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Abstract

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Keywords	detection probability; hunting; law enforcement; protected areas; ranger patrols; Cambodia;

Corresponding Author	Harriet Ibbett
Order of Authors	Harriet Ibbett, EJ Milner-Gulland, Colin Beale, Andy Dobson, Olly Griffin, Hannah J. O'Kelly, Aidan Keane

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Abstract

Reducing threats to biodiversity is the key objective of ranger patrols in protected areas. However, efforts can be hampered by rangers' inability to detect threats, and poor understanding of threat abundance and distribution in a landscape. Snares are particularly problematic due to their cryptic nature and limited selectivity with respect to captured animals' species, sex, or age. Using an experimental approach, we investigated the effect of search effort, habitat, season, and team on rangers' detection of snares in a tropical forest landscape. We provide an effort-detection curve, and use our findings to make preliminary predictions about snare detection under different scenarios of patrol effort. Results suggest that the overall probability of a searcher detecting any given snare in a 0.25/km^2 area, assuming 60 minutes (or approximately 2km) of search effort is 20% (95% CI ± 15-25%), with no significant effect of season, habitat or team. Our models suggested this would increase by approximately 10% with an additional 30mins/1km of search effort. Our preliminary predictions of the effectiveness of different patrolling scenarios show that detection opportunities are maximised at low effort levels by deploying multiple teams to a single area, but at high effort levels deploying single teams becomes more efficient. Our results suggest that snare detectability in tropical forest landscapes is likely to be low, and may not improve dramatically with increased search effort. Given this, managers need to consider whether intensive snare-removal efforts are the best use of limited resources; the answer will depend on their underlying objectives.

Keywords

Detection probability; hunting; law enforcement; protected areas; ranger patrols; Cambodia

1. Introduction

Protected area (PA) networks are a cornerstone of global efforts to conserve biodiversity (Bruner, Bruner, Gullison, Rice, & Fonseca, 2001). Their success depends on effective management, including the reduction of threats to species and habitats (Watson, Dudley, Segan, & Hockings, 2014). A primary tool available to PA managers to address threats is patrolling by ranger teams (Hilborn et al., 2006; Lynam, Porter, & Campos-Arceiz, 2016). Through regular patrolling, rangers monitor adherence to conservation rules, deter potential perpetrators, and punish infractions when detected (Keane, Jones, Edward-Jones, & Milner-Gulland, 2008). To design optimal patrol strategies, PA managers require robust information about the distribution and abundance of threats in a landscape (Critchlow et al., 2017) alongside a means of assessing which approach is most likely to yield the greatest conservation benefit at the lowest possible cost (Plumptre et al., 2014).

Data collected by rangers are increasingly used to map spatio-temporal trends in threats and evaluate patrol performance. These are often collected by patrols for little additional cost (Brashares & Sam, 2005). Subsequently, the data can be used with open-access tools such as the Spatial Monitoring and Reporting Tool (SMART) to map threats and prioritize patrol effort within conservation landscapes (Hötte et al., 2016; Stokes, 2010). However, gathering data is not the primary objective of patrols and ranger-collected data may be subject to considerable bias (Keane et al. 2011). Patrol data must therefore be handled with caution to avoid misleading conclusions and ineffective targeting of patrol effort (Critchlow et al., 2015; Keane, Jones, & Milner-Gulland, 2011). While a growing suite of statistical methods exists to account for these biases (see Critchlow et al., 2015; Marescot, Lyet, Singh, Carter, & Gimenez, 2019; J. F. Moore et al., 2017), there is also a broader need for independent tests of key aspects of patrol effectiveness, such as the amount of patrol effort required to successfully detect a certain proportion of threats present within expansive conservation landscapes (Dobson, Milner-Gulland, Beale, Ibbett, & Keane, 2018). Well-designed experiments can provide effective and affordable means to trial different approaches, and have been used to improve understanding of the effects of environmental covariates on the detectability of traps set by hunters in both tropical forest (O'Kelly et al. 2018a) and savannah (Rija, 2017) landscapes. However, no experimental study has yet explored the relationship between search effort and threat detection, knowledge of which would enable PA managers to distribute patrol effort more efficiently, and thereby improve PA effectiveness.

Hunting poses one of the greatest threats to wildlife in PAs globally (Ripple et al., 2016; Schulze et al., 2018) and snares are one of the most prevalent hunting technologies used worldwide (Gray, Hughes, et al., 2017; Harrison et al., 2016). Usually made from wire, cable, or nylon, snares are affordable, accessible, and can trap a wide range of arboreal and terrestrial species, whether diurnal or nocturnal (Borgerson, 2015; Ingram et al., 2017). Due to their limited selectivity with respect to species, sex, or age of captured animals, snares are a potent threat to biodiversity (Noss, 1998). Although animals sometimes escape snares, subsequent non-fatal injuries often jeopardize their long-term survival (Gray, Lynam, et al., 2017). For example, chimpanzees with snare injuries have been found to suffer significantly higher parasite loads than those without (Yersin, Asiimwe, Voordouw, & Zuberbühler, 2017). Unlike other forms of hunting, snares present a persistent threat to wildlife as they remain operational in the landscape after a hunter has departed, and are difficult for patrols to detect (Lindsey, Romanach, Tambling, Chartier, & Groom, 2011).

A key assumption is that the more patrol effort invested in searching, the more snares will be discovered. However, the improvement in detection with effort has not been quantified and is likely to be affected by factors such as habitat, season, atmospheric conditions (e.g. precipitation, temperature), terrain and topography and the type of snare set (Keane et al. 2011; Jachmann 2008). For example, snares which are physically connected and set in lines that stretch many hundreds of metres may be more detectable than individual snares (O'Kelly et al. 2018b). In addition, snare detection is influenced by rangers themselves. Studies of wildlife observation and plant detection have recorded considerable variability between observers depending on their experience and expertise (J. L. Moore, Hauser, Bear, Williams, & McCarthy, 2011; Sunde & Jessen, 2013). And, even if rangers are capable of finding snares, they may not always be motivated to search (Jachmann, 2008). Conservation law enforcement operations are typically under-resourced, with rangers often inadequately trained, poorly remunerated, and insufficiently equipped to work in challenging conditions (Belecky, Singh, & Moreto, 2018; Long, Grein, Boedicker, & Singh, 2016).

Here, we adopt an experimental approach to test how a vital element of patrol effectiveness – snare detection – is affected by the amount of patrol effort invested. Our study provides an effort-detection curve for snare detectability in a tropical forest context, investigates the effects of habitat and season on detection probability, and assesses the extent to which performance varies between search teams and individual searchers. We use our findings to predict the snare detection levels that could be achieved in a Cambodian PA under different patrolling scenarios.

2. Materials and Methods

2.1 Study Site

The study was conducted in Keo Seima Wildlife Sanctuary (formerly Seima Protection Forest), a 2,927km^2 PA situated in Mondulkiri Province, eastern Cambodia (12°26’70”N, 106°E 94’90”). The PA is topographically diverse, ranging in altitude from 60-750m (Evans et al., 2013). The habitat is heterogeneous, and consists of a complex forest mosaic that includes deciduous dipterocarp and fully evergreen forest (Walston, Davidson, & Men, 2001). The PA supports populations of Asian elephant *(Elephas maximus*) and wild cattle (*Bos spp.),* alongside globally significant primate populations. In 2011, a systematic survey conducted over 2200km, detected 1300 snares in 140 different locations in the PA, with an experimentally calculated detection rate of 28-36% (O’Kelly et al. 2018a).

2.2 Experimental design

Setting snares

We adapted a methodology originally piloted by O’Kelly et al. (2018b), and established five 3.25km transects around a patrol station (Fig. 1, Appendix S1). Habitat here is highly heterogenous; comprised of a mosaic that reflect vegetation types found across the wider landscape. The area also supports a full complement of species, which occur in relatively high densities. Either side of each transect, we delineated 6 x 0.25km^2 (500m x 500m) quadrats at 50m intervals (Appendix S1). This quadrat size was chosen so teams could conduct intensive searches in realistic time-frames. Within each quadrat we set between zero and 15 snares (the number randomly drawn from a Poisson distribution with mean = 7.5), based on estimates of typical snare densities identified by other studies (Dobson et al., 2019). Single foot snares made from black nylon string (5mm), an inexpensive material often used by hunters in this area, were set without a trigger mechanism to prevent harm to wildlife, and all snares were successfully removed at the end of each transect survey.

We recruited local guides from surrounding communities, who were instructed to set single snares as a local hunter might, in locations they deemed suitable to catch popular prey species such as wild pig (*Sus scrofa*), Northern red muntjac (*Muntiacus vaginalis*) and sambar (*Rusa unicolor*). Prior to setting snares, teams explored each quadrat for 30 minutes to identify suitable snare locations. Once set, teams recorded the GPS coordinates of each snare and the dominant habitat type of the quadrat. Teams were asked not to disclose the location or number of snares set in each quadrat to other teams or to leave obvious signs of their presence which future teams might use as cues.

2.3 Data Collection

Searching for snares

The experiment required four separate teams, each led by a staff member from the Wildlife Monitoring Team of Wildlife Conservation Society (WCS) Cambodia. Team leaders had expertise in snare detection, and were accompanied by two other searchers – either a local guide or another WCS staff member. WCS staff remained the same in each team, but changes in availability meant that local guides varied between transects. All team members searched for snares, with team leaders also recording data, coordinating the search strategy and ensuring searchers stayed within quadrat boundaries. Each team was allocated quadrats to search for a designated time period. No quadrat was searched simultaneously by more than one team, and teams never searched quadrats in which they had set snares. To maximize statistical power and to account for the considerable challenge of implementing the survey at a larger scale, each quadrat was searched three times, for a fixed search duration varying between 15 and 90 minutes in 15-minute intervals (Appendix S1). Every effort was made to minimize the effect of previous searches on the detectability of snares by subsequent teams.

Teams were encouraged to search purposefully by following cues in the landscape (e.g. human footprints, wildlife tracks, cut vegetation). The start and finish time, the vegetation type in the quadrat, the distance travelled, the GPS locations of the search routes and any artificial or real snares detected were recorded throughout. We also recorded search order, to account for the fact that the more a quadrat was searched, the more cues were left in the landscape. The later the search, the harder for searchers to differentiate between cues set by the snare setting team (clues) and those left by previous searchers (decoy cues). Teams were shadowed by first author HI to ensure that protocols were adhered to, and to observe and question teams on their choice of snare placement and search strategies. We included the presence of HI as a variable within our models, to assess whether her observation of the search team had any effect on detection performance. The methodology was piloted in December 2016, and conducted during dry season in January-February 2017 and wet season in October-November 2017.

2.4 Ethical Considerations

Employing local community members with relevant hunting experience helped to ensure that artificial snares were realistic, but raised several ethical issues. Firstly, by participating, local guides risked implicating themselves in illegal activity (e.g. by affirming their hunting expertise or knowledge of suitable hunting grounds within the PA). To mitigate this risk, only former hunters recommended by WCS were recruited. Prior to participation, the experimental nature and purpose of the research was explained to local guides, and voluntary verbal consent to participate was sought. Individuals were assured that no information or inferences about their hunting knowledge would be passed onto authorities. An additional concern was that the experiments would introduce individuals to new hunting grounds. However, after consultation with WCS it was decided that the risk was negligible; most local guides were born in or around the PA, and were highly familiar with the study landscape. Protocols were reviewed and approved by the University of Oxford Central University Research Ethics Committee (Ref No. R43030/RE002), with permission to conduct research granted by the Royal Government of Cambodia.

2.5 Analysis

Analyses were performed in R version 3.5.1 (R Core Team, 2017) using the package rstanarm (Goodrich, Gabry, Ali, & Brilleman, 2018). We fitted a series of hierarchical generalised linear models to the data, expressing different hypotheses about the factors influencing snare detection. These were compared using WAIC, a Bayesian information criterion akin to AIC (Watanabe, 2010). The response variable in every model was a binary indicator of whether or not each snare was detected during a given search period. The full set of predictor variables used in one or more of these models is shown in Table 1. Effort was represented by either time or distance. Based on a comparison of WAIC between models 1 and 2 (intercept and grouping parameters only, no covariates), time was chosen as the better-fitting effort measure for model explorations which included covariates, although the two measures were highly correlated (Spearman's Rho = 0.79, 95% CI =77-81; Fig. S2a). Effort measured as time was experimentally manipulated rather than observed, so was centred around 45 minutes (50% of the maximum search time) and included in the model using hours as the unit of measurement. Effort measured as distance and distance to the nearest snare were observed quantities so were scaled by subtracting the mean and dividing by two standard deviations, either precisely (for effort) or using approximate values for the mean and standard deviation (for distance to the nearest snare) to improve the interpretability of the coefficients. All other models included variables for quadrat search order and previous snare detections. Two snare density-related variables were next added, and finally we explored three models which also included variables related to season, team, or placement within the environment.

Model parameters were given weakly informative Students-t priors with 7 degrees of freedom and scale 2.5, except for the intercept which was given a Normal prior with mean 0 and standard deviation 10. Weakly informative priors were chosen to stabilise computation and to express our weak prior beliefs that very large effects would be rare (Gelman, Jakulin, Pittau, & Su, 2008). The coefficients for transect ID, quadrat ID, date, setting team ID and searching team ID were each given independent hierarchical LKJ priors with regularization parameter 1 (Lewandowski, Kurowicka, & Joe, 2009). For each model, 2000 Markov Chain Monte Carlo (MCMC) samples were drawn from four independent chains. Convergence of MCMC chains was evaluated using trace-plots and the Gelman-Rubin diagnostic, with values <1.05 taken to indicate that convergence had been reached (Gelman et al. 2013). The fit of the model with the lowest WAIC value was examined using graphical posterior predictive checks.

Using the effort-detection relationship derived from our fitted model, and assuming replication of the search strategies employed during our experiment, we explored how ~~sequentially~~ dividing search effort within a quadrat across multiple teams might affect detection probability. We assumed that n teams searched the same quadrat independently and sequentially and that each team had the same constant probability, p, of detecting snares that were present. We therefore modelled the proportion of snares remaining after all searches were completed, r, as:

$$r = 1 - (1 - p) n$$

Deploying more search teams is likely to incur transaction costs (e.g. more time is required to travel to sites, and additional salary is required to pay more team leaders). In the absence of empirical data, we incorporated these costs by expressing them in terms of effort lost from the total budget: 10 minutes of search effort was removed from the initial total for each extra team added, and the remaining effort was then split equally between all teams (i.e. at 90 minutes, four teams would search for ~~20~~ 15 minutes each). To examine the sensitivity of our findings to the steepness of the effort-detection relationship w~~W~~e also explored the difference in results when the slope of the effort-detection curve was 50% higher or lower than the observed slope on the logit scale, in order to determine the sensitivity of our results to the specific shape of the effort-detection curve.

3. Results

3.1 Effect of search effort on detection probability

3.1.1 Snare locations

In total, 886 artificial snares were set, 442 in dry season and 444 in wet season. Local guides reported that they generally sought specific features when placing snares; for example, water sources (66% of snares set), animal trails (44%), animal signs (e.g. footprints or faeces; 44%), or fruiting trees (2%).

3.1.2 Detection probability

A total of 535 artificial snare detections was recorded out of a possible 2661 opportunities, with a detection rate of 0.20 averaged across the entire experiment, or 0.24 per hour of searching. In addition, 55 real snares were detected. These detections were not included in analyses, as once detected real snares were removed, meaning subsequent search teams had no opportunity to detect them. 42% of the total population of artificial snares were discovered; 26% were found by only a single team, 13% by two teams, and 3% by all three search teams (S2, Fig. 2).

3.1.3 Predictors of snare detectability

The magnitude and direction of the effect of all covariates were consistent across the set of candidate models considered (see Appendix S2). The best-fitting model (Model 8; Table 2) included time spent searching, quadrat search order, number of times a snare was previously detected, snare clustering and density (Fig. 3), and batches of variables describing the variability between transects, between quadrats within transects, over time and between the teams responsible for setting and searching for snares (Figs. S2d-f). The model did not include season, vegetation type within the quadrat, or the proximity of the snare to water, animal trails or animal signs. Model 9, which included variables relating to the team leader, and the presence of author HI as an observer of the search team, was only marginally less supported while other models were much less well supported (Table 2). However, the effects of team leader and HI's presence in model 9 were inconclusive (Fig. S2b).

The overall probability of searchers detecting any given snare on the first search of an area was 20% (95% CI ± 15-25%), assuming 60 minutes (or approximately 2km) of search effort. Detection probability increased by approximately 10% for every additional 30mins/1km of search effort from approximately 8% with 15 mins of search to approximately 30% with 90 mins (Fig. 4). Snares which were previously detected by a search team were more likely to be detected in subsequent searches (mean raw detection rates: Never previously detected = 0.17; Detected once previously = 0.33; Detected twice previously = 0.54; Fig. 3). Perhaps because previous searchers left cues, such as footprints or cut branches, which made it easier for subsequent searchers to follow their path. Accounting for this, there was an effect of whether the quadrat was being searched for the first, second or third time, with lower rates of detection in the second search than the first, but no clear difference between the first and third searches (mean raw detection rates: First search = 0.21; Second search = 0.16; Third search = 0.24). Snares were more easily detected when they were placed in closer proximity to other snares in a quadrat, but there was no effect of snare density on detection rates (Fig. 3).

3.1.4 Team variability

The identity of the setting and searching teams had little effect on the probability of detection (Fig. S2c). Differences in success were largely attributable to the performance of specific individuals; over 40% of all snare detections were achieved by three searchers, and the best searchers were disproportionately from the professional WCS wildlife monitoring team rather than local guides (Fig. 5). Although WCS staff were responsible for recording data, there was little opportunity for them to claim snares found by others for themselves, as each searcher's detections were verifiable via timestamped GPS tracks of each individuals' search route. We found no evidence that any false recording occurred. Field observations of searchers suggested that detection was mainly influenced by skill and experience. A peer- and self-evaluation exercise suggested that peers more accurately predicted others' detection abilities than individuals did themselves (Appendix S3). The best-performing individual was a WCS employee born in a local village who hunted in childhood.

