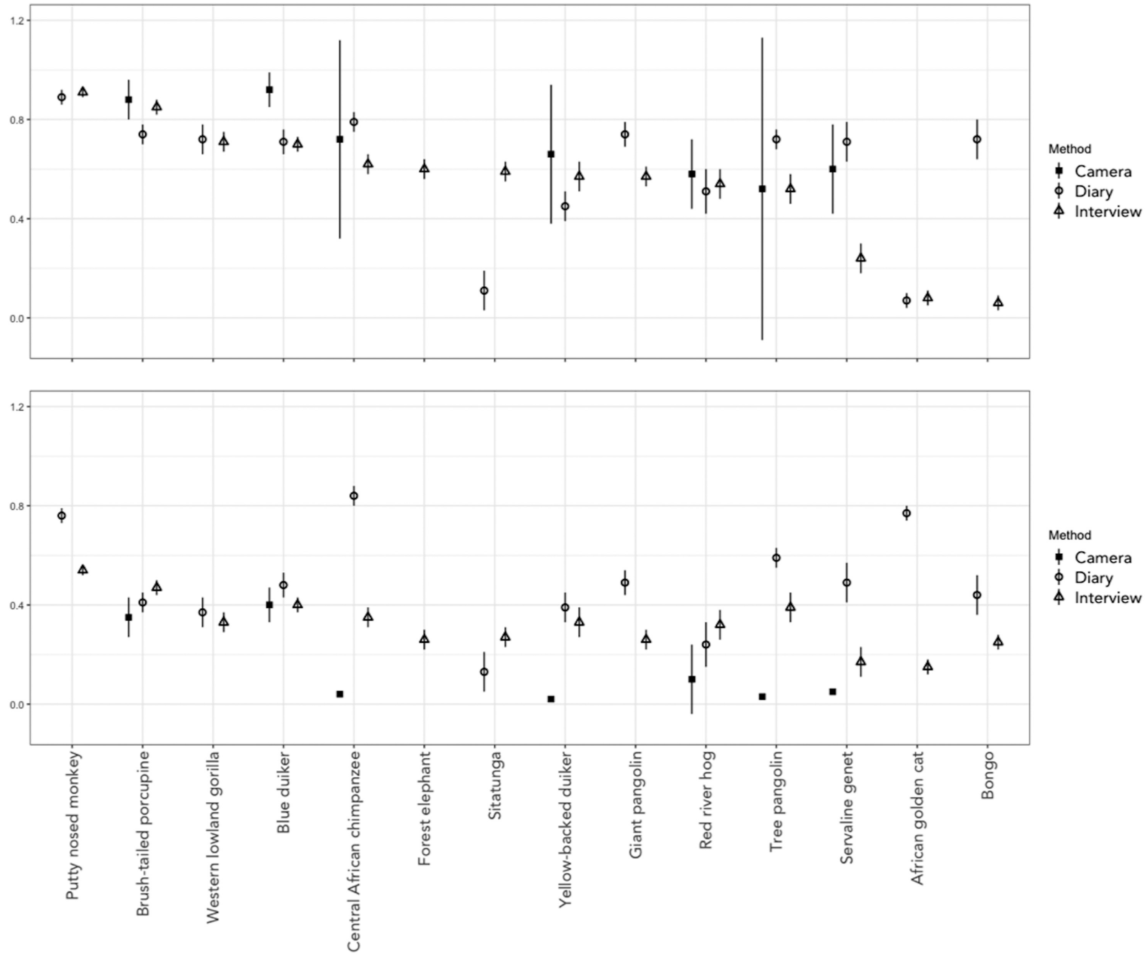

FIGURE 2 Species-specific estimates of occupancy probability (top row) and detection probability (bottom row). Estimates are derived from the models summarized in the supporting information S4. Error bars show standard errors

examples of this effect were especially prominent in the diary data. Increasing survey effort in this way may be worthwhile where the species is of conservation interest, such as gorilla, or for animals hunted for wild meat that may be important for local inhabitants, such as yellow-backed duiker (Figure 3).

