Received: 7 March 2019 | Accepted: 24 September 2019

DOI: 10.1111/1365-2664.13527

RESEARCH ARTICLE

Journal of Applied Ecology | BRITISH ECOLOGICAL SOCIETY

Predicting the effectiveness of community anti-poaching patrols for conserving threatened wildlife in the Lao PDR

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Funding information
Australian Centre for International Agricultural Research, Grant/Award Number: FST/2011/003; Australian Research Council, Grant/Award Number: DE160101306

Handling Editor: Matt Hayward

Abstract

1. Worldwide, wildlife poaching results in significant losses to biodiversity, especially for species that are most vulnerable and at risk of extinction. While studies that assess the impact of poaching have been conducted, there is limited work that evaluates strategies to reduce poaching pressure, and their subsequent effects on wildlife.
2. We develop a model to predict the effectiveness of a unique community-led anti-poaching patrol programme for conserving local wildlife in a biodiversity hotspot in the Lao People's Democratic Republic (Lao PDR). Our model scenarios are based on local villagers' proposals to undertake anti-poaching patrols. To deal with limited data availability in this region, we develop a flexible modelling framework that can incorporate a range of data sources, including expert opinion. The model can be readily altered by the user if additional data becomes available.
3. The results predict that, without intervention, 14 out of the 19 endangered species investigated are likely to be poached to local extinction over the next 10 years. Implementing anti-poaching patrols is predicted to protect individual animals and species in the area, although with diminishing marginal benefits as patrol-efforts increase.
4. *Synthesis and applications*. We present the first model developed in the Southeast Asia region to examine the effectiveness of community anti-poaching patrols on protecting wildlife populations. This work is directly linked to an innovative Payments for Environmental Services programme where villagers are being paid for community-led anti-poaching patrols. Our model results demonstrate how different patrolling strategies can help to protect vulnerable species, and are being used to determine the payment levels for different patrolling schemes.

KEYWORDS

community-based conservation, data limitations, modelling framework, poaching, poaching-patrol model, ranger patrols, South-East Asia, threatened species

1 | INTRODUCTION

Poaching—defined as violations of conservation rules, including illegal hunting, resource use, and extraction (Conteh, Gavin, & Solomon, 2015; Robbins, McSweeney, Waite, & Rice, 2006)—is a global problem which significantly impacts biodiversity (Pratt, Macmillan, & Gordon, 2004; Steinmetz, Srirattanaporn, Mor-Tip, & Seuaturien, 2014; Vongkhamheng, Johnson, & Sunquist, 2013). It has been called the greatest current threat to wild vertebrates in Southeast Asia (Steinmetz et al., 2014), particularly through the use of home-made cable or wire snares (Gray et al., 2018). Poaching methods that use baited traps and wire snares will not only catch the target species but also other animals as bycatch, leading to potential injury or death to individuals of any species occupying targeted areas (Becker et al., 2013). Removal of key species, or those which provide top-down control such as tigers and other apex predators, has widespread effects on the entire ecosystem (Burkholder, Heithaus, Fourqurean, Wirsing, & Dill, 2013; Colman, Gordon, Crowther, & Letnic, 2014). Additionally, poaching can have further socio-economic impacts such as reliance on poaching for subsistence (Pratt et al., 2004; Steinmetz et al., 2014).

We report on part of a multi-disciplinary project that developed a pilot Payment for Environmental Services (PES) scheme in the Phou Chom Voy Provincial Protected Area (PCV PPA) of the Lao People's Democratic Republic (PDR). The area is an internationally recognized biodiversity hotspot that is under threat from poaching. Our project[1] was designed to protect local biodiversity from poaching pressures by contracting local communities as wildlife patrollers to remove snares and poacher camps (Scheufele, Bennett, & Kyophilavong, 2018). In other parts of South-East Asia and Africa, it has been shown that involving local communities in conservation discussions, wildlife management, and patrolling can be a successful approach to mitigate poaching and promote the recovery of biodiversity in the patrolled areas (Johannesen & Skonhoft, 2005; Moore et al., 2018; Morgera & Wingard, 2009; Steinmetz et al., 2014). The effectiveness of patrols depends on the patrolling effort, such as the frequency of patrols and the area covered (Kimanzi, Sanderson, Rushton, & Mugo, 2014). While it has been demonstrated that wildlife patrols can discourage poaching (Becker et al., 2013; Vongkhamheng et al., 2013), there is limited understanding on the effectiveness of poaching mitigation measures (Moore et al., 2018). In particular, the link between anti-poaching patrol effort and biodiversity metrics—such as species counts and population sizes—is still unclear and research is needed to improve knowledge and inform future policy decisions.