3.2 Effective allocation of search effort

~~Simulations of search effort allocation~~Our fitted models show that as the amount of total search effort increases from 15 to 90 minutes, the proportion of snares detected by a single team ~~detection~~ can be expected to increase by approximately 20%~~ (Fig. 6)~~. Simulations of search effort allocation suggest that a~~A~~t low search efforts, a 10% increase in detection can be expected for each additional team searching (Fig. 6). For example, four teams searching the same quadrat at separate times for 5 minutes each (in total 20 minutes) may find up to 25% of snares. However, as search effort increases, it can become more efficient to deploy just one team, rather than multiple teams - particularly when the relationship between effort and snare detection is steeper.

4. Discussion

PA managers increasingly require information about the best allocation of patrol effort (Lynam et al., 2016). Our results suggest that overall, the ability of rangers to detect snares is low. Although detection increased with distance between snares and search effort, 60 minutes of searching (approximately 2 km) resulted in the detection of 20% (± 15-25%) of snares, comparable to the 15% detection reported by O'Kelly et al. (2018b) at similar levels of search effort. Higher detection rates might be achieved by deploying more teams to search within a specific area for shorter periods. However, this finding assumes teams independently search the same area, that they are not reliant on cues left by previous searchers, that detected snares are left in situ, and that each search team has equal detection probability. In reality, few of these assumptions are met. Regardless, ~~However,~~ g~~g~~iven the large size of most PAs, the~~ese~~ recommendation to deploy multiple teams within a specific area for shorter periods~~s~~ may be financially and logistically unviable unless there is a particular reason to concentrate on a specific "hotspot". Ultimately, more effective and efficient use of resources will be achieved by deploying a single team to intensively search one area.

Surprisingly, we found no effect of snare density on detection probability. While setting more snares might result in more potential opportunities for snares to be found, searchers still need to target their efforts in the right places. The skill of individual searchers, along with search effort were stronger predictors of detection probability, highlighting the need for PA managers to carefully select personnel with demonstrated skill at detecting snares for patrols. Also unexpected, was that detection was higher during the first and third searches than the second. One reason may have been due to time of day. The second search was usually conducted in the afternoon, when temperatures often exceeded 33°c. By this point individuals had already exerted substantial effort in searching and were physically and mentally fatigued. Our results along with observations during the study, highlight the need for PA managers to carefully consider environmental factors such as temperature when designing patrolling strategies. Managers must demonstrate an awareness of the physical and psychological demands patrolling places on individuals and adapt patrols accordingly (Belecky et al., 2018; Moreto, 2015).

Many PA management regimes prioritise and invest heavily in patrol-based snare removal efforts. However, the low detectability of snares, despite high levels of search effort, raises questions about the efficiency of this approach. If the primary aim of snare removal is to reduce animal mortality to sustainable levels, snare detection and removal rates must be high enough to alleviate pressure on remaining wildlife populations. Knowing what is “high enough” requires robust estimates of snare detection, as well as a good understanding of snare-related mortality rates and their impact on species population trends. Currently, however, there is virtually no empirical information on any of these parameters. If the aim is to deter snaring, then detectability must be high enough to raise costs sufficiently to make it unprofitable (Gray, Hughes, et al., 2017). If the aim is to visibly advertise to potential offenders that snaring is an issue taken seriously by PA managers, then making snare removal efforts visible to communities could be beneficial, even if the actual percentage removed is low. PA managers must therefore consider their aims carefully. All these objectives may benefit from targeted snare removal in known hunting and/or wildlife hotspots, especially if accompanied by legislative reform, consistent enforcement that criminalises the possession of snares, and measures which ensure a high proportion of successful prosecutions occur (Gray, Hughes, et al., 2017). Currently, however, little is known about whether snare removal actually deter hunters, and if so, what the spatial and temporal extents of a deterrent effect are. Better understanding of the relative deterrent effect of different law enforcement strategies on snare hunters' behaviour is urgently required. PA managers should also look beyond snare removal efforts, to other interventions, such as community outreach and alternative livelihoods, which could help to alleviate hunting pressure. However, better understanding of the effect such interventions may have on hunter behaviour is still needed. Any intervention adopted will require careful design, and must be underpinned by a rigorous monitoring and evaluation programme, so that the impact can be empirically assessed (Veríssimo and Wan, 2019).

The finding that WCS staff members were better at locating snares than local guides was contrary to our expectations, but it makes sense. WCS staff had more experience searching for other peoples’ snares, and were also more motivated to do so. Local guides were paid on a daily basis, rather than per snare detection, and thus had no long-term incentive (nor contractual obligation) to perform well. The work was considered hard for little reward, and was potentially against their own interests. Often the exercise was received with bemusement by local guides, who in some cases viewed the setting of ineffective snares as wasted effort. By contrast, WCS staff employed on permanent contracts, with personal and professional interests in protecting wildlife, expressed the desire to improve their snare-detection abilities and had a greater appreciation of the value of experimental work. Investing effort in developing incentive schemes that reward individual performance may increase detections. However, these require careful consideration to ensure they are equitable, affordable and impermeable to ‘cheating’. Few studies have assessed the impact incentives schemes have on snare removal; further experimental research would help to clarify their potential for impacting snare abundance and the prevalence of snare hunting.

There is a debate about the costs and benefits associated with hiring rangers from local communities versus those from ‘outside’ (Paley, 2015). Whilst our study provides some evidence of the benefits of the former, realistically our sample size was too small to draw any credible conclusions. Additionally, we must consider that the artificial nature of our experiment meant that it was devoid of the usual conflicts of interest which can occur when employing local rangers to remove snares possibly set by relatives or neighbours (Paley 2015). Within conservation, the social factors that affect the behaviour and performance of rangers is relatively under-researched (although see Moreto et al. 2015; Spira et al. 2019), and greater empirical understanding of the factors that incentivise and disincentivise rangers during different patrolling activities is needed.

Prior to the study we hypothesised that both habitat and season would affect snare detection, however we found no evidence for either effect in our experiment. In the case of habitat, this might be due to the relatively high within-quadrat habitat variability. Working in the same PA, (O’Kelly et al. (2018b) found a 9% difference in the detectability of single snares in mixed forest (14%) compared to evergreen forest (23%). However, O’Kelly et al.’s comparisons were made between two spatially distinct areas with very different habitats, while the habitat measurements within this study recorded small differences between vegetation within a single area. The lack of an effect of season is perhaps more surprising. In tropical forests, hunters are usually more active during wet season, when soil conditions are more amenable to snare placement (Ibbett et al., n.d.; van Vliet and Nasi, 2008). We expected that the soft soil would also make the tracks of wildlife and snare setters more visible, providing searchers with clues to follow. The lack of seasonal difference in our study may be due to logistical constraints, which forced us to conduct surveys towards the end of the wet season (October-November). Unfortunately, a shorter wet season in 2017 meant that rains had effectively stopped by the time we surveyed the last two transects, resulting in less contrast in physical and meteorological conditions than expected.

Our study demonstrates the utility of a field experiment as an effective and affordable approach to hypothesis testing. Rarely used in conservation contexts, experiments have many advantages; they can be replicable, results can be independently verified, and importantly, they enable researchers to control for extraneous variables so conclusions about the effects of individual variables can more confidently be drawn (Karban, Huntzinger, & Pearse, 2014). However, as with any scientific research, they require careful design and there are limits to their ability to accurately mimic reality. For example, in our experiments, searches were carried out over small areas (0.25km^2), and only teams of three were deployed. In reality, PA managers work at much larger spatial and temporal resolutions; patrols are planned over hundreds of km^2, effort is measured in days rather than minutes, and patrols are usually comprised of 4-7 rangers (Bowman, 2013). The maximum number of snares set per quadrat was limited to 15, yet local guides reported that in reality they saturate suitable areas (e.g. around salt licks, or fruiting trees) with snares to maximise capture opportunities. During the experiment they felt unable to do so due to the limited number of snares, and because they didn't want to increase snare detectability for other teams. Indeed, our results confirm that snares set in closer proximity to each other were more likely to be found than those set-in isolation. Guides sometimes felt required to set snares even in the absence of suitable habitat or wildlife signs, potentially resulting in unrealistic snare placement and/or densities too high for the habitat type. While we acknowledge this bias may have affected snare detectability, we mitigated its impact on our estimates by explicitly modelling the effect of the setting team on detection probability. This variation may also be reflective of reality. Hunters naturally vary in their hunting skill and experience, meaning some snares will always be set in suboptimal locations, and some will be harder to detect than others.

This study provides an effort-detection curve for snare removal for a tropical forest context, and highlights how a quantitative understanding of snare detectability can benefit PA managers. In addition, our parameter estimates can be incorporated into statistical analyses of ranger-collected data to draw more robust conclusions about snare abundance and distribution within this conservation landscape. Although the applicability of our findings is limited to sites characterised by similar habitat types and hunting behaviours, our experimental protocol provides a framework adaptable to different contexts, which can be used to explore efficient allocation of resources for other conservation threats.

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Data accessibility

Data available from https://ukdataservice.ac.uk/.

References

Belecky, M., Singh, R., & Moreto, W. D. (2018). *Life on the frontline 2018*. Woking, UK.

Borgerson, C. (2015). The Effects of Illegal Hunting and Habitat on Two Sympatric Endangered Primates. *International Journal of Primatology*, *36*(1), 74–93. doi:10.1007/s10764-015-9812-x

Bowman, M. (2013). *PROTECT - PRotected-area Operational & Tactical Enforcement Conservation Training - Enforcement Manual* (Fourth Edi). Bangkok, Thailand: FREELAND Foundation.

Brashares, J. S., & Sam, M. K. (2005). How much is enough? Estimating the minimum sampling required for effective monitoring of African reserves. *Biodiversity and Conservation*, *14*(11), 2709–2722. doi:10.1007/s10531-005-8404-z

Bruner, A. G., Bruner, A. G., Gullison, R. E., Rice, R. E., & Fonseca, G. A. B. (2001). Effectiveness of Parks in Protecting Tropical Biodiversity. *Science*, *291*(5501), 125–128. doi:10.1126/science.291.5501.125

Critchlow, R., Plumptre, A. J., Andira, B., Nsubuga, M., Driciru, M., Rwetsiba, A., … Beale, C. M. (2017). Improving law enforcement effectiveness and efficiency in protected areas using ranger-collected monitoring data. *Conservation Letters*, *10*(5), 572–580. doi:10.1111/conl.12288

Critchlow, R., Plumptre, A. J., Driciru, M., Rwetsiba, A., Stokes, E. J., Tumwesigye, C., … Beale, C. M. (2015). Spatiotemporal trends of illegal activities from ranger-collected data in a Ugandan national park: Trends in Illegal Activities. *Conservation Biology*, *0*(0), 1–13. doi:10.1111/cobi.12538

Dobson, A. D. M., Milner-Gulland, E. J., Beale, C. M., Ibbett, H., & Keane, A. (2018). Detecting deterrence from patrol data. *Conservation Biology*, *0*(0), 1–11. doi:10.1111/cobi.13222

Dobson. A.D.M, Milner-Gulland. E.J., Ingram. D.J, Keane. A. (2019). A framework for assessing impacts of wild meat hunting practices in the Tropics. *Human Ecology*, 47, 449–464

Evans, T. D., O'Kelly, H. J., Soriyun, M., Hor, N. M., Phaktra, P., Pheakdey, S., & Pollard, E. (2013). Seima Protection Forest. In T. C. H. Sunderland, J. A. Sayer, & H. Minh-Ha (Eds.), *Evidence-Based Conservation: Lessons from the Lower Mekong* (pp. 157–186). Bogor, Indonesia: CIFOR. doi:10.4324/9780203128466

Gelman, A., Jakulin, A., Pittau, M. G., & Su, Y. S. (2008). A weakly informative default prior distribution for logistic and other regression models. *Annals of Applied Statistics*, *2*(4), 1360–1383. doi:10.1214/08-AOAS191

Gelman, A., Carlin, J. B., Stern, H. S., Dunson, D. B., Vehtari, A., & Rubin, D. B. (2013). Bayesian Data Analysis. CRC Press.

Goodrich, B., Gabry, J., Ali, I., & Brilleman, S. (2018). rstanarm: Bayesian applied regression modeling via

Stan R package.

Gray, T. N. E., Hughes, A. C., Laurance, W. F., Long, B., Lynam, A. J., Kelly, H. O., … Scotson, L. (2017). The wildlife snaring crisis: an insidious and pervasive threat to biodiversity in Southeast Asia. *Biodiversity and Conservation*, 1–7. doi:10.1007/s10531-017-1450-5

Gray, T. N. E., Lynam, A. J., Seng, T., Laurance, W. F., Long, B., Scotson, L., & Ripple, W. J. (2017). Wildlife-snaring crisis in Asian forests. *Science*, *3*(6322), 255–256. doi:10.1126/science.aal4463

Harrison, R. D., Sreekar, R., Brodie, J. F., Brook, S. M., Luskin, M., O'Kelly, H. J., … Velho, N. (2016). Impacts of hunting on tropical forests in Southeat Asia. *Conservation Biology*, *30*(5), 972–981. doi:10.1017/CBO9781107415324.004

Hilborn, R., Arcese, P., Borner, M., Hando, J., Hopcraft, G., Loibooki, M., … Sinclair, A. R. E. (2006). Effective enforcement in a conservation area. *Science (New York, N.Y.)*, *314*(5803), 1266. doi:10.1126/science.1132780

Hötte, M. H. H., Kolodin, I. A., Bereznuk, S. L., Slaght, J. C., Kerley, L. L., Soutyrina, S. V, … Miquelle, D. G. (2016). Indicators of success for smart Law enforcement in protected areas: A case study for Russian Amur Tiger (Panthera tigris altaica) reserves. *Integrative Zoology*, *11*, 2–15. doi:10.1111/1749-4877.12168

Ibbett, H., Keane, A., Griffin, O., Dobson, A., Travers, H., & Milner-Gulland, E. (in press). Estimating hunting prevalence and ~~wild meat~~ reliance on wild meat in Cambodia's Eastern Plains. *Oryx.*

Ingram, D. J., Coad, L., Abernethy, K., Maisels, F., Stokes, E. J., Bobo, K. S., … Waltert, M. (2017). Assessing Africa-Wide Pangolin Exploitation by Scaling Local Data. *Conservation Letters*, *00*(0), 1–9. doi:10.1111/conl.12389

Jachmann, H. (2008). Monitoring law-enforcement performance in nine protected areas in Ghana. *Biological Conservation*, *141*(1), 89–99. doi:10.1016/j.biocon.2007.09.012

Karban, R., Huntzinger, M., & Pearse, I. S. (2014). *How to do ecology: a concise handbook*. Princeton, New Jersey; Oxfordshire, England: Princeton University Press.

Keane, A., Jones, J. P. G., Edward-Jones, G., & Milner-Gulland, E. J. (2008). The sleeping policeman: understanding issues of enforcement and compliance in conservation. *Animal Conservation*, *11*, 75–82. doi:10.1111/j.1469-1795.2008.00170.x

Keane, A., Jones, J. P. G., & Milner-Gulland, E. J. (2011). Encounter data in resource management and ecology: Pitfalls and possibilities. *Journal of Applied Ecology*, *48*(5), 1164–1173. doi:10.1111/j.1365-2664.2011.02034.x

Lewandowski, D., Kurowicka, D., & Joe, H. (2009). Generating random correlation matrices based on vines and extended onion method. *Journal of Multivariate Analysis*, *100*(9), 1989–2001. doi:10.1016/j.jmva.2009.04.008

Lindsey, P. A. P. A., Romanach, S. ., Tambling, C. J., Chartier, K., & Groom, R. (2011). Ecological and financial impacts of illegal bushmeat trade in Zimbabwe. *Oryx*, *45*(1), 96–111. doi:10.1017/S0030605310000153

Long, B., Grein, G., Boedicker, N., & Singh, R. (2016). Are Rangers Adequately Protected By Insurance Schemes ? *Parks: The International Journal of Protected Areas and Conservation*, *22*(November), 83–93.

Lynam, A. J., Porter, L., & Campos-Arceiz, A. (2016). Conservation focus: the challenge of conservation in changing tropical southeast asia. *Conservation Biology*, *30*(5), 931–932. doi:10.1111/cobi.12781

Marescot, L., Lyet, A., Singh, R., Carter, N., & Gimenez, O. (2019). Inferring wildlife poaching in Southeast Asia with multispecies dynamic site-occupancy models. *BioRxiv*, 520114. doi:10.1101/520114

Moore, J. F., Mulindahabi, F., Masozera, M. K., Nichols, J. D., Hines, J. E., Turikunkiko, E., & Oli, M. K. (2017). Are ranger patrols effective in reducing poaching - related threats within protected areas ? *Journal of Applied Ecology*, (June), 1–9. doi:10.1111/1365-2664.12965

Moore, J. L., Hauser, C. E., Bear, J. L., Williams, N. S. G., & McCarthy, M. A. (2011). Estimating detection – effort curves for plants using search experiments. *Ecological Applications*, *21*(2), 601–607. doi:10.1890/10-0590.1

Moreto, W. D. (2015). Occupational stress among law enforcement rangers: insights from Uganda. *Oryx, 50(4),* 646-654. doi:10.1017/S0030605315000356

Moreto, W. D., Brunson, R. K., & Braga, A. A. (2015). 'Such Misconducts Don't Make a Good Ranger': Examining Law Enforcement Ranger Wrongdoing in Uganda. *British Journal of Criminology*, *55*(2), 359–380. doi:10.1093/bjc/azu079

Noss, A. J. (1998). The impacts of cable snare hunting on wildlife populations in the forests of the Central African Republic. *Conservation Biology*, *12*(2), 390–398. doi:10.1111/j.1523-1739.1998.96027.x

O'Kelly, H. J., Rowcliffe, M. J., Durant, S. M., & Milner-Gulland, E. J. (2018a). Robust estimation of snare prevalence within a tropical forest context using N-mixture models. *Biological Conservation*, *217*, 75–82. doi:10.1016/j.biocon.2017.10.007

O'Kelly, H. J., Rowcliffe, M. J., Durant, S., & Milner-Gulland, E. J. (2018b). Experimental estimation of snare detectability for robust threat monitoring. *Ecology and Evolution*, *DOI: 10.10*(August 2017), 1–8. doi:10.1002/ece3.3655

Paley, R. (2015). Managing protected areas in Cambodia. The challenge for conservation bureaucracies in a hostile governance environment. In S. Milne & S. Mahanty (Eds.), *Conservation and Development in Cambodia: Exploring frontiers of change in nature, state and society.* (pp. 141–159). Routledge.