Where 80% power to detect change was already achievable, increasing the number of repeat visits allowed smaller changes in occupancy to be detected (e.g., able to detect a 30% change in occupancy, rather than a 50% change with 80% power). Monitoring that can capture smaller changes in occupancy may be worthwhile where the animals are of conservation interest or highly sensitive to change, such as chimpanzee (Figure 3).

As the median number of repeat visits per site for diary data was low ($n = 2$), doubling or tripling the number of visits greatly improved power compared to the current monitoring plan for many species (e.g., porcupine, Figure 3). Halving the number of repeat visits from four to two was possible for interview cases where occupancy was 0.52, but this resulted in diminished ability to detect smaller levels of change, such as for blue duiker (Figure 3). Halving the number of occasions for camera trap data from 12 to six reduced the power below 80% in many cases where detectability was 0.03, such as for red river hog (Figure 3). See Supporting Information S5 for all species power curves under varying repeat visits and sites.

3.4 | Identifying the most efficient survey effort to detect trends

Here, species that were detected by all three methods are presented in Figure 4. All other species figures are in the Supporting Information S6. For interview data, the survey effort required to detect 10% change was prohibitive (e.g., to detect a 10% change in blue duiker or gorilla occupancy, at least 800 sites need to be visited eight times, see Supporting Information S6), unless occupancy was greater than 0.85, such as for brush-tailed porcupine (Figure 4). Detecting 50% change was possible in many

TABLE 1 Power to detect growth and decline in species occupancy under the current monitoring plan for interviews, daily diaries and camera trapping. Grey cells indicate power 〉 80%. NA = not applicable because the rate of growth or decline is not possible, given the estimated probability of occupancy

Species	IUCN	Ψ	p	80% decline	50% decline	30% decline	10% decline	10% growth	30% growth	50% growth	80% growth
Seasonal interviews											
Putty nosed monkey	LC	0.91	.54	1	1	1	0.57	0.79	NA	NA	NA
Brush-tailed porcupine	LC	0.85	.47	1	1	1	0.36	0.43	1	NA	NA
Western gorilla	CR	0.71	.33	1	0.99	0.99	0.15	0.15	0.99	0.99	1
Blue duiker	LC	0.7	.4	1	1	0.99	0.19	0.19	0.99	1	1
Central African chimpanzee	EN	0.62	.35	1	0.99	0.99	0.14	0.14	0.99	0.99	1
Forest elephant	VU	0.60	.26	0.99	0.99	0.92	0.09	0.09	0.83	0.98	0.99
Sitatunga	LC	0.59	.27	0.99	0.99	0.94	0.09	0.09	0.85	0.98	0.99
Yellow-backed duiker	LC	0.57	.33	1	0.99	0.98	0.12	0.11	0.96	0.99	0.99
Giant pangolin	VU	0.57	.26	0.99	0.99	0.91	0.09	0.08	0.08	0.97	0.99
Red river hog	LC	0.54	.32	1	0.99	0.97	0.11	0.11	0.92	0.99	0.99
Tree pangolin	VU	0.52	.39	1	0.99	0.99	0.13	0.12	0.98	0.99	1
Servaline genet	LC	0.24	.17	0.78	0.50	0.35	0.05	0.05	0.17	0.28	0.41
African golden cat	VU	0.08	.15	0.28	0.16	0.10	0.05	0.05	0.08	0.10	0.14
Bongo	NT	0.06	.25	0.49	0.28	0.15	0.05	0.05	0.11	0.16	0.22
Camera traps											
Blue duiker	LC	0.92	.40	1	0.99	0.98	0.17	0.47	NA	NA	NA
Tree pangolin	VU	0.88	.35	1	0.99	0.96	0.14	0.23	NA	NA	NA
Brush-tailed porcupine	LC	0.88	.35	1	0.99	0.96	0.14	0.22	NA	NA	NA
Central African chimpanzee	EN	0.72	.04	0.99	0.96	0.68	0.07	0.07	0.88	0.99	NA
Yellow-backed duiker	LC	0.66	.02	0.88	0.59	0.31	0.05	0.05	0.25	0.44	0.67
Servaline genet	LC	0.60	.05	0.99	0.90	0.57	0.06	0.07	0.66	0.96	0.99
Red river hog	LC	0.52	.03	0.93	0.68	0.36	0.06	0.05	0.31	0.56	0.80
Daily diaries											
Putty nosed monkey	LC	0.89	.76	1	1	0.99	0.20	0.26	NA	NA	NA
Central African chimpanzee	EN	0.79	.84	1	0.99	0.99	0.16	0.19	1	NA	NA
Giant pangolin	VU	0.74	.49	0.99	0.95	0.66	0.07	0.07	0.55	0.84	0.97
Brush-tailed porcupine	LC	0.74	.41	0.97	0.78	0.45	0.06	0.06	0.33	0.56	0.77
Tree pangolin	VU	0.72	.59	0.99	0.99	0.85	0.08	0.08	0.84	0.99	0.99
Gorilla	CR	0.72	.37	0.91	0.65	0.34	0.06	0.06	0.24	0.41	0.59
Servaline genet	LC	0.71	.49	0.99	0.93	0.63	0.07	0.06	0.52	0.81	0.96
Blue duiker	LC	0.71	.48	0.99	0.92	0.60	0.07	0.07	0.49	0.78	0.94
Red river hog	LC	0.51	.24	0.33	0.19	0.11	0.05	0.05	0.08	0.12	0.16
Yellow duiker	LC	0.45	.39	0.72	0.48	0.25	0.05	0.05	0.17	0.28	0.42
Sitatunga	LC	0.113	.13	0.06	0.05	0.05	0.05	0.05	0.05	0.05	0.05
African golden cat	VU	0.07	.77	0.18	0.12	0.08	0.05	0.05	0.07	0.10	0.13