Our work aims to fill this knowledge gap by developing a dynamic stochastic population model to investigate how poaching influences target species in Lao PDR and what the likely outcomes of anti-poaching patrols will be on specific species. The model shows whether the patrolling efforts proposed by local villagers in the PES scheme are sufficient to meet conservation targets, and thus whether the payments are warranted. Such predictions are essential to the successful execution of any PES scheme. Assessing the effects of wildlife patrols on threatened species in this region is complicated by the sparsity of species counts and abundance data (Vongkhamheng et al., 2013). We demonstrate how a generalized model based upon the best available data from SE Asia can provide valuable information about the effects of different poaching management scenarios on conservation species.

[1]Effective Implementation of Payments for Environmental Services Schemes in Lao PDR; https://ipesl.crawford.anu.edu.au/.

2 | MATERIALS AND METHODS

2.1 | The Phou Chom Voy Provincial Protected Area

Lao PDR is part of an international biodiversity hotspot and is home to many endangered species (Conservation International, 2017). Hunting and logging represent the greatest current threats to the region's threatened species (Gray et al., 2018). These activities occur both legally through controlled and subsistence hunting and logging, and illegally through land clearing, degradation and poaching (Johnson, Singh, Dongdala, & Vongsa, 2003; Steinmetz et al., 2014; Timmins, 1996; Vongkhamheng et al., 2013).

The PES pilot scheme was implemented in the Phou Chom Voy Provincial Protected Area (PCV PPA), located in the Annamite Ranges; a large mountain formation along the Lao PDR/Vietnam border (Figure 1). The region has a forest cover of over 63%, which is home to at least 100 vulnerable and (critically) endangered animal and plant species (IUCN, 2016). Although poaching and logging within protected areas is illegal, protected area laws are poorly enforced or not enforced at all (Duckworth et al., 2012). Illegal hunting is the main cause of biodiversity loss in the area (Hilborn et al., 2006; Pratt et al., 2004). Poachers target endangered species (see Appendix S1), which fetch a high price when traded on the international market and are used as traditional medicines—predominantly in Vietnam and China (Duckworth, Salter & Khounbline, 1999).

2.2 | The poaching-patrols model

Our study aims to predict how poaching might impact selected conservation species in the PCV PPA, and how community patrols could help to mitigate poaching pressures in the region. A dynamic simulation model was developed in the R software environment (R Core Team, 2017) to represent (a) wildlife habitat and accessibility of the PCV PPA; (b) maturation, reproduction, and natural deaths for selected conservation species; (c) poacher activity; and (d) community anti-poaching patrols. Where possible, parameter values for the various model components were based on available data, but due to the limited data available for the PCV PPA, many values were estimated based on advice and discussion with local villagers and wildlife experts, led by Dr C. Vongkhamheng. Space and movement of animals, poachers and patrols are represented implicitly; the connection between individual cells is not explicitly represented. The full model code is provided in the Supporting Materials together with associated input files (Appendix S3).