Plumptre, A. J., Fuller, R. A., Rwetsiba, A., Wanyama, F., Kujirakwinja, D., Driciru, M., … Possingham, H. P. (2014). Efficiently targeting resources to deter illegal activities in protected areas. *Journal of Applied Ecology*, *51*(3), 714–725. doi:10.1111/1365-2664.12227

R Core Team. (2017). R: A language and environment for statistical computing. Vienna, Austria, Vienna, Austria: R Foundation for Statistical Computing.

Rija, A. (2017) Spatial Pattern of Illegal Activities and the Impact on Wildlife Populations in Protected Areas in the Serengeti Ecosystem. Doctorate in Philosophy. Department of Biology, University of York. http://etheses.whiterose.ac.uk/20276/

Ripple, W. J., Abernethy, K., Betts, M. G., Chapron, G., Dirzo, R., Galetti, M., … Young, H. (2016). Bushmeat hunting and extinction risk to the world's mammals. *Royal Society Open Science*, *3*, 160498. doi:10.1098/rsos.160498

Schulze, K., Knights, K., Coad, L., Geldmann, J., Leverington, F., Eassom, A., … Burgess, N. D. (2018). An assessment of threats to terrestrial protected areas. *Conservation Letters*, *11*(3), 1–10. doi:10.1111/conl.12435

Spira, C., Kirkby, A. E., & Plumptre, A. J. (2019). Understanding ranger motivation and job satisfaction to improve wildlife protection in Kahuzi–Biega National Park, eastern Democratic Republic of the Congo. *Oryx*. doi:10.1017/S0030605318000856

Stokes, E. J. (2010). Improving effectiveness of protection efforts in tiger source sites: Developing a framework for law enforcement monitoring using MIST. *Integrative Zoology*, *5*, 363–377. doi:10.1111/j.1749-4877.2010.00223.x

Sunde, P., & Jessen, L. (2013). It counts who counts: an experimental evaluation of the importance of observer effects on spotlight count estimates. *European Journal of Wildlife Research*, *59*, 645–653. doi:10.1007/s10344-013-0717-8

van Vliet, N., & Nasi, R. (2008). Hunting for Livelihood in Northeast Gabon: Patterns, Evolution, and Sustainability. *Ecology and Society*, *13*(2), 33. doi:10.5751/ES-02560-130233

Walston, J., Davidson, P., & Men, S. (2001). *A Wildlife Survey of Southern Mondulkiri Province, Cambodia*. Phnom Penh, Cambodia.

Watanabe, S. (2010). Asymptotic equivalence of Bayes cross validation and Widely Applicable Information Criterion in singular learning theory. *Journal of Machine Learning Research*, *11*, 3571–

3594.

Watson, J. E. M., Dudley, N., Segan, D. B., & Hockings, M. (2014). The performance and potential of protected areas. *Nature*, *515*, 67–73. doi:10.1038/nature13947

Wilfred, P., & Maccoll, A. (2014). The pattern of poaching signs in Ugalla Game Reserve, western Tanzania. *African Journal of Ecology*, *52*(4), 543–551. doi:10.1111/aje.12161

Yersin, H., Asiimwe, C., Voordouw, M. J., & Zuberbühler, K. (2017). Impact of Snare Injuries on Parasite Prevalence in Wild Chimpanzees (Pan troglodytes). *International Journal of Primatology*, *38*(1), 21–30. doi:10.1007/s10764-016-9941-x

Figures

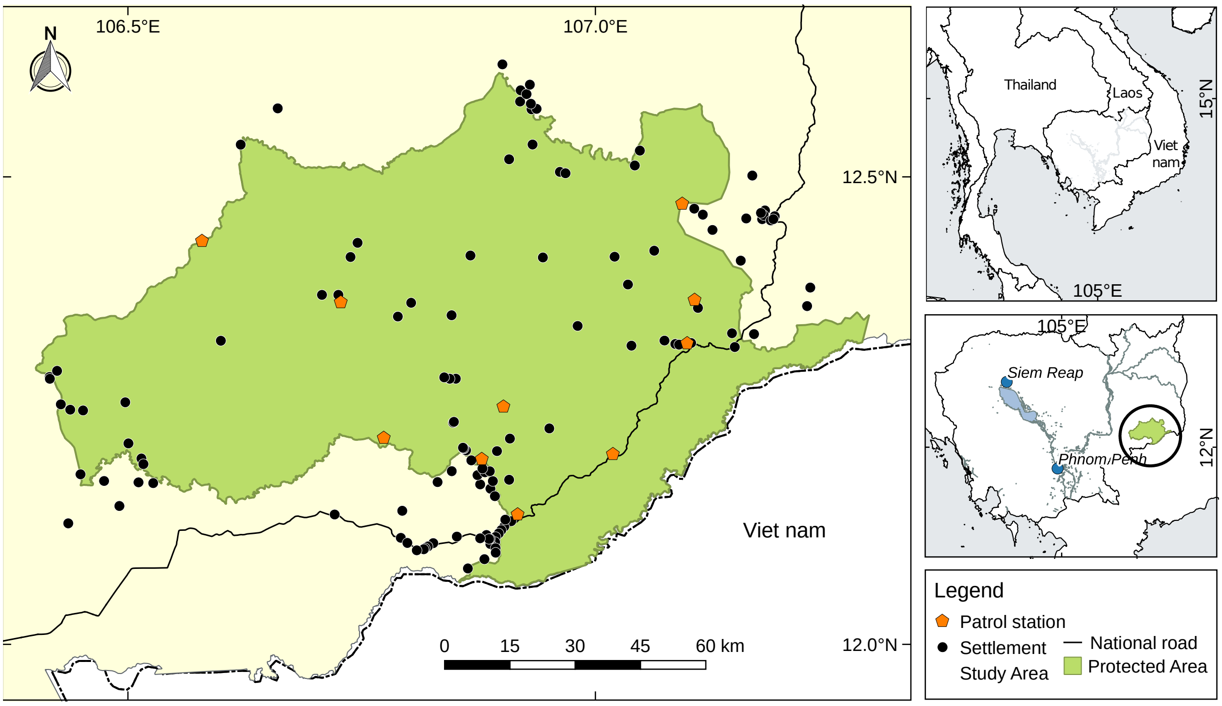

Figure 1. Keo Seima Wildlife Sanctuary, Mondulkiri province, Cambodia. Study area highlighted in grey circle.

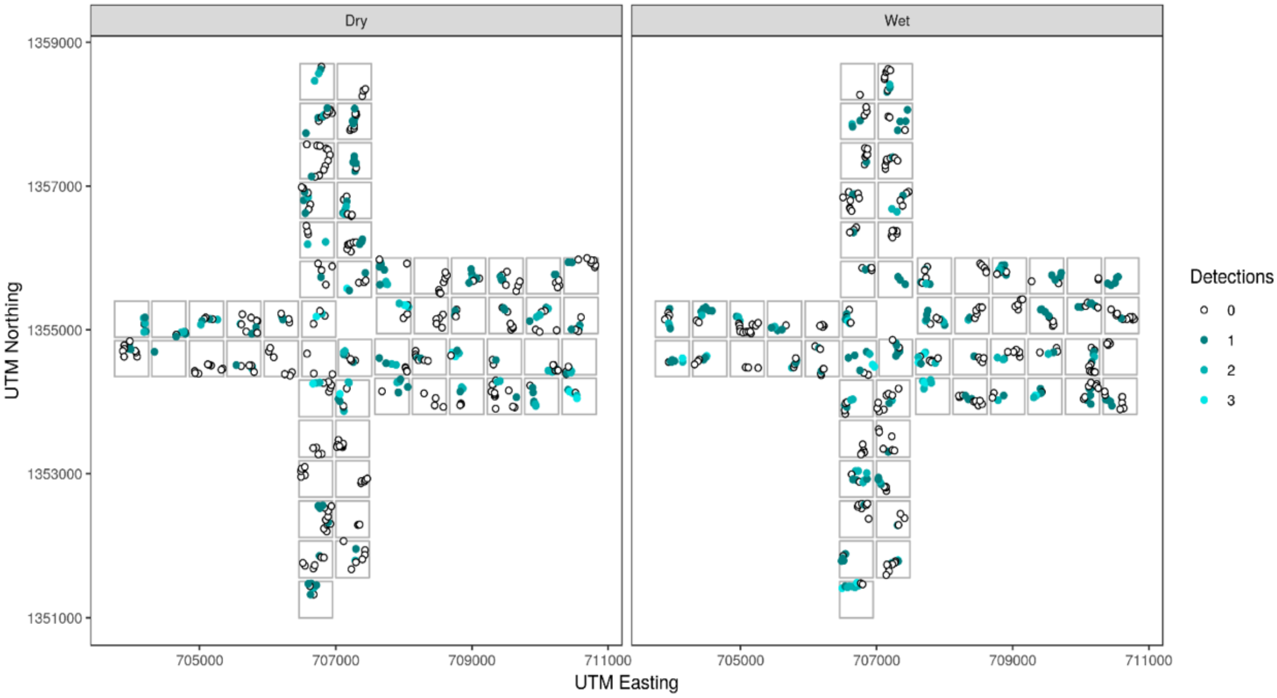

Figure 2. Detections in situ; colour coding represents the number of teams which detected a given snare.

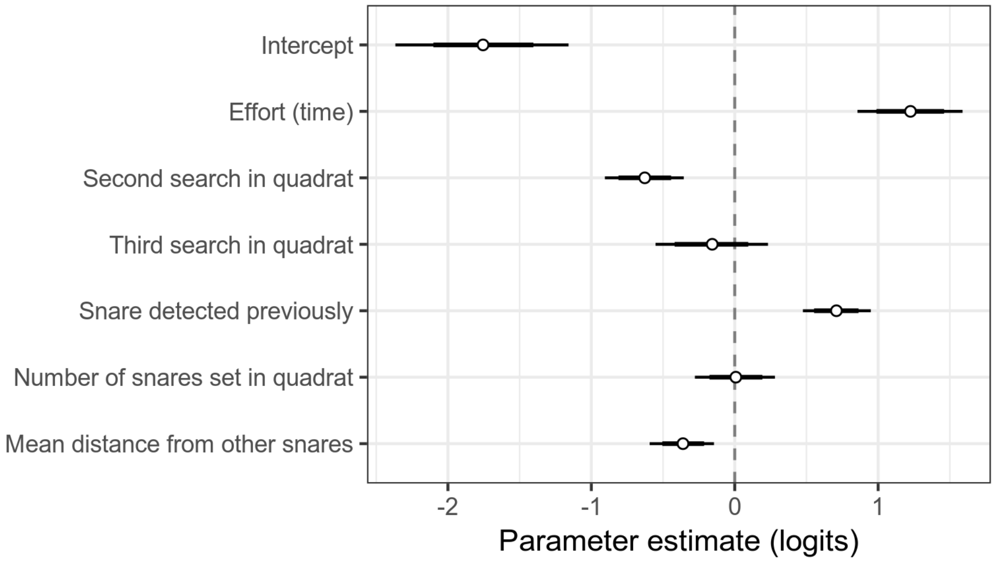

Figure 3. Parameter estimates for the best-fitting model, Model 8. Points represent the mean estimate; thick lines represent 80% credible intervals and thinner lines represent 95% credible intervals.

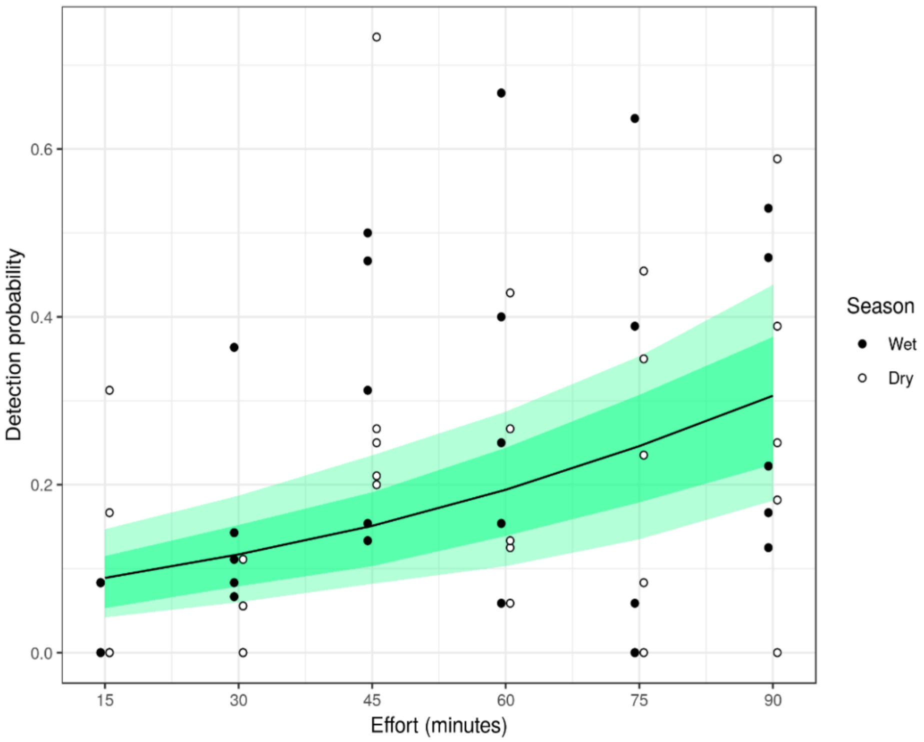

Figure 4. Effort-detection curve. Black line indicates mean probability of snare detection at differing levels of effort, predicted from the best-fitting model (Model 8) under the assumption that the quadrat has not previously been searched. Light green shading indicates the 95% credible interval for detection probability, while the darker green shading indicates the 85% credible interval. Summaries of the proportion of snares detected in each transect in the raw data are plotted as filled circles for wet season and open circles for dry season.

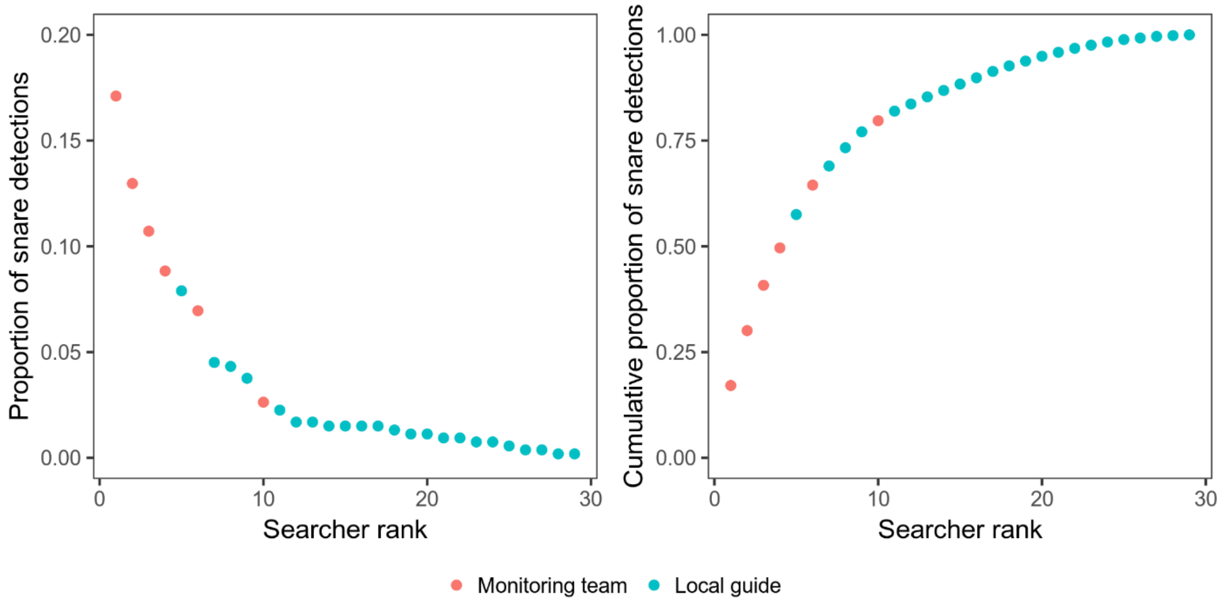

Figure 5. Proportion of snares detected by individual searchers.