IUCN Red List categories: CR, critically endangered; EN, endangered; LC, least concern; NT, near threatened; VU, vulnerable.

cases, with only minimum additional effort over that required for 80% change (e.g., yellow-backed duiker, chimpanzee and tree pangolin, Figure 4) However, considerable effort was required to detect 30% change, especially where detectability was <0.4 such as for red river hog, tree pangolin, chimpanzee, and yellow-backed duiker; a minimum of 3–4 repeat visits per site was required to reduce the number of required sites to below 400, and allow adequate estimation from a realistic number of sites.

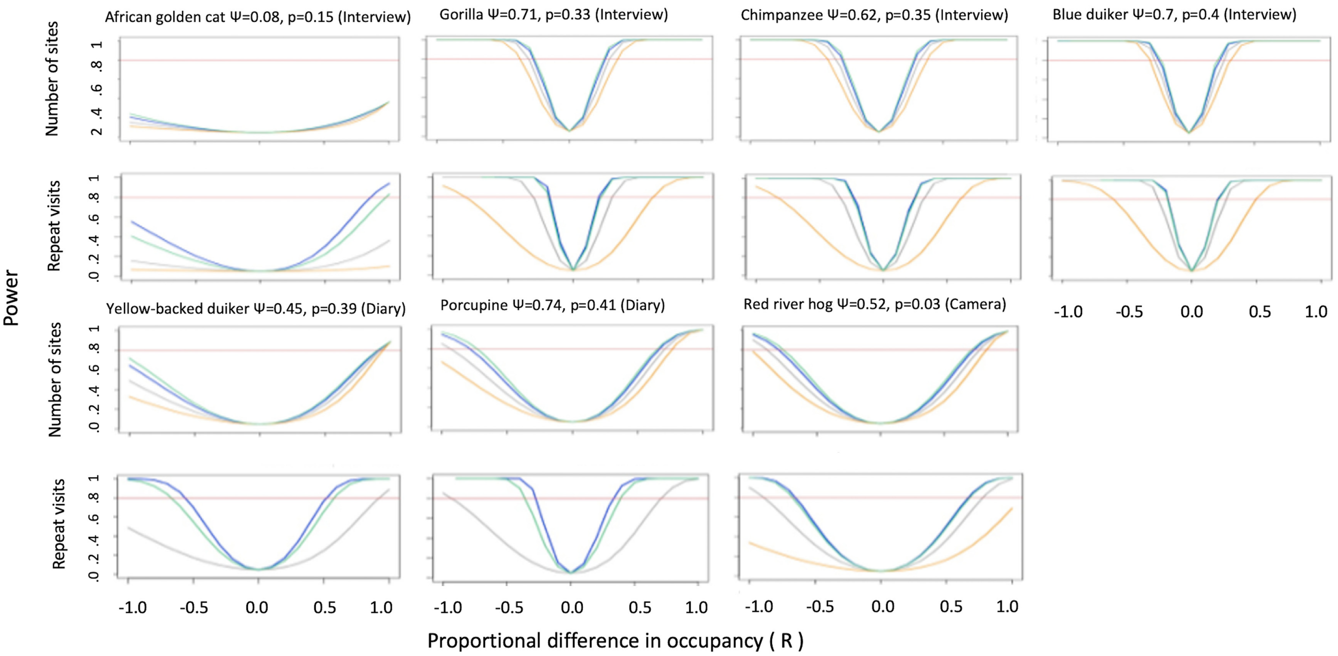

FIGURE 3 Example power curves, showing the relative proportion of change in occupancy that can be detected (R, where R > 0 is a decline, R < 0 is growth) for various total number of sites (top row) and number of repeat visits per site (bottom row) from seasonal interview data. Gray line indicated current monitoring effort for each method. Yellow = half the number of sites or repeat surveys, green = double the sites or repeat surveys, blue = triple the sites or repeat surveys

For diary data, the necessary survey effort reduced by half if four or more repeat visits were undertaken, as did the additional effort required to decrease detectable change from 80% to 30%. A greater effort was required to detect 10% change (e.g., for tree pangolin and chimpanzee, Figure 4). This effort may often be prohibitive; 500–600 sites with eight repeat surveys were required for all species except putty-nosed monkey, which had an occupancy of 0.89 and required 100 sites with four repeat surveys per site to detect a 10% change (Figure 4 and supporting information S6).

Finally, for camera data, species with occupancy 0.8 required substantially fewer repeat visits to detect a given change than those with a lower occupancy; 10 rather than 40 repeat visits across the same number of sites. Furthermore, detecting 30% change could be achieved with the same effort required to detect 80% change if occupancy 0.88. See Supporting Information S6, for all species figures to identify the most effective survey effort.

