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Cost-efficient effort allocation for camera-trap occupancy surveys of mammals

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ABSTRACT

Camera-traps are increasingly used to survey threatened mammal species and are an important tool for estimating habitat occupancy. To date, cost-efficient occupancy survey effort allocation studies have focused on trade-offs between number of sample units (SUs) and sampling occasions, with simplistic accounts of associated costs which do not reflect camera-trap survey realities. Here we examine camera-trap survey costs as a function of the number of SUs, survey duration and camera-traps per SU, linking costs to precision in occupancy estimation. We evaluate survey effort trade-offs for hypothetical species representing different levels of occupancy (ψ) and detection (p) probability to identify optimal design strategies. We apply our cost function to three threatened species as worked examples. Additionally, we use an extensive camera-trap data set to evaluate independence between multiple camera traps per SU. The optimal number of sampling occasions that result in minimum cost decrease as detection probability increases, irrespective of whether the species is rare ($\psi < 0.25$) or common ($\psi > 0.5$). The most expensive survey scenarios occur for elusive ($p < 0.25$) species with a large home range (>10 km^2), where the survey is conducted on foot. Minimum survey costs for elusive species can be achieved with fewer sampling occasions and multiple cameras per SU. Multiple camera-traps set within a single SU can yield independent species detections. We provide managers and researchers with guidance for conducting cost-efficient camera-trap occupancy surveys. Efficient use of survey budgets will ultimately contribute to the conservation of threatened and data deficient mammals.

1. Introduction

To conserve threatened species effectively, conservationists must first assess the status of populations. With financial resources generally in short supply, wildlife researchers and managers need to adopt cost-efficient monitoring survey protocols to gather baseline data to inform appropriate conservation interventions (Fryxell et al., 2014). Terrestrial mammals can be a particular challenge to survey due to their elusive nature, the fact that they often occur at low densities and, in many cases, are difficult to distinguish individually. As such, population status inferences where individuals are undistinguishable or unmarked rely frequently on presence-absence data and the estimation of species occupancy (i.e. the proportion of sites occupied or used by the species). The value of presence-absence data has increased markedly in recent years as a result of significant developments in occupancy modelling techniques (Vojta, 2005) including, for example, being able to account explicitly for the imperfect detection of elusive species (MacKenzie et al., 2006; Guillera-Arroita, 2016).

Camera-traps are a widely used tool in ecology and conservation (Rowcliffe and Carbone, 2008; O'Connell et al., 2010; Burton et al., 2015). They are particularly valuable for surveying elusive mammals because they are non-invasive, can work independently in remote areas and perform effectively in comparison to alternative detection methods (Gompper et al., 2006; Long et al., 2007; Balme et al., 2009). Camera-traps have therefore been deployed in a broad array of circumstances, ranging from monitoring single species populations (Linkie et al., 2013) and constructing mammal inventories in tropical forests (Tobler et al., 2008), through to evaluating the value of modified landscapes for threatened species (Linkie et al., 2007). The number of occupancy studies based on camera-trap data is growing rapidly, with the majority of focal species being unmarked carnivores or ungulates (Burton et al., 2015).

Despite the abundance of camera-trap occupancy studies being conducted and published globally, there is a paucity of research examining how to allocate survey effort to optimize statistical estimation precision taking into account operational costs. In the context of occupancy modelling, survey effort guidelines have been developed to address the trade-off between the number of sample units (hereafter SUs) and the effort applied within each unit (e.g. number of repeat visits per SU) (MacKenzie and Royle, 2005; Field et al., 2005; Bailey et al., 2007;

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Guillera-Arroita et al., 2010; Guillera-Arroita and Lahoz-Monfort, 2012). All these studies consider simplistic cost functions, where total survey cost is proportional to the total number of survey visits (i.e. number of SUs x survey visits/SU). The underlying assumed scenario is that a field team member revisits the SUs in each sampling occasion. MacKenzie and Royle (2005) go further and account for extra initial set-up costs at each SU, for cases where the first sampling occasion at a SU may be more expensive than subsequent visits. This previous work, whilst useful, does not accurately represent camera-trap surveys where the length of a survey can be extended (i.e. more "sampling occasions" conducted) without directly adding costs. This is because, once installed, camera-traps can work independently for periods of time between installation, maintenance checks and/or retrieval without a specific associated cost.

Another important consideration is that camera-trap survey effort per SU can be increased by both extending survey length and the number of devices deployed per SU. Species with low detection probability require long surveys to obtain precise estimates (Shannon et al., 2014). This is often the case for species with large home ranges, as they might be difficult to detect due to non-random movement across a large area. By installing independent camera-traps, one can achieve the same level of detection probability with fewer sampling occasions (Long and Zielinski, 2008). However, it is unclear where the optimal balance lies between survey length and number of camera-traps per SU once realistic survey costs are accounted for Increasing the number of camera-traps per SU may also be required if the survey length is somehow constrained (e.g. 100 days maximum survey of all SUs).