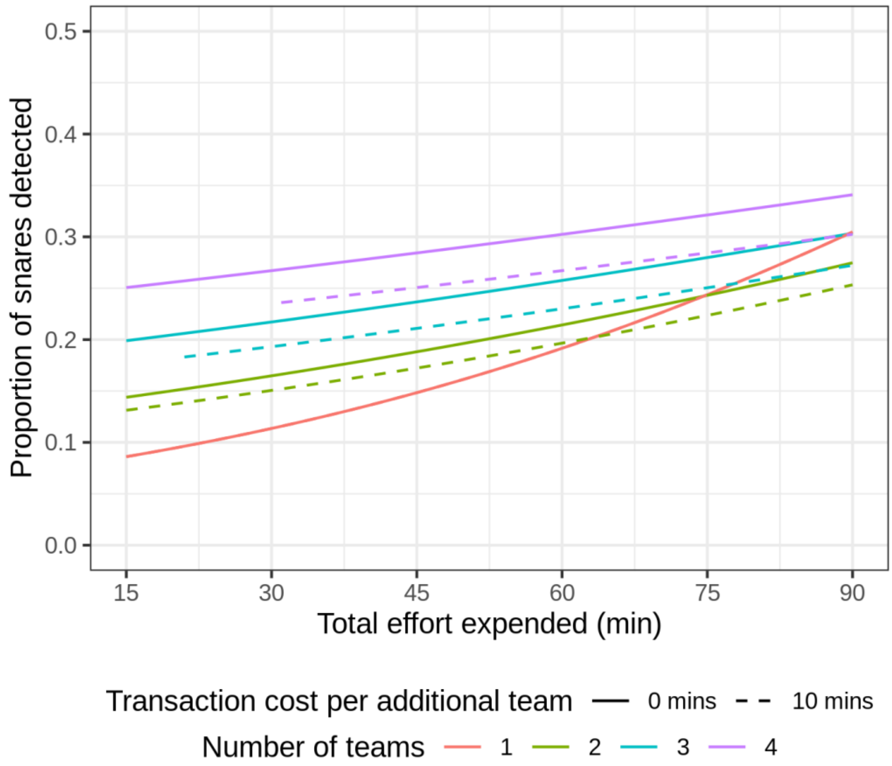

Figure 6. Modelled effect of dividing total search effort across multiple search teams on detection probability, when effects of effort on detection and transaction costs vary.

Tables

Table 1. Description of variables and interaction terms, and their inclusion in the candidate models fitted to the snare detection data. Grouping variables are shown below the dividing line.

				Model										
Variable	**Description**	**Type**	**Levels**	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Effort (time)	Time (minutes) spent searching each quadrat for snares	Continuous	Centred on 45 minutes & scaled by dividing by 60		X		X	X	X	X	X	X	X	X
Effort (distance)	Total distanced travelled (km) during each search	Continuous	Centred on its mean value & scaled by two standard deviations			X								
Quadrat search order	Search order	Factor	1st, 2nd, 3rd				X	X	X	X	X	X	X	X
Previous snare detections	Number of times the snare was previously detected by other teams	Factor	0, 1, 2				X	X	X	X	X	X	X	X
Distance to nearest snare	Mean distance (m) of a snare to other snares within the same quadrat	Continuous	Centred on 150m & scaled by dividing by 100					X	X	X	X	X	X	X
No. of snares set in quadrat	Total number of snares set in the quadrat	Continuous	0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15					X	X	X	X	X	X	X
Season	Season in which quadrat was searched	Factor	Wet, Dry						X	X				X
Season: Effort	Interaction term									X				X
HI present during search	Whether HI accompanied the team during the quadrat search	Factor	Yes, No										X	X
Team leader	ID of the team leader	Factor	1, 2, 3, 4										X	X
Vegetation type	Dominant vegetation type within the quadrat	Factor	Bamboo, mixed-deciduous, semi-evergreen								X			X
Presence of animal trail	Whether the snare was set on an animal trail	Factor	Yes, No								X			X
Presence of animal sign	Whether the snare was set near wildlife signs (e.g. foot prints, dung)	Factor	Yes, No								X			X

Presence of water	Whether the snare was set near a stream, river, pond or salt lick	Factor	Yes, No								X			X
Transect	Transect ID	Factor	1, 2, 3, 4, 5	X	X	X	X	X	X	X	X	X	X	X
Quadrat within transect	Quadrat ID	Factor	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12	X	X	X	X	X	X	X	X	X	X	X
Date	Date each search was conducted	Factor	DD-MM-YY	X	X	X	X	X	X	X	X	X	X	X
Team setting snares	ID of the team that set snares in the quadrat	Factor	W1, W2, W3, W4, D1, D2, D3, D4									X	X	X
Team searching for snares	ID of the team searching for snares in the quadrat	Factor	1, 2, 3, 4									X	X	X

Table 2. WAIC values for the fitted models, the difference from the best-fitting model (δWAIC) and the standard error of that difference (SE(δWAIC)). See Table 1 for models.

Model	WAIC	δWAIC	SE(δWAIC)
8	2412.7	0.0	--
9	2414.1	1.5	1.8
10	2424.2	11.5	3.4
4	2461.4	48.7	14.4
5	2462.9	50.2	14.4
7	2465.3	52.6	14.2
6	2465.5	52.9	14.4
3	2471.8	59.1	16.0
1	2515.5	102.8	21.6
0	2527.6	114.9	23.0
2	2532.9	120.2	22.4

Experimentally assessing the effect of search effort on snare detectability

Authors

Harriet Ibbett[1*], EJ Milner-Gulland[1], Colin Beale[2], Andy Dobson[3], Oliver Griffin[4], Hannah O'Kelly[5], Aidan Keane[3]

Institutions

[1] Department of Zoology, University of Oxford, Oxford, OX1 3SZ, UK

[2] Department of Biology, University of York, York, YO10 5DD, UK

[3] School of Geosciences, University of Edinburgh, Edinburgh, EH8 9XP, UK

[4] Wildlife Conservation Society - Cambodia Programme, Phnom Penh, Cambodia

[5] Independent (okellyhj@gmail.com)

*** Corresponding Author**

School of Natural Sciences, Thoday Building, Bangor University, Bangor, Gwynedd,

harriet.ibbett@bangor.ac.uk +44 (0)7895 787992

Author Contributions

The research was primarily led by HI, but all authors contributed to the research conception and study design. HI collected the data; AK analysed the data; HI led the writing of the manuscript. All authors contributed critically to the drafts and granted final approval for publication.

Experimentally assessing the effect of search effort on snare detectability

Abstract

Reducing threats to biodiversity is the key objective of ranger patrols in protected areas. However, efforts can be hampered by rangers' inability to detect threats, and poor understanding of threat abundance and distribution in a landscape. Snares are particularly problematic due to their cryptic nature and limited selectivity with respect to captured animals' species, sex, or age. Using an experimental approach, we investigated the effect of search effort, habitat, season, and team on rangers' detection of snares in a tropical forest landscape. We provide an effort-detection curve, and use our findings to make preliminary predictions about snare detection under different scenarios of patrol effort. Results suggest that the overall probability of a searcher detecting any given snare in a 0.25/km^2 area, assuming 60 minutes (or approximately 2km) of search effort is 20% (95% CI ± 15-25%), with no significant effect of season, habitat or team. Our models suggested this would increase by approximately 10% with an additional 30mins/1km of search effort. Our preliminary predictions of the effectiveness of different patrolling scenarios show that detection opportunities are maximised at low effort levels by deploying multiple teams to a single area, but at high effort levels deploying single teams becomes more efficient. Our results suggest that snare detectability in tropical forest landscapes is likely to be low, and may not improve dramatically with increased search effort. Given this, managers need to consider whether intensive snare-removal efforts are the best use of limited resources; the answer will depend on their underlying objectives.

Keywords

Detection probability; hunting; law enforcement; protected areas; ranger patrols; Cambodia

1. Introduction

Protected area (PA) networks are a cornerstone of global efforts to conserve biodiversity (Bruner, Bruner, Gullison, Rice, & Fonseca, 2001). Their success depends on effective management, including the reduction of threats to species and habitats (Watson, Dudley, Segan, & Hockings, 2014). A primary tool available to PA managers to address threats is patrolling by ranger teams (Hilborn et al., 2006; Lynam, Porter, & Campos-Arceiz, 2016). Through regular patrolling, rangers monitor adherence to conservation rules, deter potential perpetrators, and punish infractions when detected (Keane, Jones, Edward-Jones, & Milner-Gulland, 2008). To design optimal patrol strategies, PA managers require robust information about the distribution and abundance of threats in a landscape (Critchlow et al., 2017) alongside a means of assessing which approach is most likely to yield the greatest conservation benefit at the lowest possible cost (Plumptre et al., 2014).

Data collected by rangers are increasingly used to map spatio-temporal trends in threats and evaluate patrol performance. These are often collected by patrols for little additional cost (Brashares & Sam, 2005). Subsequently, the data can be used with open-access tools such as the Spatial Monitoring and Reporting Tool (SMART) to map threats and prioritize patrol effort within conservation landscapes (Hötte et al., 2016; Stokes, 2010). However, gathering data is not the primary objective of patrols and ranger-collected data may be subject to considerable bias (Keane et al. 2011). Patrol data must therefore be handled with caution to avoid misleading conclusions and ineffective targeting of patrol effort (Critchlow et al., 2015; Keane, Jones, & Milner-Gulland, 2011). While a growing suite of statistical methods exists to account for these biases (see Critchlow et al., 2015; Marescot, Lyet, Singh, Carter, & Gimenez, 2019; J. F. Moore et al., 2017), there is also a broader need for independent tests of key aspects of patrol effectiveness, such as the amount of patrol effort required to successfully detect a certain proportion of threats present within expansive conservation landscapes (Dobson, Milner-Gulland, Beale, Ibbett, & Keane, 2018). Well-designed experiments can provide effective and affordable means to trial different approaches, and have been used to improve understanding of the effects of environmental covariates on the detectability of traps set by hunters in both tropical forest (O'Kelly et al. 2018a) and savannah (Rija, 2017) landscapes. However, no experimental study has yet explored the relationship between search effort and threat detection, knowledge of which would enable PA managers to distribute patrol effort more efficiently, and thereby improve PA effectiveness.

Hunting poses one of the greatest threats to wildlife in PAs globally (Ripple et al., 2016; Schulze et al., 2018) and snares are one of the most prevalent hunting technologies used worldwide (Gray, Hughes, et al., 2017; Harrison et al., 2016). Usually made from wire, cable, or nylon, snares are affordable, accessible, and can trap a wide range of arboreal and terrestrial species, whether diurnal or nocturnal (Borgerson, 2015; Ingram et al., 2017). Due to their limited selectivity with respect to species, sex, or age of captured animals, snares are a potent threat to biodiversity (Noss, 1998). Although animals sometimes escape snares, subsequent non-fatal injuries often jeopardize their long-term survival (Gray, Lynam, et al., 2017). For example, chimpanzees with snare injuries have been found to suffer significantly higher parasite loads than those without (Yersin, Asiimwe, Voordouw, & Zuberbühler, 2017). Unlike other forms of hunting, snares present a persistent threat to wildlife as they remain operational in the landscape after a hunter has departed, and are difficult for patrols to detect (Lindsey, Romanach, Tambling, Chartier, & Groom, 2011).

A key assumption is that the more patrol effort invested in searching, the more snares will be discovered. However, the improvement in detection with effort has not been quantified and is likely to be affected by factors such as habitat, season, atmospheric conditions (e.g. precipitation, temperature), terrain and topography and the type of snare set (Keane et al. 2011; Jachmann 2008). For example, snares which are physically connected and set in lines that stretch many hundreds of metres may be more detectable than individual snares (O'Kelly et al. 2018b). In addition, snare detection is influenced by rangers themselves. Studies of wildlife observation and plant detection have recorded considerable variability between observers depending on their experience and expertise (J. L. Moore, Hauser, Bear, Williams, & McCarthy, 2011; Sunde & Jessen, 2013). And, even if rangers are capable of finding snares, they may not always be motivated to search (Jachmann, 2008). Conservation law enforcement operations are typically under-resourced, with rangers often inadequately trained, poorly remunerated, and insufficiently equipped to work in challenging conditions (Belecky, Singh, & Moreto, 2018; Long, Grein, Boedicker, & Singh, 2016).

Here, we adopt an experimental approach to test how a vital element of patrol effectiveness – snare detection – is affected by the amount of patrol effort invested. Our study provides an effort-detection curve for snare detectability in a tropical forest context, investigates the effects of habitat and season on detection probability, and assesses the extent to which performance varies between search teams and individual searchers. We use our findings to predict the snare detection levels that could be achieved in a Cambodian PA under different patrolling scenarios.

2. Materials and Methods

2.1 Study Site

The study was conducted in Keo Seima Wildlife Sanctuary (formerly Seima Protection Forest), a 2,927km^2 PA situated in Mondulkiri Province, eastern Cambodia (12°26'70"N, 106°E 94'90"). The PA is topographically diverse, ranging in altitude from 60-750m (Evans et al., 2013). The habitat is heterogeneous, and consists of a complex forest mosaic that includes deciduous dipterocarp and fully evergreen forest (Walston, Davidson, & Men, 2001). The PA supports populations of Asian elephant *(Elephas maximus*) and wild cattle (*Bos spp.),* alongside globally significant primate populations. In 2011, a systematic survey conducted over 2200km, detected 1300 snares in 140 different locations in the PA, with an experimentally calculated detection rate of 28-36% (O'Kelly et al. 2018a).

2.2 Experimental design

Setting snares

We adapted a methodology originally piloted by O'Kelly et al. (2018b), and established five 3.25km transects around a patrol station (Fig. 1, Appendix S1). Habitat here is highly heterogenous; comprised of a mosaic that reflect vegetation types found across the wider landscape. The area also supports a full complement of species, which occur in relatively high densities. Either side of each transect, we delineated 6 x 0.25km^2 (500m x 500m) quadrats at 50m intervals (Appendix S1). This quadrat size was chosen so teams could conduct intensive searches in realistic time-frames. Within each quadrat we set between zero and 15 snares (the number randomly drawn from a Poisson distribution with mean = 7.5), based on estimates of typical snare densities identified by other studies (Dobson et al., 2019). Single foot snares made from black nylon string (5mm), an inexpensive material often used by hunters in this area, were set without a trigger mechanism to prevent harm to wildlife, and all snares were successfully removed at the end of each transect survey.

We recruited local guides from surrounding communities, who were instructed to set single snares as a local hunter might, in locations they deemed suitable to catch popular prey species such as wild pig (*Sus scrofa*), Northern red muntjac (*Muntiacus vaginalis*) and sambar (*Rusa unicolor*). Prior to setting snares, teams explored each quadrat for 30 minutes to identify suitable snare locations. Once set, teams recorded the GPS coordinates of each snare and the dominant habitat type of the quadrat. Teams were asked not to disclose the location or number of snares set in each quadrat to other teams or to leave obvious signs of their presence which future teams might use as cues.

2.3 Data Collection

Searching for snares

The experiment required four separate teams, each led by a staff member from the Wildlife Monitoring Team of Wildlife Conservation Society (WCS) Cambodia. Team leaders had expertise in snare detection, and were accompanied by two other searchers – either a local guide or another WCS staff member. WCS staff remained the same in each team, but changes in availability meant that local guides varied between transects. All team members searched for snares, with team leaders also recording data, coordinating the search strategy and ensuring searchers stayed within quadrat boundaries. Each team was allocated quadrats to search for a designated time period. No quadrat was searched simultaneously by more than one team, and teams never searched quadrats in which they had set snares. To maximize statistical power and to account for the considerable challenge of implementing the survey at a larger scale, each quadrat was searched three times, for a fixed search duration varying between 15 and 90 minutes in 15-minute intervals (Appendix S1). Every effort was made to minimize the effect of previous searches on the detectability of snares by subsequent teams.

Teams were encouraged to search purposefully by following cues in the landscape (e.g. human footprints, wildlife tracks, cut vegetation). The start and finish time, the vegetation type in the quadrat, the distance travelled, the GPS locations of the search routes and any artificial or real snares detected were recorded throughout. We also recorded search order, to account for the fact that the more a quadrat was searched, the more cues were left in the landscape. The later the search, the harder for searchers to differentiate between cues set by the snare setting team (clues) and those left by previous searchers (decoy cues). Teams were shadowed by first author HI to ensure that protocols were adhered to, and to observe and question teams on their choice of snare placement and search strategies. We included the presence of HI as a variable within our models, to assess whether her observation of the search team had any effect on detection performance. The methodology was piloted in December 2016, and conducted during dry season in January-February 2017 and wet season in October-November 2017.

2.4 Ethical Considerations

Employing local community members with relevant hunting experience helped to ensure that artificial snares were realistic, but raised several ethical issues. Firstly, by participating, local guides risked implicating themselves in illegal activity (e.g. by affirming their hunting expertise or knowledge of suitable hunting grounds within the PA). To mitigate this risk, only former hunters recommended by WCS were recruited. Prior to participation, the experimental nature and purpose of the research was explained to local guides, and voluntary verbal consent to participate was sought. Individuals were assured that no information or inferences about their hunting knowledge would be passed onto authorities. An additional concern was that the experiments would introduce individuals to new hunting grounds. However, after consultation with WCS it was decided that the risk was negligible; most local guides were born in or around the PA, and were highly familiar with the study landscape. Protocols were reviewed and approved by the University of Oxford Central University Research Ethics Committee (Ref No. R43030/RE002), with permission to conduct research granted by the Royal Government of Cambodia.

2.5 Analysis

Analyses were performed in R version 3.5.1 (R Core Team, 2017) using the package rstanarm (Goodrich, Gabry, Ali, & Brilleman, 2018). We fitted a series of hierarchical generalised linear models to the data, expressing different hypotheses about the factors influencing snare detection. These were compared using WAIC, a Bayesian information criterion akin to AIC (Watanabe, 2010). The response variable in every model was a binary indicator of whether or not each snare was detected during a given search period. The full set of predictor variables used in one or more of these models is shown in Table 1. Effort was represented by either time or distance. Based on a comparison of WAIC between models 1 and 2 (intercept and grouping parameters only, no covariates), time was chosen as the better-fitting effort measure for model explorations which included covariates, although the two measures were highly correlated (Spearman's Rho = 0.79, 95% CI =77-81; Fig. S2a). Effort measured as time was experimentally manipulated rather than observed, so was centred around 45 minutes (50% of the maximum search time) and included in the model using hours as the unit of measurement. Effort measured as distance and distance to the nearest snare were observed quantities so were scaled by subtracting the mean and dividing by two standard deviations, either precisely (for effort) or using approximate values for the mean and standard deviation (for distance to the nearest snare) to improve the interpretability of the coefficients. All other models included variables for quadrat search order and previous snare detections. Two snare density-related variables were next added, and finally we explored three models which also included variables related to season, team, or placement within the environment.