When comparing the survey effort required to detect varying changes in occupancy between each method, we see that 10% changes in occupancy for species with a high occupancy, such as porcupine and blue duiker, can be realistically detected with camera traps. However, 10%–30% changes in occupancy for species with a lower detection, such as tree pangolin or chimpanzee, are detected with less survey effort using interviews and diaries, than with cameras. A greater effort is needed to detect 30% change in red river hog and yellow-backed duiker occupancy compared to interviews, but the effort required to detect 50–80% change for both species is comparable after four repeat visits.

In summary, comparable effort is required to detect 50% as 80% change for all methods, except where occupancy <0.13 (diary data), 0.03 (camera), or 0.6 (interviews). In most cases, the power to detect change was comparable if five or more repeat visits were made to sites, other than for 10% change, which required significantly more survey effort. Overall, where occupancy <0.54, 200 sites and four repeat visits were required to detect at least a 30% change.

3.5 | Costing a realistic conservation monitoring programme

Assuming a target to detect a 50% change in occupancy over a three-year period with 80% power, interviews and diary data allow for more species of conservation interest to be monitored more intensively, for less money than camera trap data, with diary data providing the cheapest monitoring method (Table 2). Multiple species can be monitored for the cost of the most expensive species. For example, a 50% change in occupancy for three species of conservation importance (gorilla, chimpanzee, and pangolin) could be detectable for under £750,000 using