Here we provide effort allocation guidelines for cost-efficient camera-trap occupancy studies of terrestrial mammals. We develop a detailed cost function for camera-trap surveys, which we parameterise with operational installation efficiency values (e.g. minutes to install a camera-trap) provided by practitioners (e.g. wildlife managers, researchers). This is then used to consider trade-offs in survey effort allocation in terms of optimal survey length and number of camera-traps within a SU needed to achieve occupancy precision targets at minimum costs. We assess a range of occupancy and detection probability scenarios for species with different home range sizes, as well as considering two types of transport between SUs: vehicular and walking. We also discuss survey design alternatives, using three threatened mammals as worked examples, illustrating how our cost function can be employed to identify cost-efficient strategies. For one of the case study species, for which an extensive survey dataset exists, we additionally investigate the deployment of multiple camera-traps per SU. Camera-trap independence is evaluated in terms of detection history similarity and how this varies with: (i) camera placement in contiguous habitat; and, (ii) distance between camera-traps. Our aim is to provide researchers with a transparent and robust tool, which can be adapted to meet project-specific conditions, to inform the efficient use of scarce financial resources when conducting camera-trap occupancy surveys.

2. Methods

2.1. Sample unit definition and survey length

SU size directly influences the interpretation of occupancy as a state variable. SU size also affects the amount of time spent in the field, by increasing field team member movement time both within and between SUs. When it comes to monitoring populations of mammals over large geographic areas, a common recommendation is that the size of the home range should determine the area of, and distance between, independent SUs (MacKenzie et al., 2006). Following this approach, we define the minimum distance between SUs (D_s) as the diameter of the circular area representing the typical home range size of the species R:

$$D_s = \sqrt{\frac{4R}{\pi}}(1+\alpha) \tag{1}$$

where α allows including a user-defined buffer as a proportion of home range size that can be used as a conservative approach to account for home range size uncertainty and or extra space to facilitate variable camera placement within the SU (e.g. not in exact centre). For multiple species surveys, just as for single species studies, the size of R must be decided based on the research objectives and what is meaningful for the interpretation of parameters at the community scale (e.g. Burton et al., 2012).

The duration or length of a particular survey (L) has implications with respect to model assumptions, affecting the interpretation of the estimated occupancy parameter (Guillera-Arroita, 2016). The total survey length can be defined as the number of days over which all SUs are surveyed. A maximum length, L_{max}, should be set a priori and in accordance with survey objectives (e.g. whether the aim is to capture a "snapshot" of the system, or identifying the areas used by the species over longer time periods). In practice, to fit occupancy models, the continuous data collected by the camera-traps can be divided into discrete replicate segments, and treated as separate sampling occasions (but see Guillera-Arroita et al., 2011).

2.2. Calculation of survey costs

The total cost of a camera-trap survey is a function of the number of SUs (S), the duration of the survey (and hence the number of sampling occasions K), and the number of camera-traps per SU (n). We can write the cost function in a general form as:

$$C_T(S,K,n) = C_F + S{\cdot}C_{SU}(K,n) + C_V(K,n,S) \tag{2}$$

We use C_F to represent fixed costs, which are, those not associated with in-situ operations and particular to each project (e.g. maintenance of a field station or field vehicle, salaries of permanent staff and international flights). Hereafter we do not consider fixed costs because they do not affect optimal design strategy determination as they are independent of the choice of K and n. C_{SU} is the cost of surveying one SU, which is dependent on K and n. We assume that all SUs are surveyed the same amount of time. Finally C_V encompasses other costs associated with the survey that are affected by the final design (see Section 2.2.5).

We consider that C_{SU} consists of four types of costs:

$$C_{SU}(K,n) = C_1(K,n) + C_2(K,n) + C_3(n) + C_4(K,n) \tag{3}$$

where $C_1(K,n)$ is camera-trap operational cost within the SU associated with salaries and fuel consumption between sample units during instalment, maintenance, retrieval; $C_2(K,n)$ relates to field logistics during the survey (e.g. travel to survey area and food); $C_3(n)$ comprises camera-trap equipment cost and, $C_4(K,n)$ is post-survey image processing cost. We provide detail about the construction of each of these four elements.

2.2.1. Operational costs per sample unit

Operational cost C_1 includes personnel salaries and fuel consumption associated with installing, retrieving and conducting maintenance service checks for the camera-traps in a single SU. We assume that installation involves the preparation of a single camera-trap (i.e. loading batteries, memory card and checking overall function) and its positioning for the duration of the survey. Retrieval consists of data collection (e.g. downloading the memory card), note-taking and camera-trap removal after the survey is complete. Maintenance involves checking/changing batteries, lures, baits and memory cards during the survey.

To calculate C_1, we compute the time spent at a particular SU during installation H_i, retrieval H_r or maintenance checks H_c:

$$H_x = \left\{ t_x + \frac{d(n-1)}{V_w} + \frac{2D_s}{V_y} \right\} \tag{4}$$

where: t_x (t_i,t_r,t_c) is the time (hours) spent handling each of the n cameras in the SU; d is the travel distance between a pair of cameras within