Model parameters were given weakly informative Students-t priors with 7 degrees of freedom and scale 2.5, except for the intercept which was given a Normal prior with mean 0 and standard deviation 10. Weakly informative priors were chosen to stabilise computation and to express our weak prior beliefs that very large effects would be rare (Gelman, Jakulin, Pittau, & Su, 2008). The coefficients for transect ID, quadrat ID, date, setting team ID and searching team ID were each given independent hierarchical LKJ priors with regularization parameter 1 (Lewandowski, Kurowicka, & Joe, 2009). For each model, 2000 Markov Chain Monte Carlo (MCMC) samples were drawn from four independent chains. Convergence of MCMC chains was evaluated using trace-plots and the Gelman-Rubin diagnostic, with values <1.05 taken to indicate that convergence had been reached (Gelman et al. 2013). The fit of the model with the lowest WAIC value was examined using graphical posterior predictive checks.

Using the effort-detection relationship derived from our fitted model, and assuming replication of the search strategies employed during our experiment, we explored how dividing search effort within a quadrat across multiple teams might affect detection probability. We assumed that n teams searched the same quadrat independently and sequentially and that each team had the same constant probability, p, of detecting snares that were present. We therefore modelled the proportion of snares remaining after all searches were completed, r, as:

$$r = 1 - (1 - p) n$$

Deploying more search teams is likely to incur transaction costs (e.g. more time is required to travel to sites, and additional salary is required to pay more team leaders). In the absence of empirical data, we incorporated these costs by expressing them in terms of effort lost from the total budget: 10 minutes of search effort was removed from the initial total for each extra team added, and the remaining effort was then split equally between all teams (i.e. at 90 minutes, four teams would search for 15 minutes each). To examine the sensitivity of our findings to the steepness of the effort-detection relationship we also explored the difference in results when the slope of the effort-detection curve was 50% higher or lower than the observed slope on the logit scale, in order to determine the sensitivity of our results to the specific shape of the effort-detection curve.

3. Results

3.1 Effect of search effort on detection probability

3.1.1 Snare locations

In total, 886 artificial snares were set, 442 in dry season and 444 in wet season. Local guides reported that they generally sought specific features when placing snares; for example, water sources (66% of snares set), animal trails (44%), animal signs (e.g. footprints or faeces; 44%), or fruiting trees (2%).

3.1.2 Detection probability

A total of 535 artificial snare detections was recorded out of a possible 2661 opportunities, with a detection rate of 0.20 averaged across the entire experiment, or 0.24 per hour of searching. In addition, 55 real snares were detected. These detections were not included in analyses, as once detected real snares were removed, meaning subsequent search teams had no opportunity to detect them. 42% of the total population of artificial snares were discovered; 26% were found by only a single team, 13% by two teams, and 3% by all three search teams (S2, Fig. 2).

3.1.3 Predictors of snare detectability

The magnitude and direction of the effect of all covariates were consistent across the set of candidate models considered (see Appendix S2). The best-fitting model (Model 8; Table 2) included time spent searching, quadrat search order, number of times a snare was previously detected, snare clustering and density (Fig. 3), and batches of variables describing the variability between transects, between quadrats within transects, over time and between the teams responsible for setting and searching for snares (Figs. S2d-f). The model did not include season, vegetation type within the quadrat, or the proximity of the snare to water, animal trails or animal signs. Model 9, which included variables relating to the team leader, and the presence of author HI as an observer of the search team, was only marginally less supported while other models were much less well supported (Table 2). However, the effects of team leader and HI's presence in model 9 were inconclusive (Fig. S2b).

The overall probability of searchers detecting any given snare on the first search of an area was 20% (95% CI ± 15-25%), assuming 60 minutes (or approximately 2km) of search effort. Detection probability increased by approximately 10% for every additional 30mins/1km of search effort from approximately 8% with 15 mins of search to approximately 30% with 90 mins (Fig. 4). Snares which were previously detected by a search team were more likely to be detected in subsequent searches (mean raw detection rates: Never previously detected = 0.17; Detected once previously = 0.33; Detected twice previously = 0.54; Fig. 3). Perhaps because previous searchers left cues, such as footprints or cut branches, which made it easier for subsequent searchers to follow their path. Accounting for this, there was an effect of whether the quadrat was being searched for the first, second or third time, with lower rates of detection in the second search than the first, but no clear difference between the first and third searches (mean raw detection rates: First search = 0.21; Second search = 0.16; Third search = 0.24). Snares were more easily detected when they were placed in closer proximity to other snares in a quadrat, but there was no effect of snare density on detection rates (Fig. 3).

3.1.4 Team variability

The identity of the setting and searching teams had little effect on the probability of detection (Fig. S2c). Differences in success were largely attributable to the performance of specific individuals; over 40% of all snare detections were achieved by three searchers, and the best searchers were disproportionately from the professional WCS wildlife monitoring team rather than local guides (Fig. 5). Although WCS staff were responsible for recording data, there was little opportunity for them to claim snares found by others for themselves, as each searcher's detections were verifiable via timestamped GPS tracks of each individuals' search route. We found no evidence that any false recording occurred. Field observations of searchers suggested that detection was mainly influenced by skill and experience. A peer- and self-evaluation exercise suggested that peers more accurately predicted others' detection abilities than individuals did themselves (Appendix S3). The best-performing individual was a WCS employee born in a local village who hunted in childhood.

3.2 Effective allocation of search effort

Our fitted models show that as the amount of total search effort increases from 15 to 90 minutes, the proportion of snares detected by a single team can be expected to increase by approximately 20%. Simulations of search effort allocation suggest that at low search efforts, a 10% increase in detection can be expected for each additional team searching (Fig. 6). For example, four teams searching the same quadrat at separate times for 5 minutes each (in total 20 minutes) may find up to 25% of snares. However, as search effort increases, it can become more efficient to deploy just one team, rather than multiple teams - particularly when the relationship between effort and snare detection is steeper.

4. Discussion

PA managers increasingly require information about the best allocation of patrol effort (Lynam et al., 2016). Our results suggest that overall, the ability of rangers to detect snares is low. Although detection increased with distance between snares and search effort, 60 minutes of searching (approximately 2 km) resulted in the detection of 20% (± 15-25%) of snares, comparable to the 15% detection reported by O'Kelly et al. (2018b) at similar levels of search effort. Higher detection rates might be achieved by deploying more teams to search within a specific area for shorter periods. However, this finding assumes teams independently search the same area, that they are not reliant on cues left by previous searchers, that detected snares are left in situ, and that each search team has equal detection probability. In reality, few of these assumptions are met. Regardless, given the large size of most PAs, the recommendation to deploy multiple teams within a specific area for shorter periods may be financially and logistically unviable unless there is a particular reason to concentrate on a specific "hotspot". Ultimately, more effective and efficient use of resources will be achieved by deploying a single team to intensively search one area.

Surprisingly, we found no effect of snare density on detection probability. While setting more snares might result in more potential opportunities for snares to be found, searchers still need to target their efforts in the right places. The skill of individual searchers, along with search effort were stronger predictors of detection probability, highlighting the need for PA managers to carefully select personnel with demonstrated skill at detecting snares for patrols. Also unexpected, was that detection was higher during the first and third searches than the second. One reason may have been due to time of day. The second search was usually conducted in the afternoon, when temperatures often exceeded 33°c. By this point individuals had already exerted substantial effort in searching and were physically and mentally fatigued. Our results along with observations during the study, highlight the need for PA managers to carefully consider environmental factors such as temperature when designing patrolling strategies. Managers must demonstrate an awareness of the physical and psychological demands patrolling places on individuals and adapt patrols accordingly (Belecky et al., 2018; Moreto, 2015).

Many PA management regimes prioritise and invest heavily in patrol-based snare removal efforts. However, the low detectability of snares, despite high levels of search effort, raises questions about the efficiency of this approach. If the primary aim of snare removal is to reduce animal mortality to sustainable levels, snare detection and removal rates must be high enough to alleviate pressure on remaining wildlife populations. Knowing what is "high enough" requires robust estimates of snare detection, as well as a good understanding of snare-related mortality rates and their impact on species population trends. Currently, however, there is virtually no empirical information on any of these parameters. If the aim is to deter snaring, then detectability must be high enough to raise costs sufficiently to make it unprofitable (Gray, Hughes, et al., 2017). If the aim is to visibly advertise to potential offenders that snaring is an issue taken seriously by PA managers, then making snare removal efforts visible to communities could be beneficial, even if the actual percentage removed is low. PA managers must therefore consider their aims carefully. All these objectives may benefit from targeted snare removal in known hunting and/or wildlife hotspots, especially if accompanied by legislative reform, consistent enforcement that criminalises the possession of snares, and measures which ensure a high proportion of successful prosecutions occur (Gray, Hughes, et al., 2017). Currently, however, little is known about whether snare removal actually deter hunters, and if so, what the spatial and temporal extents of a deterrent effect are. Better understanding of the relative deterrent effect of different law enforcement strategies on snare hunters' behaviour is urgently required. PA managers should also look beyond snare removal efforts, to other interventions, such as community outreach and alternative livelihoods, which could help to alleviate hunting pressure. However, better understanding of the effect such interventions may have on hunter behaviour is still needed. Any intervention adopted will require careful design, and must be underpinned by a rigorous monitoring and evaluation programme, so that the impact can be empirically assessed (Veríssimo and Wan, 2019).

The finding that WCS staff members were better at locating snares than local guides was contrary to our expectations, but it makes sense. WCS staff had more experience searching for other peoples' snares, and were also more motivated to do so. Local guides were paid on a daily basis, rather than per snare detection, and thus had no long-term incentive (nor contractual obligation) to perform well. The work was considered hard for little reward, and was potentially against their own interests. Often the exercise was received with bemusement by local guides, who in some cases viewed the setting of ineffective snares as wasted effort. By contrast, WCS staff employed on permanent contracts, with personal and professional interests in protecting wildlife, expressed the desire to improve their snare-detection abilities and had a greater appreciation of the value of experimental work. Investing effort in developing incentive schemes that reward individual performance may increase detections. However, these require careful consideration to ensure they are equitable, affordable and impermeable to 'cheating'. Few studies have assessed the impact incentives schemes have on snare removal; further experimental research would help to clarify their potential for impacting snare abundance and the prevalence of snare hunting.

There is a debate about the costs and benefits associated with hiring rangers from local communities versus those from 'outside' (Paley, 2015). Whilst our study provides some evidence of the benefits of the former, realistically our sample size was too small to draw any credible conclusions. Additionally, we must consider that the artificial nature of our experiment meant that it was devoid of the usual conflicts of interest which can occur when employing local rangers to remove snares possibly set by relatives or neighbours (Paley 2015). Within conservation, the social factors that affect the behaviour and performance of rangers is relatively under-researched (although see Moreto et al. 2015; Spira et al. 2019), and greater empirical understanding of the factors that incentivise and disincentivise rangers during different patrolling activities is needed.

Prior to the study we hypothesised that both habitat and season would affect snare detection, however we found no evidence for either effect in our experiment. In the case of habitat, this might be due to the relatively high within-quadrat habitat variability. Working in the same PA, (O'Kelly et al. (2018b) found a 9% difference in the detectability of single snares in mixed forest (14%) compared to evergreen forest (23%). However, O'Kelly et al.'s comparisons were made between two spatially distinct areas with very different habitats, while the habitat measurements within this study recorded small differences between vegetation within a single area. The lack of an effect of season is perhaps more surprising. In tropical forests, hunters are usually more active during wet season, when soil conditions are more amenable to snare placement (Ibbett et al., n.d.; van Vliet and Nasi, 2008). We expected that the soft soil would also make the tracks of wildlife and snare setters more visible, providing searchers with clues to follow. The lack of seasonal difference in our study may be due to logistical constraints, which forced us to conduct surveys towards the end of the wet season (October-November). Unfortunately, a shorter wet season in 2017 meant that rains had effectively stopped by the time we surveyed the last two transects, resulting in less contrast in physical and meteorological conditions than expected.

Our study demonstrates the utility of a field experiment as an effective and affordable approach to hypothesis testing. Rarely used in conservation contexts, experiments have many advantages; they can be replicable, results can be independently verified, and importantly, they enable researchers to control for extraneous variables so conclusions about the effects of individual variables can more confidently be drawn (Karban, Huntzinger, & Pearse, 2014). However, as with any scientific research, they require careful design and there are limits to their ability to accurately mimic reality. For example, in our experiments, searches were carried out over small areas ($0.25km^2$), and only teams of three were deployed. In reality, PA managers work at much larger spatial and temporal resolutions; patrols are planned over hundreds of km^2, effort is measured in days rather than minutes, and patrols are usually comprised of 4-7 rangers (Bowman, 2013). The maximum number of snares set per quadrat was limited to 15, yet local guides reported that in reality they saturate suitable areas (e.g. around salt licks, or fruiting trees) with snares to maximise capture opportunities. During the experiment they felt unable to do so due to the limited number of snares, and because they didn’t want to increase snare detectability for other teams. Indeed, our results confirm that snares set in closer proximity to each other were more likely to be found than those set-in isolation. Guides sometimes felt required to set snares even in the absence of suitable habitat or wildlife signs, potentially resulting in unrealistic snare placement and/or densities too high for the habitat type. While we acknowledge this bias may have affected snare detectability, we mitigated its impact on our estimates by explicitly modelling the effect of the setting team on detection probability. This variation may also be reflective of reality. Hunters naturally vary in their hunting skill and experience, meaning some snares will always be set in suboptimal locations, and some will be harder to detect than others.

This study provides an effort-detection curve for snare removal for a tropical forest context, and highlights how a quantitative understanding of snare detectability can benefit PA managers. In addition, our parameter estimates can be incorporated into statistical analyses of ranger-collected data to draw more robust conclusions about snare abundance and distribution within this conservation landscape. Although the applicability of our findings is limited to sites characterised by similar habitat types and hunting behaviours, our experimental protocol provides a framework adaptable to different contexts, which can be used to explore efficient allocation of resources for other conservation threats.

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Data accessibility

Data available from https://ukdataservice.ac.uk/.

References

Belecky, M., Singh, R., & Moreto, W. D. (2018). *Life on the frontline 2018*. Woking, UK.

Borgerson, C. (2015). The Effects of Illegal Hunting and Habitat on Two Sympatric Endangered Primates. *International Journal of Primatology*, *36*(1), 74–93. doi:10.1007/s10764-015-9812-x

Bowman, M. (2013). *PROTECT - PRotected-area Operational & Tactical Enforcement Conservation Training - Enforcement Manual* (Fourth Edi). Bangkok, Thailand: FREELAND Foundation.

Brashares, J. S., & Sam, M. K. (2005). How much is enough? Estimating the minimum sampling required for effective monitoring of African reserves. *Biodiversity and Conservation*, *14*(11), 2709–2722. doi:10.1007/s10531-005-8404-z

Bruner, A. G., Bruner, A. G., Gullison, R. E., Rice, R. E., & Fonseca, G. A. B. (2001). Effectiveness of Parks in Protecting Tropical Biodiversity. *Science*, *291*(5501), 125–128. doi:10.1126/science.291.5501.125

Critchlow, R., Plumptre, A. J., Andira, B., Nsubuga, M., Driciru, M., Rwetsiba, A., … Beale, C. M. (2017). Improving law enforcement effectiveness and efficiency in protected areas using ranger-collected monitoring data. *Conservation Letters*, *10*(5), 572–580. doi:10.1111/conl.12288

Critchlow, R., Plumptre, A. J., Driciru, M., Rwetsiba, A., Stokes, E. J., Tumwesigye, C., … Beale, C. M. (2015). Spatiotemporal trends of illegal activities from ranger-collected data in a Ugandan national park: Trends in Illegal Activities. *Conservation Biology*, *0*(0), 1–13. doi:10.1111/cobi.12538

Dobson, A. D. M., Milner-Gulland, E. J., Beale, C. M., Ibbett, H., & Keane, A. (2018). Detecting deterrence from patrol data. *Conservation Biology*, *0*(0), 1–11. doi:10.1111/cobi.13222

Dobson. A.D.M, Milner-Gulland. E.J., Ingram. D.J, Keane. A. (2019). A framework for assessing impacts of wild meat hunting practices in the Tropics. *Human Ecology*, 47, 449–464

Evans, T. D., O’Kelly, H. J., Soriyun, M., Hor, N. M., Phaktra, P., Pheakdey, S., & Pollard, E. (2013). Seima Protection Forest. In T. C. H. Sunderland, J. A. Sayer, & H. Minh-Ha (Eds.), *Evidence-Based Conservation: Lessons from the Lower Mekong* (pp. 157–186). Bogor, Indonesia: CIFOR. doi:10.4324/9780203128466

Gelman, A., Jakulin, A., Pittau, M. G., & Su, Y. S. (2008). A weakly informative default prior distribution for logistic and other regression models. *Annals of Applied Statistics*, *2*(4), 1360–1383. doi:10.1214/08-AOAS191

Gelman, A., Carlin, J. B., Stern, H. S., Dunson, D. B., Vehtari, A., & Rubin, D. B. (2013). Bayesian Data Analysis. CRC Press.

Goodrich, B., Gabry, J., Ali, I., & Brilleman, S. (2018). rstanarm: Bayesian applied regression modeling via

Stan R package.