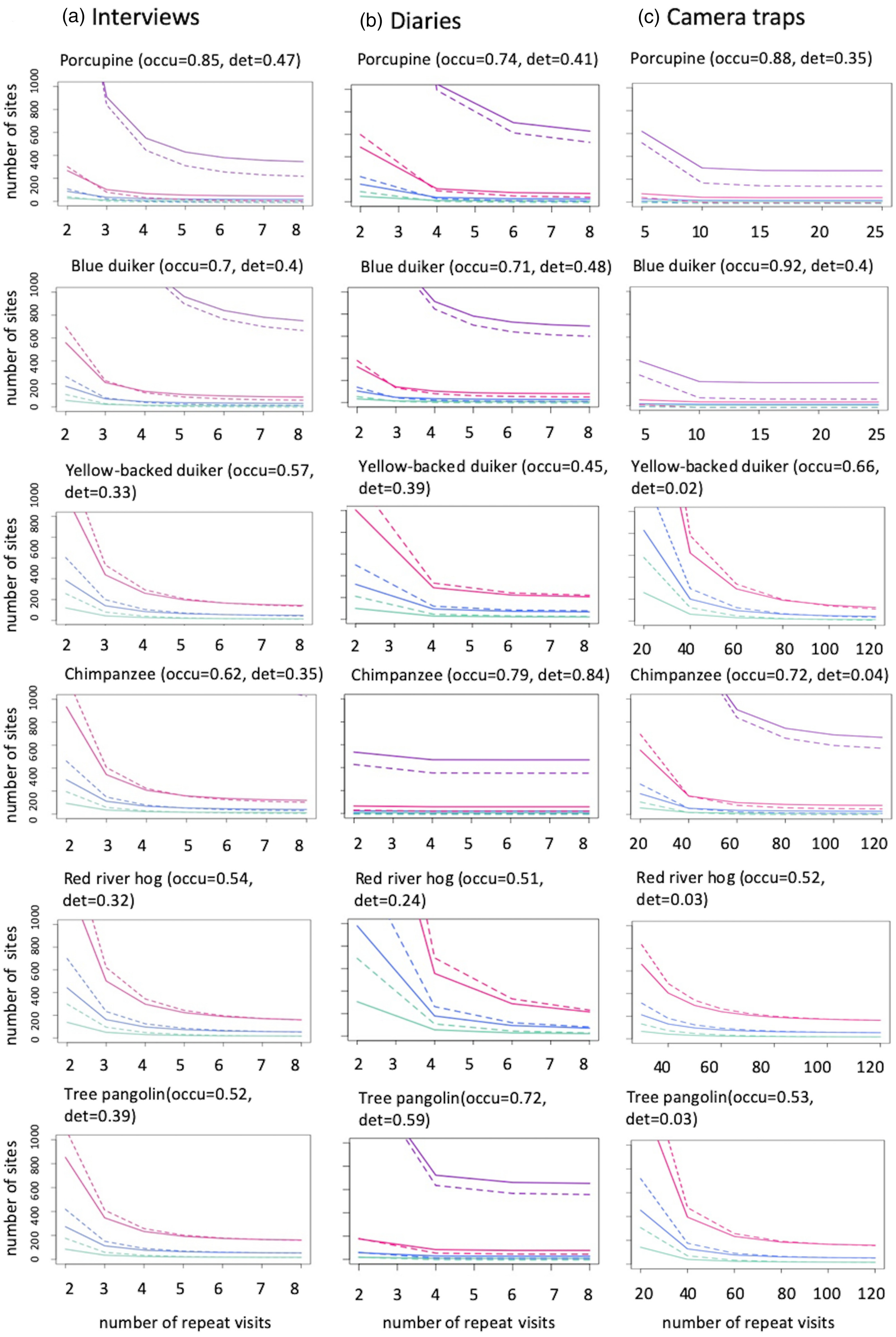

FIGURE 4 Example graphs where the species was detected by all three methods, showing the number of repeat visits and total sites required to achieve 80% power to detect growth (dashed line) and decline (solid line) of 80% (green), 50% (blue), 30% (pink), and 10% (purple) for the given number of sites and repeat visits in two seasons

TABLE 2 The cost of a three-year monitoring project in two villages that allows for 50% growth or decline in occupancy to be detected with 80% power while accounting for imperfect detection, and the species that can be monitored for that cost

	Scenario A		**Scenario B**		**Scenario C**		**Scenario D**	
	50% decline	50% growth	50% decline	50% growth	50% decline	50% growth	50% decline	50% growth
Interviews								
<£250,000	Putty-nosed money	Brush-tailed porcupine	Putty-nosed monkey + brush-tailed porcupine	Putty-nosed monkey + brush-tailed porcupine	Putty-nosed monkey + brush-tailed porcupine	Putty-nosed monkey + brush-tailed porcupine	Putty-nosed monkey + brush-tailed porcupine	Putty-nosed monkey + brush-tailed porcupine
£251–£500,000	Brush-tailed porcupine	Putty-nosed money	Blue duiker + Chimpanzee+ Gorilla+ Tree pangolin	Blue duiker	Blue duiker	Blue duiker	Blue duiker+ Chimpanzee+ Gorilla+ Red river hog+ Tree pangolin + Yellow-backed duiker	Blue duiker+ Chimpanzee+ Gorilla+ Tree pangolin
£501–£750,000	Blue duiker	Blue duiker	Yellow-backed duiker	Chimpanzee+ Gorilla+ Tree pangolin	Chimpanzee+ Gorilla+ Tree pangolin		Sitatunga	Yellow-backed duiker
Diaries								
<£250,000	Chimpanzee+ Putty-nosed monkey	Chimpanzee+ Genet+ Giant pangolin+ Tree pangolin+ Porcupine+ Putty-nosed monkey	Blue duiker+ Chimpanzee+ Genet+ Giant pangolin+ Tree pangolin+ Porcupine+ Putty-nosed monkey	Blue duiker+ Chimpanzee+ Genet+ Giant pangolin+ Tree pangolin+ Porcupine+ Putty-nosed monkey	Blue duiker+ Chimpanzee+ Genet+ Giant pangolin+ Tree pangolin+ Porcupine+ Putty-nosed monkey+ yellow-backed duiker	Blue duiker+ Chimpanzee+ Genet+ Giant pangolin+ Tree pangolin+ Porcupine+ Putty-nosed monkey+ yellow-backed duiker	Blue duiker+ Chimpanzee+ Genet+ Giant pangolin+ Tree pangolin+ Porcupine+ Putty-nosed monkey+ yellow-backed duiker	Blue duiker+ Chimpanzee+ Genet+ Giant pangolin+ Tree pangolin+ Porcupine+ Putty-nosed monkey+ yellow-backed duiker
£251–£500,000	Blue duiker+ Genet+ Giant pangolin+ Gorilla+ Tree pangolin+ Porcupine	Blue duiker+ Gorilla	Yellow-backed duiker		Red river hog		Red river hog	Red river hog
£501–£750,000				Yellow-backed duiker		Red river hog		

(Continues)

TABLE 2 (Continued)

	Scenario A		Scenario B		Scenario C		Scenario D	
Camera traps								
<£250,000	Blue duiker+ Porcupine	Blue duiker+ Porcupine	Blue duiker+ Porcupine	Blue duiker+ Porcupine	Blue duiker+ Porcupine	Blue duiker+ Porcupine	Blue duiker+ Porcupine	Blue duiker+ Porcupine
£251–£500,000								
£501–£750,000								

interview or diary methods, while the same species would either not be detected, or would be prohibitively expensive to monitor sufficiently to detect 50% changes in occupancy, using camera traps (Table 2). See Supporting information S7 for the estimated costs of monitoring associated with each species.

4 | DISCUSSION

It is important to understand *a priori* whether a given monitoring goal is achievable using a selected survey design, to avoid wasting valuable conservation resources (Rist et al., 2010; Robinson et al., 2018). Conservation practitioners may have more or less power to detect trends in occupancy depending on the underlying occupancy of the species, the monitoring method used, the intensity of the sampling strategy (which is budget-dependent), and the species detectability (which depends both on species characteristics, the method and observer characteristics). In designing occupancy surveys, balancing the number of repeat visits with the number of sites monitored is critical.

Where occupancy and detection were high, increasing the number of repeat visits per site had a greater effect on the power to detect change than increasing the total number of sites surveyed. The results are in line with the recommendations made by Mackenzie and Royle (2005), that more sampling units should be surveyed less intensively where detection is low, while fewer sampling units should be surveyed more intensively for species with high detection.

As community-based monitoring programmes become more popular, covering a range of species, and using various informal and formal data collection methods (Danielsen et al., 2009), it is crucial to understand their power to detect changes in species occupancy. This will enable a realistic assessment of the conservation benefits of such programmes, to complement their social benefits (Earle, 2016).