Gray, T. N. E., Hughes, A. C., Laurance, W. F., Long, B., Lynam, A. J., Kelly, H. O., … Scotson, L. (2017). The wildlife snaring crisis: an insidious and pervasive threat to biodiversity in Southeast Asia. *Biodiversity and Conservation*, 1–7. doi:10.1007/s10531-017-1450-5

Gray, T. N. E., Lynam, A. J., Seng, T., Laurance, W. F., Long, B., Scotson, L., & Ripple, W. J. (2017). Wildlife-snaring crisis in Asian forests. *Science*, *3*(6322), 255–256. doi:10.1126/science.aal4463

Harrison, R. D., Sreekar, R., Brodie, J. F., Brook, S. M., Luskin, M., O'Kelly, H. J., … Velho, N. (2016). Impacts of hunting on tropical forests in Southeat Asia. *Conservation Biology*, *30*(5), 972–981. doi:10.1017/CBO9781107415324.004

Hilborn, R., Arcese, P., Borner, M., Hando, J., Hopcraft, G., Loibooki, M., … Sinclair, A. R. E. (2006). Effective enforcement in a conservation area. *Science (New York, N.Y.)*, *314*(5803), 1266. doi:10.1126/science.1132780

Hötte, M. H. H., Kolodin, I. A., Bereznuk, S. L., Slaght, J. C., Kerley, L. L., Soutyrina, S. V, … Miquelle, D. G. (2016). Indicators of success for smart Law enforcement in protected areas: A case study for Russian Amur Tiger (Panthera tigris altaica) reserves. *Integrative Zoology*, *11*, 2–15. doi:10.1111/1749-4877.12168

Ibbett, H., Keane, A., Griffin, O., Dobson, A., Travers, H., & Milner-Gulland, E. (in press). Estimating hunting prevalence and reliance on wild meat in Cambodia's Eastern Plains. *Oryx.*

Ingram, D. J., Coad, L., Abernethy, K., Maisels, F., Stokes, E. J., Bobo, K. S., … Waltert, M. (2017). Assessing Africa-Wide Pangolin Exploitation by Scaling Local Data. *Conservation Letters*, *00*(0), 1–9. doi:10.1111/conl.12389

Jachmann, H. (2008). Monitoring law-enforcement performance in nine protected areas in Ghana. *Biological Conservation*, *141*(1), 89–99. doi:10.1016/j.biocon.2007.09.012

Karban, R., Huntzinger, M., & Pearse, I. S. (2014). *How to do ecology: a concise handbook*. Princeton, New Jersey; Oxfordshire, England: Princeton University Press.

Keane, A., Jones, J. P. G., Edward-Jones, G., & Milner-Gulland, E. J. (2008). The sleeping policeman: understanding issues of enforcement and compliance in conservation. *Animal Conservation*, *11*, 75–82. doi:10.1111/j.1469-1795.2008.00170.x

Keane, A., Jones, J. P. G., & Milner-Gulland, E. J. (2011). Encounter data in resource management and ecology: Pitfalls and possibilities. *Journal of Applied Ecology*, *48*(5), 1164–1173. doi:10.1111/j.1365-2664.2011.02034.x

Lewandowski, D., Kurowicka, D., & Joe, H. (2009). Generating random correlation matrices based on vines and extended onion method. *Journal of Multivariate Analysis*, *100*(9), 1989–2001. doi:10.1016/j.jmva.2009.04.008

Lindsey, P. A. P. A., Romanach, S. ., Tambling, C. J., Chartier, K., & Groom, R. (2011). Ecological and financial impacts of illegal bushmeat trade in Zimbabwe. *Oryx*, *45*(1), 96–111. doi:10.1017/S0030605310000153

Long, B., Grein, G., Boedicker, N., & Singh, R. (2016). Are Rangers Adequately Protected By Insurance Schemes ? *Parks: The International Journal of Protected Areas and Conservation*, *22*(November), 83–93.

Lynam, A. J., Porter, L., & Campos-Arceiz, A. (2016). Conservation focus: the challenge of conservation in changing tropical southeast asia. *Conservation Biology*, *30*(5), 931–932. doi:10.1111/cobi.12781

Marescot, L., Lyet, A., Singh, R., Carter, N., & Gimenez, O. (2019). Inferring wildlife poaching in Southeast Asia with multispecies dynamic site-occupancy models. *BioRxiv*, 520114. doi:10.1101/520114

Moore, J. F., Mulindahabi, F., Masozera, M. K., Nichols, J. D., Hines, J. E., Turikunkiko, E., & Oli, M. K. (2017). Are ranger patrols effective in reducing poaching - related threats within protected areas ? *Journal of Applied Ecology*, (June), 1–9. doi:10.1111/1365-2664.12965

Moore, J. L., Hauser, C. E., Bear, J. L., Williams, N. S. G., & McCarthy, M. A. (2011). Estimating detection – effort curves for plants using search experiments. *Ecological Applications*, *21*(2), 601–607. doi:10.1890/10-0590.1

Moreto, W. D. (2015). Occupational stress among law enforcement rangers: insights from Uganda. *Oryx, 50(4),* 646-654. doi:10.1017/S0030605315000356

Moreto, W. D., Brunson, R. K., & Braga, A. A. (2015). 'Such Misconducts Don't Make a Good Ranger': Examining Law Enforcement Ranger Wrongdoing in Uganda. *British Journal of Criminology*, *55*(2), 359–380. doi:10.1093/bjc/azu079

Noss, A. J. (1998). The impacts of cable snare hunting on wildlife populations in the forests of the Central African Republic. *Conservation Biology*, *12*(2), 390–398. doi:10.1111/j.1523-1739.1998.96027.x

O'Kelly, H. J., Rowcliffe, M. J., Durant, S. M., & Milner-Gulland, E. J. (2018a). Robust estimation of snare prevalence within a tropical forest context using N-mixture models. *Biological Conservation*, *217*, 75–82. doi:10.1016/j.biocon.2017.10.007

O'Kelly, H. J., Rowcliffe, M. J., Durant, S., & Milner-Gulland, E. J. (2018b). Experimental estimation of snare detectability for robust threat monitoring. *Ecology and Evolution*, *DOI: 10.10*(August 2017), 1–8. doi:10.1002/ece3.3655

Paley, R. (2015). Managing protected areas in Cambodia. The challenge for conservation bureaucracies in a hostile governance environment. In S. Milne & S. Mahanty (Eds.), *Conservation and Development in Cambodia: Exploring frontiers of change in nature, state and society.* (pp. 141–159). Routledge.

Plumptre, A. J., Fuller, R. A., Rwetsiba, A., Wanyama, F., Kujirakwinja, D., Driciru, M., … Possingham, H. P. (2014). Efficiently targeting resources to deter illegal activities in protected areas. *Journal of Applied Ecology*, *51*(3), 714–725. doi:10.1111/1365-2664.12227

R Core Team. (2017). R: A language and environment for statistical computing. Vienna, Austria, Vienna, Austria: R Foundation for Statistical Computing.

Rija, A. (2017) Spatial Pattern of Illegal Activities and the Impact on Wildlife Populations in Protected Areas in the Serengeti Ecosystem. Doctorate in Philosophy. Department of Biology, University of York. http://etheses.whiterose.ac.uk/20276/

Ripple, W. J., Abernethy, K., Betts, M. G., Chapron, G., Dirzo, R., Galetti, M., … Young, H. (2016). Bushmeat hunting and extinction risk to the world's mammals. *Royal Society Open Science*, *3*, 160498. doi:10.1098/rsos.160498

Schulze, K., Knights, K., Coad, L., Geldmann, J., Leverington, F., Eassom, A., … Burgess, N. D. (2018). An assessment of threats to terrestrial protected areas. *Conservation Letters*, *11*(3), 1–10. doi:10.1111/conl.12435

Spira, C., Kirkby, A. E., & Plumptre, A. J. (2019). Understanding ranger motivation and job satisfaction to improve wildlife protection in Kahuzi–Biega National Park, eastern Democratic Republic of the Congo. *Oryx*. doi:10.1017/S0030605318000856

Stokes, E. J. (2010). Improving effectiveness of protection efforts in tiger source sites: Developing a framework for law enforcement monitoring using MIST. *Integrative Zoology*, *5*, 363–377. doi:10.1111/j.1749-4877.2010.00223.x

Sunde, P., & Jessen, L. (2013). It counts who counts: an experimental evaluation of the importance of observer effects on spotlight count estimates. *European Journal of Wildlife Research*, *59*, 645–653. doi:10.1007/s10344-013-0717-8

van Vliet, N., & Nasi, R. (2008). Hunting for Livelihood in Northeast Gabon: Patterns, Evolution, and Sustainability. *Ecology and Society*, *13*(2), 33. doi:10.5751/ES-02560-130233

Walston, J., Davidson, P., & Men, S. (2001). *A Wildlife Survey of Southern Mondulkiri Province, Cambodia*. Phnom Penh, Cambodia.

Watanabe, S. (2010). Asymptotic equivalence of Bayes cross validation and Widely Applicable Information Criterion in singular learning theory. *Journal of Machine Learning Research*, *11*, 3571–

3594.

Watson, J. E. M., Dudley, N., Segan, D. B., & Hockings, M. (2014). The performance and potential of protected areas. *Nature*, *515*, 67–73. doi:10.1038/nature13947

Wilfred, P., & Maccoll, A. (2014). The pattern of poaching signs in Ugalla Game Reserve, western Tanzania. *African Journal of Ecology*, *52*(4), 543–551. doi:10.1111/aje.12161

Yersin, H., Asiimwe, C., Voordouw, M. J., & Zuberbühler, K. (2017). Impact of Snare Injuries on Parasite Prevalence in Wild Chimpanzees (Pan troglodytes). *International Journal of Primatology*, *38*(1), 21–30. doi:10.1007/s10764-016-9941-x

Figures

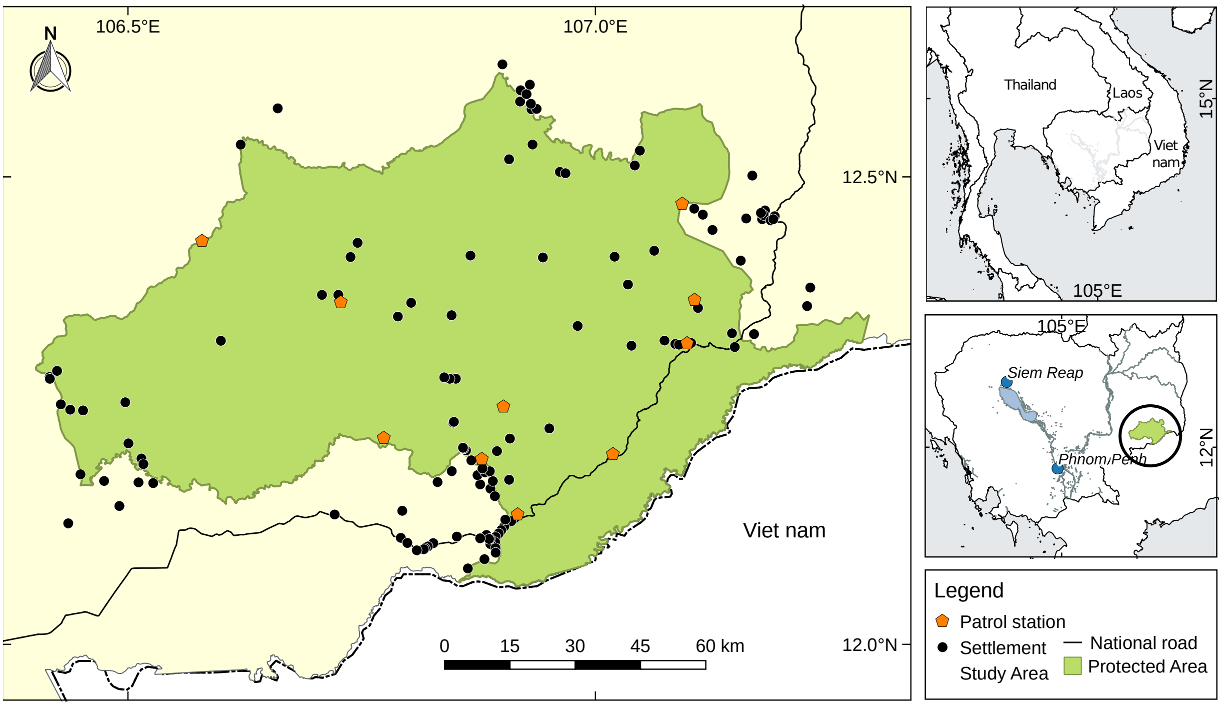

Figure 1. Keo Seima Wildlife Sanctuary, Mondulkiri province, Cambodia. Study area highlighted in grey circle.

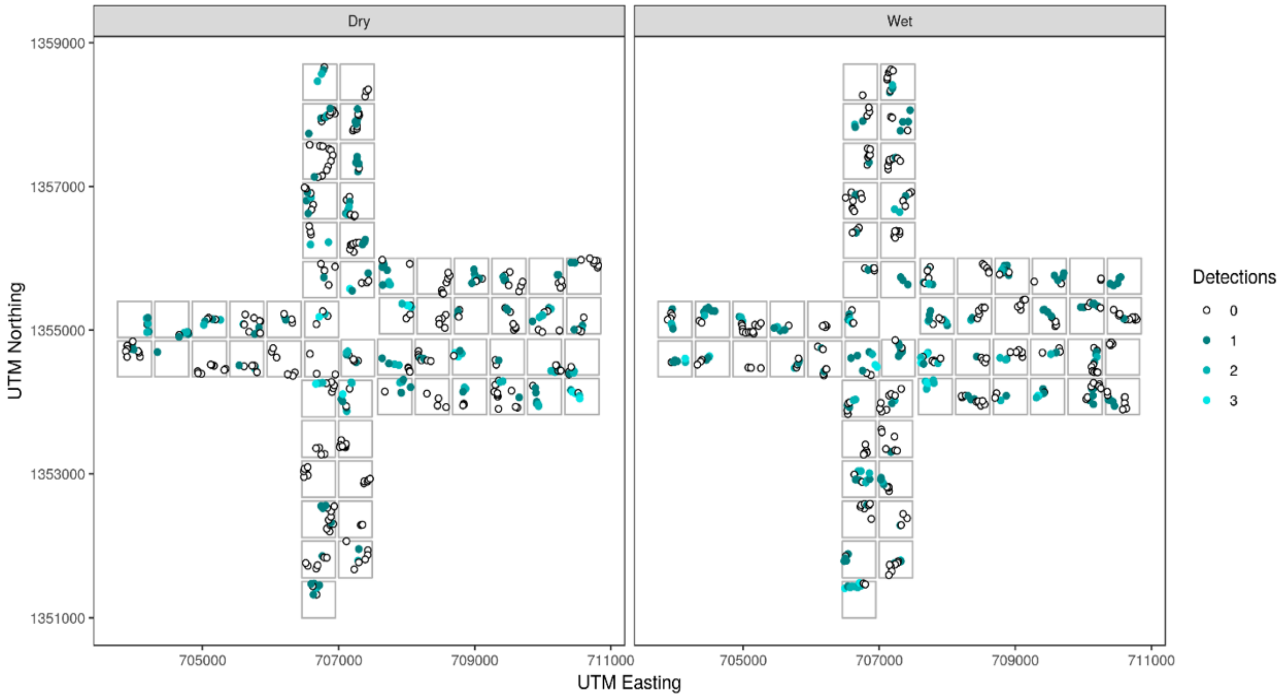

Figure 2. Detections in situ; colour coding represents the number of teams which detected a given snare.

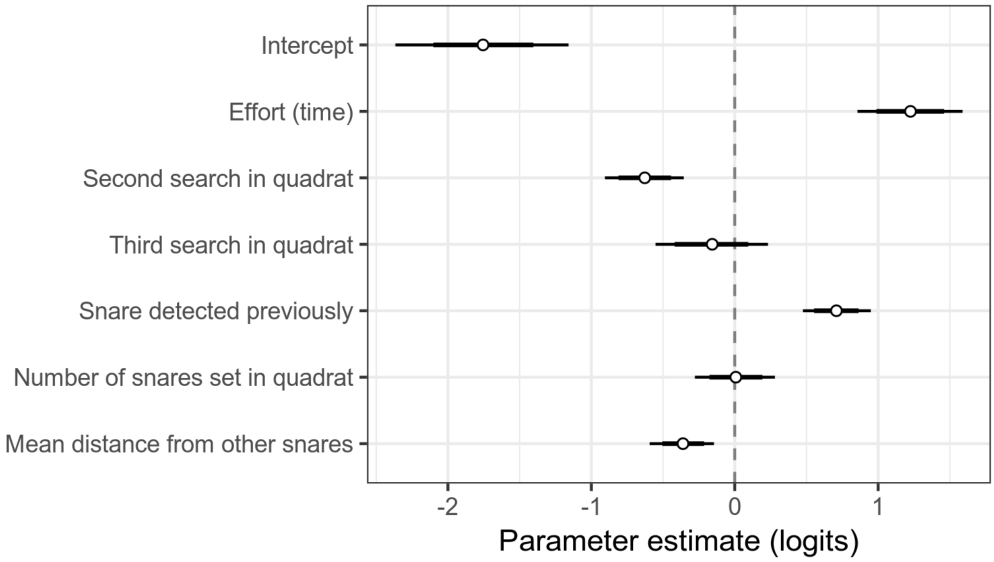

Figure 3. Parameter estimates for the best-fitting model, Model 8. Points represent the mean estimate; thick lines represent 80% credible intervals and thinner lines represent 95% credible intervals.