No monitoring method is free from bias. However, steps can be taken to try and remove or reduce these biases, to ensure that the results are as robust as possible. Previous studies have suggested that wildlife distribution data informed by local people are unreliable, but they did not control for variable detectability in their study (Caruso et al., 2016; Petracca et al., 2017). By carrying out occupancy analysis, including both observer-based and environmental variables, we were able to account for variation in both occupancy and detection. This work adds to the growing body of research that combines interview-based data with occupancy analysis and finds that the results are robust, informative and cost-effective (Brittain et al., 2018; Brittain et al., 2022; Camino et al., 2020; Martínez-Martí et al., 2016).

However, some biases cannot be accounted for with occupancy analysis, and must instead be addressed during the survey design and data collection phases. For example, reporting or recall bias, which may affect the diary and interview data, occur when participants are unwilling to report hunted or detected species, perhaps in part due to social desirability biases (Nuno & St John, 2014). However, this study does not suggest that respondents withheld information on species detections in either the hunter diaries or the interviews, as protected species were well reported in both. Furthermore, efforts were made in the survey design to reduce the likelihood of bias from misidentification by omitting data from participants who were unable to correctly identify the species in the study from a series of photos, shown before the research started. Further, we took care to not interview more than one member of the same hunting group, to avoid double counting.

Species occupancy and detection vary greatly from location to location. As such, it is not our intention to provide estimates that are applicable elsewhere. However, poor detectability and challenging monitoring conditions are commonly encountered issues in tropical forests globally, as is the need for robust and cost-effective monitoring methods. We further the applicability of the formula developed by Guillera-Arroita and Lahoz-Montfort (2012) to assessing the power of locally informed monitoring methods, which are increasingly used in conservation research and practice, and which have clear applications for the challenges encountered when monitoring in tropical forests in particular.

Cost analyses such as ours are useful to explore which species can be effectively monitored for a given budget. Such an analysis could help NGOs to better allocate their funds. Regardless of the study design, we found significant differences in the financial investment required for monitoring depending on the method. While camera trapping performed well for abundant ungulates and rodents (blue duiker and brush-tailed porcupine), its cost to detect a 50% change in occupancy with 80% power was prohibitive for all other species. By contrast, monitoring that incorporates local knowledge was much more cost-effective, as also found by Danielsen et al., 2010; Turvey et al., 2013; Parry & Peres, 2015. This makes it especially useful where data is lacking, or in challenging habitats such as forests (Turvey et al., 2015; Martínez-Marti et al., 2016). In our study, diary data provided the greatest power to detect change for primates and pangolins, both hunted in this area. Since diary respondents were active hunters, these results may reflect the reliable knowledge of the animals that respondents are actively targeting (Martínez-Marti et al., 2016). It may also be that hunters completing the diaries were actively visiting sites occupied by pangolins, therefore increasing their chances of detecting them.

Power analysis that accounts for imperfect detection is a valuable tool to assess the effort required to monitor different species and identify the best monitoring methods and designs for a desired monitoring outcome. It is important that conservationists are realistic in their assessments of whether their monitoring efforts are worthwhile. For our study site, we showed that monitoring programmes with small budgets cannot detect useful changes in occupancy with sufficient power, if species have very low detection rates. This includes many species of conservation importance. However, where detection rates are higher, species may be monitored using locally informed data.

AUTHORS' CONTRIBUTIONS

Stephanie Brittain, Samantha Earle, E.J. Milner-Gulland, and Marcus J. Rowcliffe conceived the ideas and provided guidance on analysis and survey design. Stephanie Brittain, Fabrice Kentatchime, and Cedric Thibaut Kamogne Tagne collected the data. Stephanie Brittain analyzed the data and led the writing of the manuscript. All authors reviewed and commented on the manuscript.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest that could be perceived as prejudicing the impartiality of the research reported.

DATA ACCESSIBILITY STATEMENT

Data are available upon request form the lead author, Stephanie Brittain (stephanie.brittain@zoo.ox.ac.uk).

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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