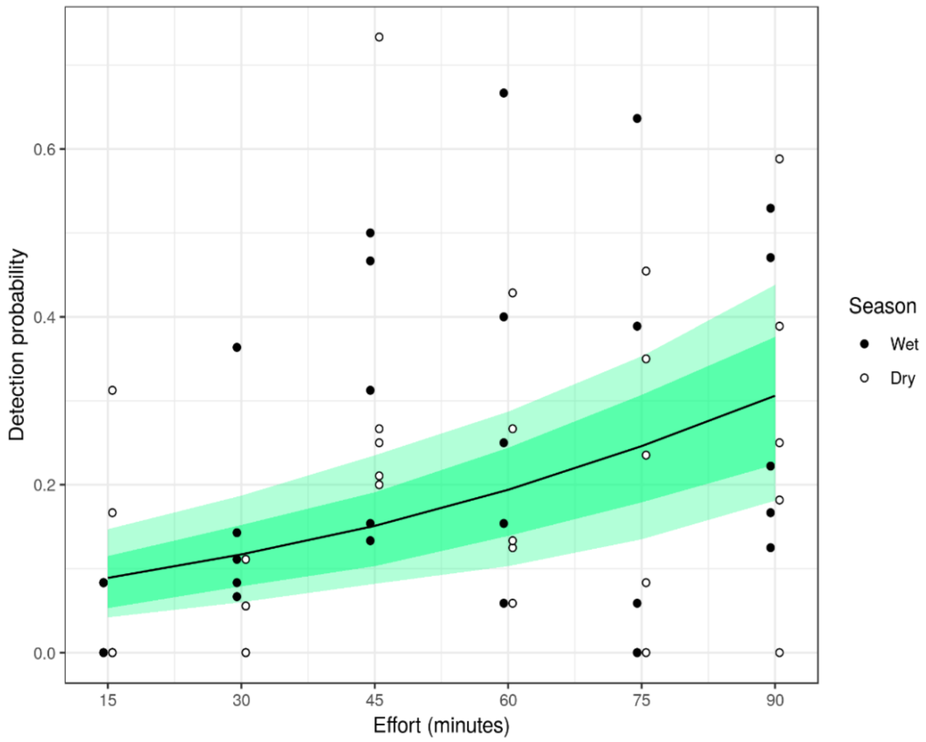

Figure 4. Effort-detection curve. Black line indicates mean probability of snare detection at differing levels of effort, predicted from the best-fitting model (Model 8) under the assumption that the quadrat has not previously been searched. Light green shading indicates the 95% credible interval for detection probability, while the darker green shading indicates the 85% credible interval. Summaries of the proportion of snares detected in each transect in the raw data are plotted as filled circles for wet season and open circles for dry season.

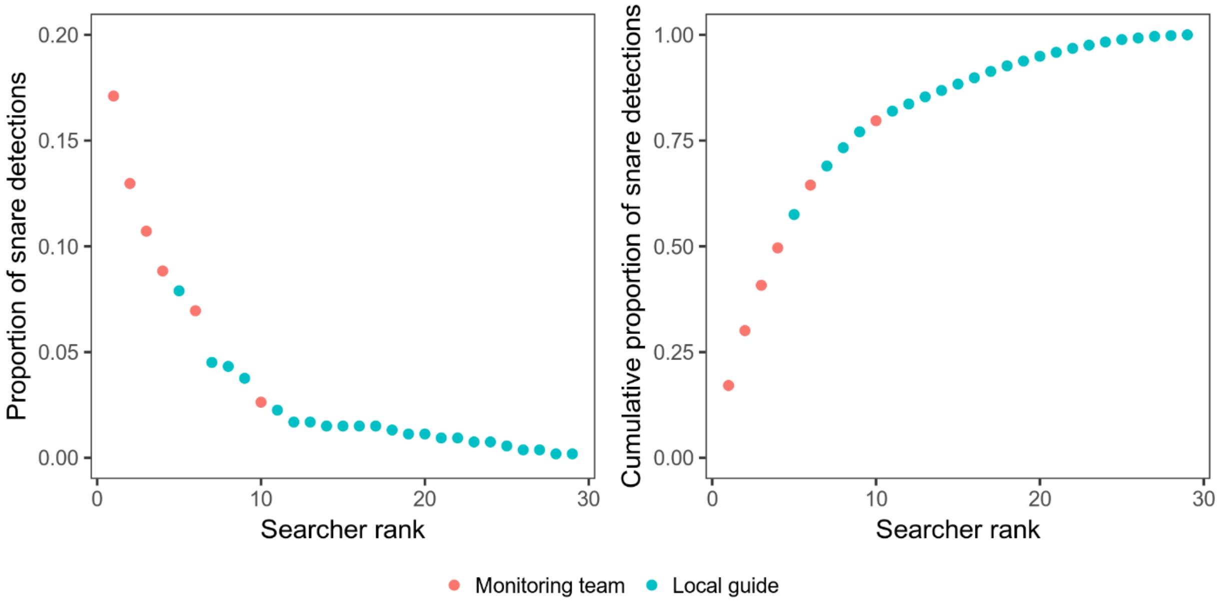

Figure 5. Proportion of snares detected by individual searchers.

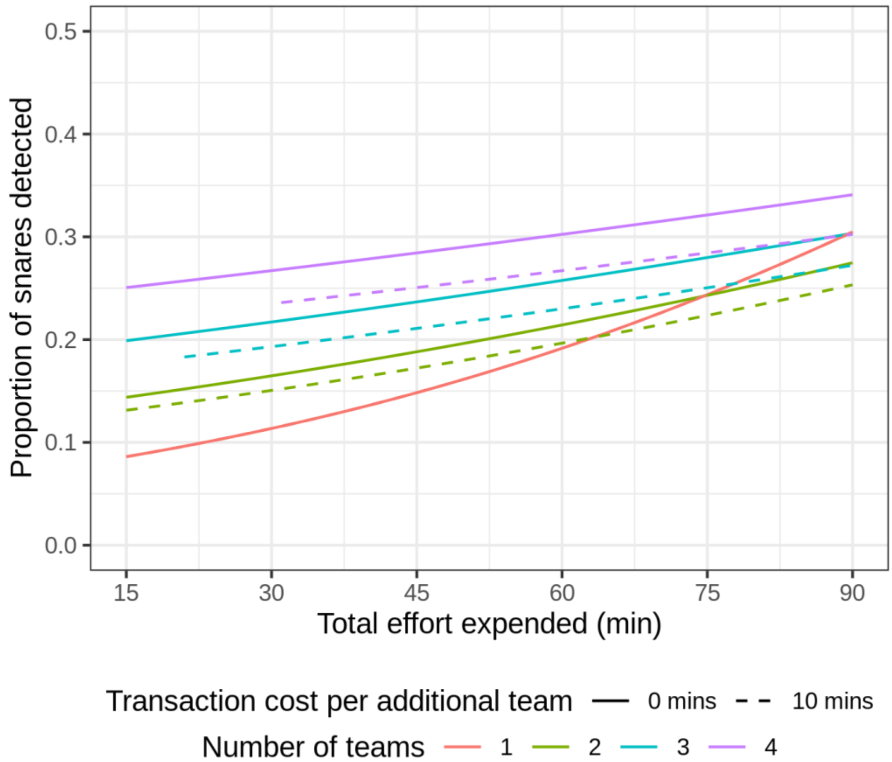

Figure 6. Modelled effect of dividing total search effort across multiple search teams on detection probability, when effects of effort on detection and transaction costs vary.

Tables

Table 1. Description of variables and interaction terms, and their inclusion in the candidate models fitted to the snare detection data. Grouping variables are shown below the dividing line.

				Model										
Variable	**Description**	**Type**	**Levels**	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Effort (time)	Time (minutes) spent searching each quadrat for snares	Continuous	Centred on 45 minutes & scaled by dividing by 60		X		X	X	X	X	X	X	X	X
Effort (distance)	Total distanced travelled (km) during each search	Continuous	Centred on its mean value & scaled by two standard deviations			X								
Quadrat search order	Search order	Factor	1st, 2nd, 3rd				X	X	X	X	X	X	X	X
Previous snare detections	Number of times the snare was previously detected by other teams	Factor	0, 1, 2				X	X	X	X	X	X	X	X
Distance to nearest snare	Mean distance (m) of a snare to other snares within the same quadrat	Continuous	Centred on 150m & scaled by dividing by 100					X	X	X	X	X	X	X
No. of snares set in quadrat	Total number of snares set in the quadrat	Continuous	0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15					X	X	X	X	X	X	X
Season	Season in which quadrat was searched	Factor	Wet, Dry						X	X				X
Season: Effort	Interaction term									X				X
HI present during search	Whether HI accompanied the team during the quadrat search	Factor	Yes, No										X	X
Team leader	ID of the team leader	Factor	1, 2, 3, 4										X	X
Vegetation type	Dominant vegetation type within the quadrat	Factor	Bamboo, mixed-deciduous, semi-evergreen								X			X
Presence of animal trail	Whether the snare was set on an animal trail	Factor	Yes, No								X			X
Presence of animal sign	Whether the snare was set near wildlife signs (e.g. foot prints, dung)	Factor	Yes, No								X			X

Presence of water	Whether the snare was set near a stream, river, pond or salt lick	Factor	Yes, No								X			X
Transect	Transect ID	Factor	1, 2, 3, 4, 5	X	X	X	X	X	X	X	X	X	X	X
Quadrat within transect	Quadrat ID	Factor	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12	X	X	X	X	X	X	X	X	X	X	X
Date	Date each search was conducted	Factor	DD-MM-YY	X	X	X	X	X	X	X	X	X	X	X
Team setting snares	ID of the team that set snares in the quadrat	Factor	W1, W2, W3, W4, D1, D2, D3, D4									X	X	X
Team searching for snares	ID of the team searching for snares in the quadrat	Factor	1, 2, 3, 4									X	X	X

Table 2. WAIC values for the fitted models, the difference from the best-fitting model (δWAIC) and the standard error of that difference (SE(δWAIC)). See Table 1 for models.

Model	WAIC	δWAIC	SE(δWAIC)
8	2412.7	0.0	--
9	2414.1	1.5	1.8
10	2424.2	11.5	3.4
4	2461.4	48.7	14.4
5	2462.9	50.2	14.4
7	2465.3	52.6	14.2
6	2465.5	52.9	14.4
3	2471.8	59.1	16.0
1	2515.5	102.8	21.6
0	2527.6	114.9	23.0
2	2532.9	120.2	22.4

Experimentally assessing the effect of search effort on snare detectability

Electronic Supplementary Materials

Appendix S1. Experimental Design

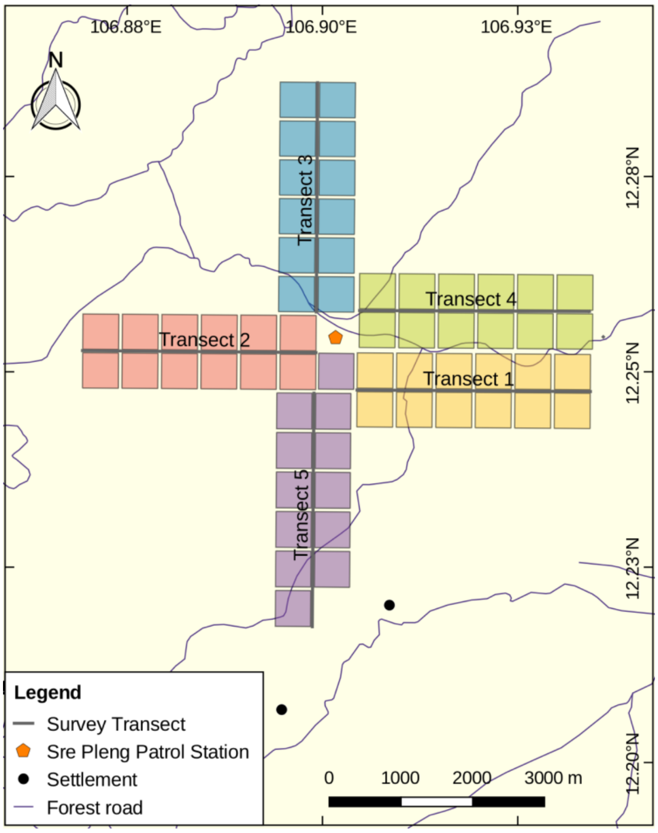

Figure S1a. Location of transects within Keo Seima Wildlife Sanctuary. Five 3.25km long transects were established radiating out from Sre Pleng patrol station. The bottom right quadrat on Transect 5 was relocated to directly below the patrol station due to insufficient forest cover in the original location. Along each transect, 12x 0.25km^2 (500m x 500m) quadrats were demarcated in QGIS. Each quadrat was numbered, with quadrats 1 & 2 always nearest the patrol station, and quadrats 11 & 12 always furthest from the patrol station.

Table S1a. Example of allocation of a team's quadrat searches. Numbers in the table represent quadrat ID numbers.

Team	Quadrats in which team set snares	Quadrat search order								
		1st	2nd	3rd	4th	5th	6th	7th	8th	9th
1	6, 10, 12	1	3	5	7	9	11	2	4	8
2	2, 4, 8	11	9	7	5	3	1	6	10	12
3	5, 9, 11	2	4	6	8	10	12	1	3	7
4	1, 3, 7	12	10	8	6	4	2	5	9	11
	Day 1	Day 2						Day 3		

Figure S1b. Levels of search effort allocated per quadrat in a given transect. Search times were fixed across transects. Quadrat ID is shown in the centre of each quadrat.

Appendix S2. Further analyses

Table S2a. Repeated snare detections

	Dry		Wet		Total	
Season	**N**	**%**	**N**	**%**	**N**	**%**
Snares detected by 0 teams	265	60%	249	56%	514	58%
Snares detected by 1 team	104	23%	130	30%	234	26%
Snares detected by 2 teams	61	14%	52	12%	113	13%
Snares detected by 3 teams	12	3%	13	3%	25	3%
Total detections	177	40%	195	44%	372	42%

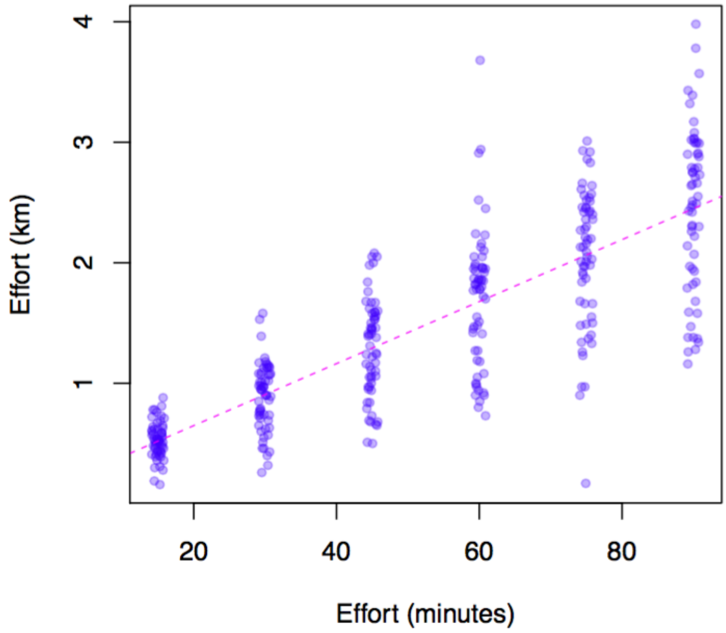

Figure S2a. Relationship between two different measures of effort - distance searched (km) and time spent searching (minutes)

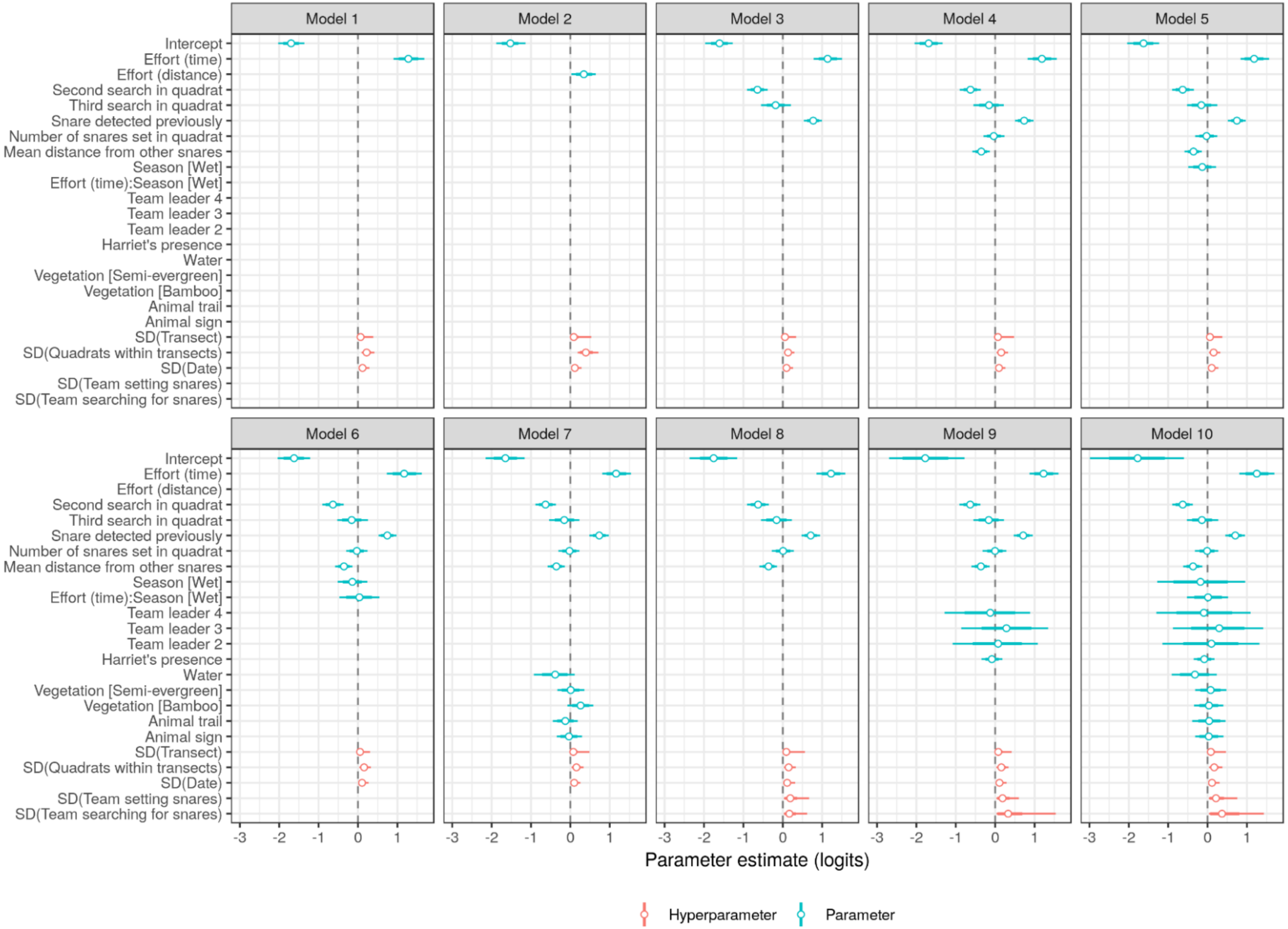

Figure S2b. Parameter estimates for the full candidate set of 10 models. Points represent the mean estimate; thick lines represent 80% credible intervals and thin lines represent 95% credible intervals. Estimates for the standard deviations of hyperpriors for grouping variables are coloured pink while other parameters are coloured turquoise.

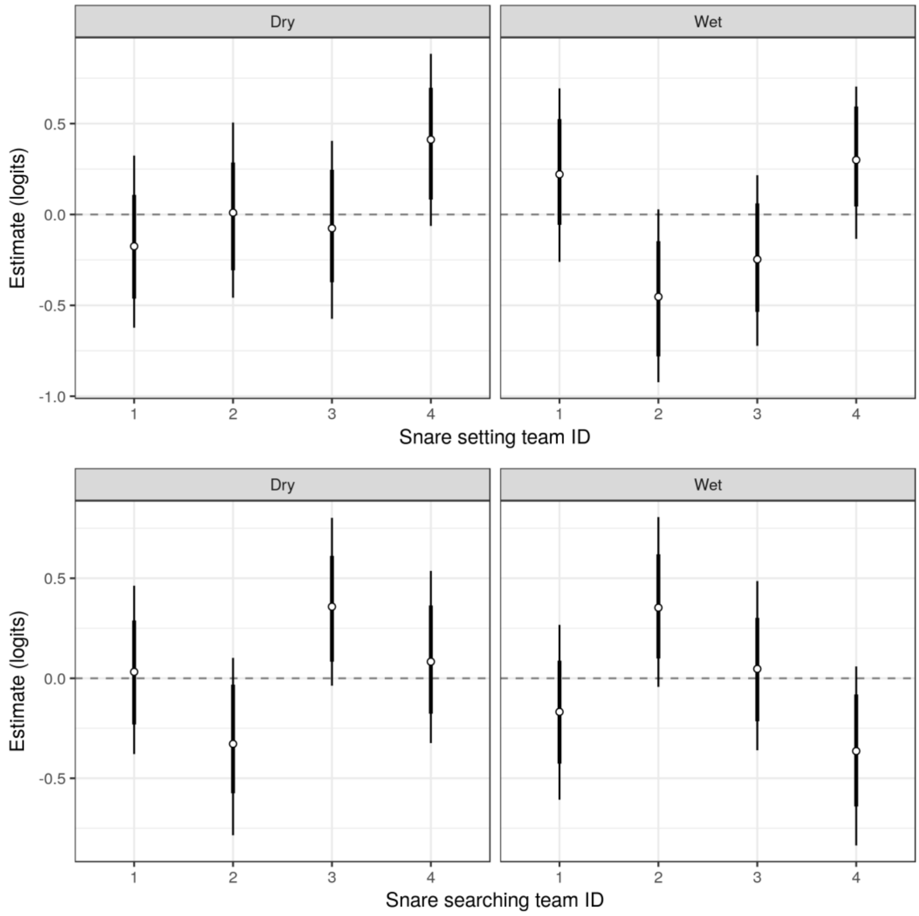

Figure S2c. Comparison of parameter estimates for the effects of the snare setting team (top) and the team searching for snares (bottom) on snare detectability. Results show variability between seasons, but broadly teams that set snares that were less detectable, were more likely find snares set by other teams (e.g. Team 2 in wet season).

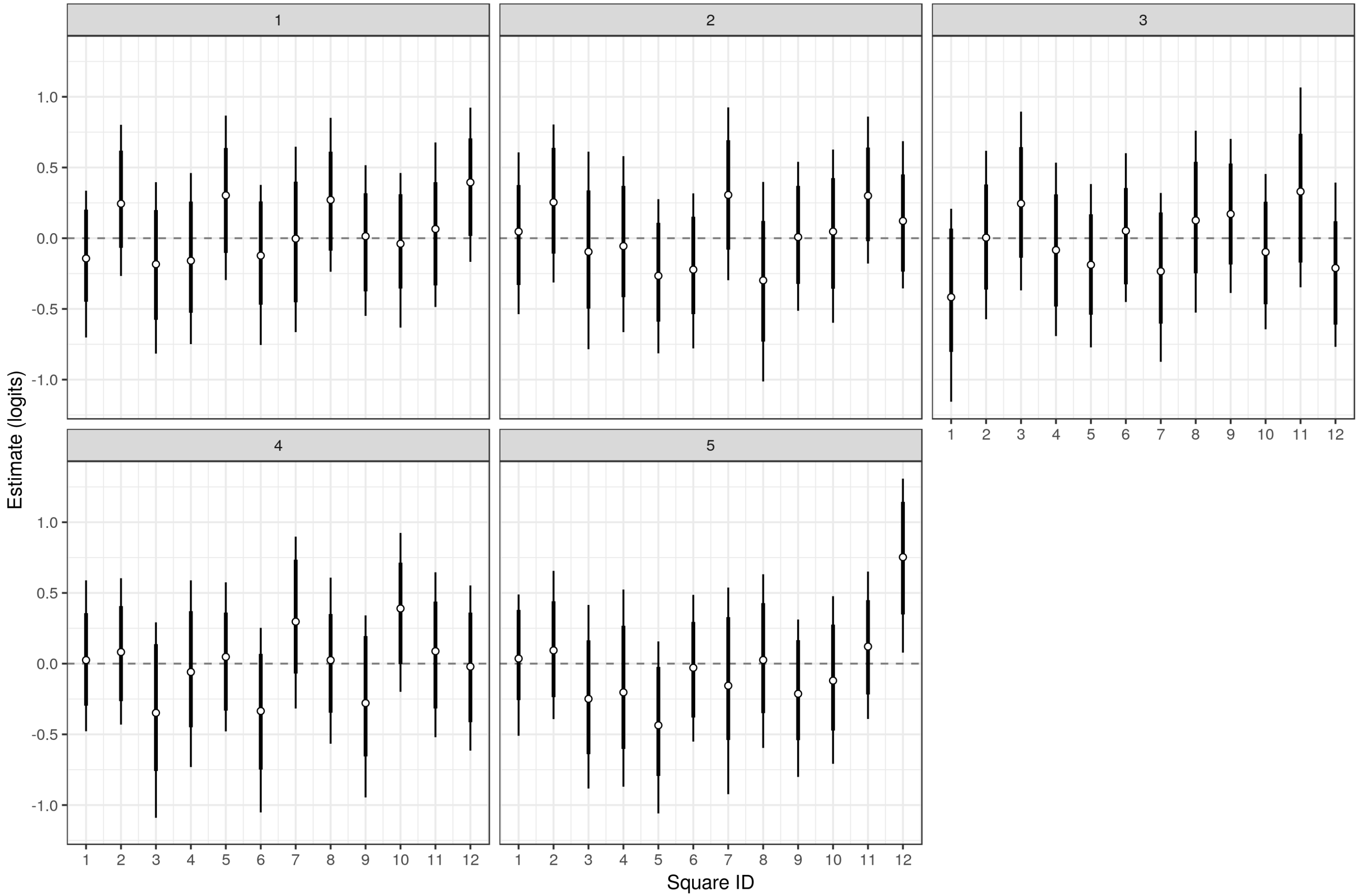

Figure S2d. Comparison of parameter estimates for the effects of Quadrat ID on snare detectability. Results show variability between quadrats, but broadly this was non-significant.

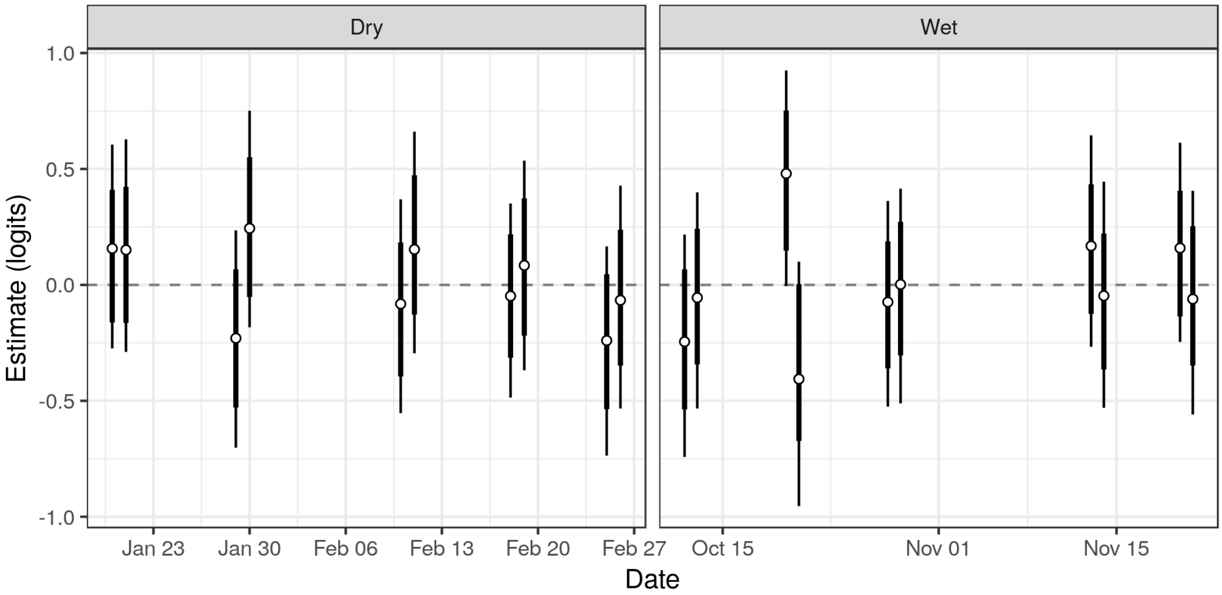

Figure S2e. Comparison of parameter estimates for the effects of season on snare detectability.

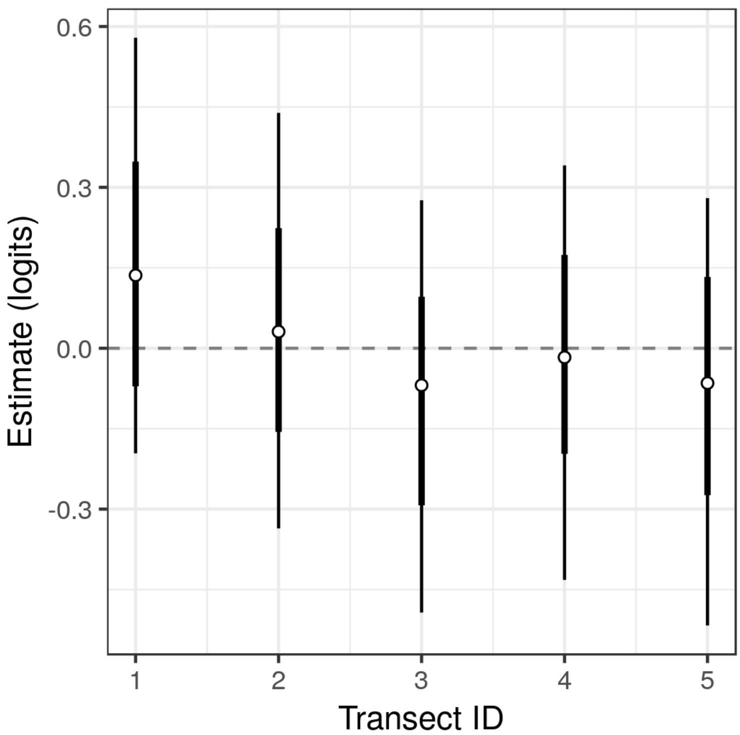

Figure S2f. Comparison of parameter estimates for the effects of transect on snare detectability.

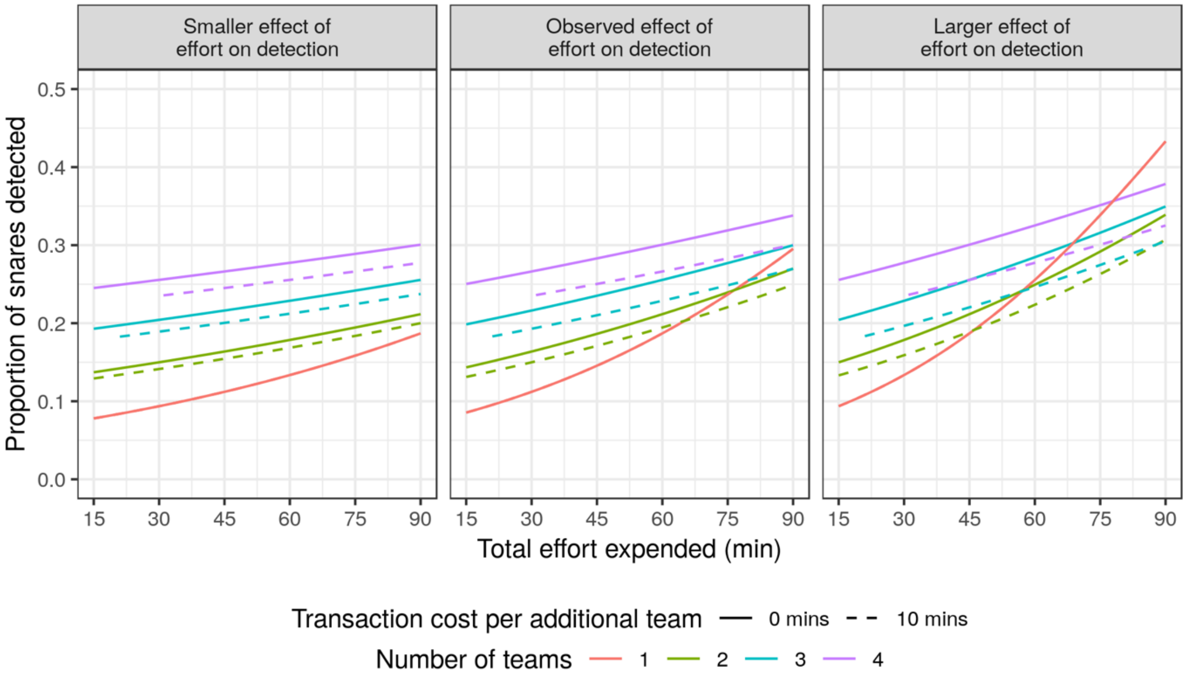

Figure S2g. Variations in modelled effect of dividing total search effort across multiple search teams on detection probability, when effects of effort on detection and transaction costs vary.

Appendix S3. Assessing the performance of individual searchers

Typically, the assignment of rangers to patrolling tasks is undertaken by supervisors, who allocate roles based on their assessment of individual's ability to perform them. Those in possession of certain characteristics (e.g. years on the job, rank, age) may be perceived to be experts, and are therefore assumed to perform better. However, this assumption does not always hold true. The relationship between perceived expertise and actual performance has not been explored in PA management, including the relationship between perceived ability to find snares and actual snare-finding ability.

Predicting performance

Prior to the start of the dry season survey, we asked searchers basic questions about their expertise with regards to setting and searching for snares, how long they had lived or worked in the study area, and whether they thought snares would be easier to find in the wet or dry season. In order to gauge expectations of self-performance we asked individuals *"How well do you think you will perform? where 0 = means you will find no snares, and 10 = means you will find all the snares"*. We then asked each individual to judge how well they thought each of their peers would perform by asking the question *"How well do you think XXXX will perform? If 0 = means they will find no snares, and 10 = means they will find all the snares".* This exercise was conducted on the first day of the snare experiment fieldwork. Only eight of the 29 local guides were present for this exercise, meaning that consistent predictions of performance and actual performance rankings were only available for the five WCS staff.

We averaged the predictions of performance given to each individual by their peers, and ranked the scores to identify who peers expected to perform best and worst. During analysis, we compared both self and peer predictions against actual performance.

Results

Searcher experience

In total, 35 searchers participated in the study; six individuals from WCS, and 29 local guides. Only one WCS member grew up in KSWS and had experience setting snares as a child, all others originated from different parts of the country. WCS staff had spent on average 11.5 years (37% of their lives) working in KSWS. In contrast, most local guides had lived in KSWS their whole life, and all but one guide set snares as a child. Based on the length of time spent living in KSWS we predicted that local guides would be more familiar with the forest habitat, distribution of wildlife and hunting techniques and thus would be better at detecting snares than WCS staff. However, we found this to be untrue. The mean number of snares detected per transect by each

WCS employee was 6 (min: 2; max: 22) compared to 3 snares per local guides (min: 0, max: 9). The six WCS staff were responsible for detecting 59% of the total snares found.

Self-prediction vs peer-prediction

Of WCS staff, two individuals thought they would find more snares than their peers expected them to (Table 3). These two individuals were both older and in more senior positions. The other three WCS staff members expected to find fewer snares than their peers predicted. No group estimates were available for Searcher F. Results showed that once averaged and ranked, peer-predictions accurately predicted actual performance. Only one individual (the worst performing individual) correctly predicted their own performance. Overall, aggregated and ranked peer-predictions provided a better estimate of performance than self-prediction.

Table 3: Self and peer predictions of performance versus actual performance, measured by the number of successful detections per individual divided by the number of detection opportunities.

	Self		**Peer**				
Participant	**Prediction**	**Rank**	**Prediction**	**Rank**	**Actual performance** *(Detections / Opportunities)*		**Rank**
Searcher C	*7*	*4.5*	*8.7*	*1*	*91 / 597*	*15%*	*1*
Searcher F	*7*	*4.5*	*NA*	*NA*	*70 / 670*	*10%*	*2*
Searcher E	*8*	*2.5*	*8.1*	*2*	*57 / 670*	*8%*	*3*
Searcher D	*9*	*1*	*7.5*	*3*	*47 / 668*	*7%*	*4*
Searcher A	*8*	*2.5*	*7.3*	*4*	*35 / 658*	*5%*	*5*
Searcher B	*4*	*6*	*6.6*	*5*	*14 / 483*	*3%*	*6*
					314 / 2661	*12%*	

*Predictions based on a scale where 0 = Will find no snares, 10 = Will find all snares.