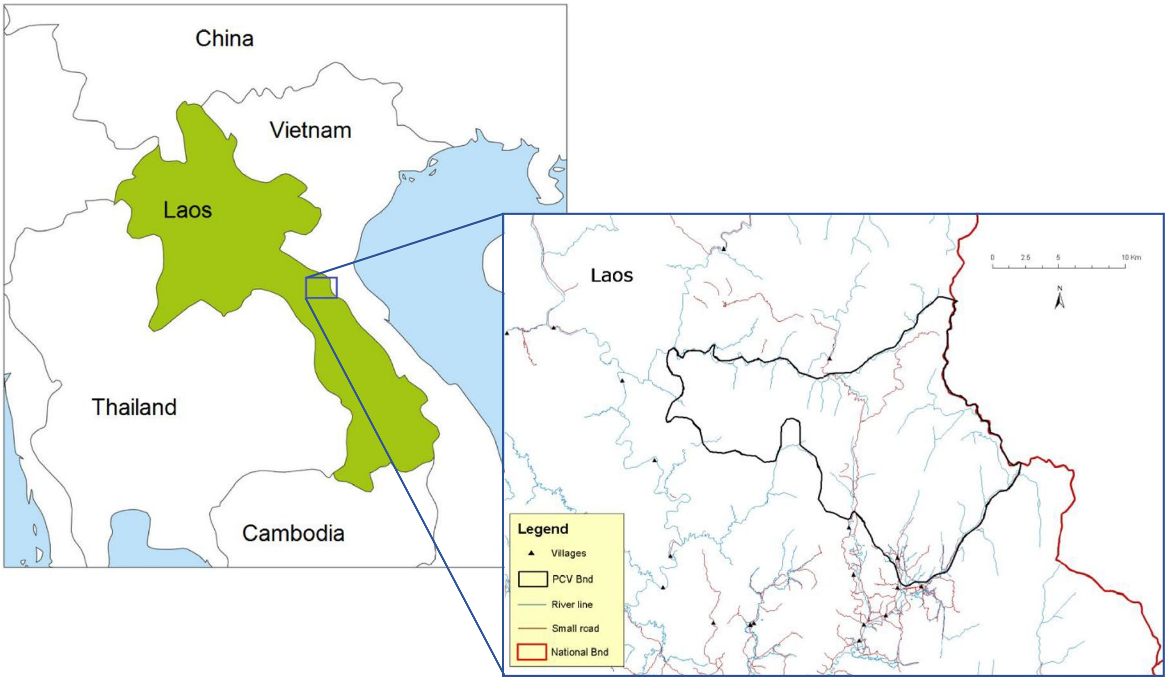

FIGURE 1 Location of the Phou Chom Voy (PCV) Provincial Protected Area, Lao PDR (Image sourced from Provincial Agriculture & Forestry Office, 2010; bnd = Boundary)

2.3 | Landscape components

The 223 km^2 PCV PPA is represented in the model as a list of cells, each representing 1 km^2, which was created using a Google Earth image from 2015 and park boundaries sourced from the PCV PPA Management Plan (Provincial Agriculture & Forestry Office, 2010). The model runs on a monthly time step to match the wildlife patrolling agreements with local villagers.

Based on our general knowledge of biodiversity systems in the PCV PPA and in consultation with local experts, a habitat quality index Q_j for each grid cell j was determined as a function of proximity to water bodies and forest cover, with 1 being the highest possible habitat quality value. Habitat quality was assumed to reduce with distance from water bodies and increase with higher density of forest cover. For each grid cell, the proportion of forest cover and the presence of minor and major water bodies were mapped using visual inspection of Google Earth and Google Maps images. The specific functional forms and parameter values used to define the habitat quality index are available in Appendix S3. While habitat quality could well affect different species in different ways, we did not have the data on the relevance of different habitat qualities for different species. Our local expert advice also did not raise species-specific habitat requirements as an issue that needed to be included in the model. If data became available then it would be relatively straightforward to include this in the model.

An 'accessibility' index was defined for each cell to reflect that areas further from roads or villages are harder to reach (because of the thick forest and understory) and thus less likely to be targeted by poachers (Moore et al., 2018; Timmins & Khounboline, 1996). Google Earth imagery of the PCV PPA was visually inspected for roads (R) and villages (V) within and surrounding the PPA. Villages were assigned an index value of 1, which can be thought of as indicating maximum (100%) accessibility. Roads were assigned a lower value of 0.7. This assumption of relatively lower accessibility is because roads in this area are small dirt roads that are not always in good condition. The remaining cells were assigned accessibility values using a hyperbolic distance-decay function (see Supporting Information).

2.4 | Species component

An investigation of the scientific and grey literature on conservation species in Lao PDR plus expert consultation indicated that many globally significant species exist, or are likely to exist, within the PCV PPA (see Appendix S1). In some cases (e.g. Saola spp.), Lao PDR is the last remaining place on earth harbouring populations (Turvey et al., 2015). A subset of 19 target conservation species (Table 1) was selected to be included in the PCV PPA model. These were selected based on (a) the conservation significance of the species, both globally and nationally; (b) confirmation from expert opinion and survey data that the species is likely to exist in the study area; (c) the species being targeted by poachers; and (d) being target species for the PES scheme.

Each species in the model is defined by a set of parameter values (Table 1). Values are based on information from the literature using data for Lao PDR where available or information from other areas in SE Asia or elsewhere where data did not exist for Lao PDR (data sources for each species are provided in Appendix S2). Field surveys (Newton, Thai, Roberton, & Bell, 2008; e.g. Timmins et al. 1996, 1998, Tizard, 1996) and interviews with local conservation experts

TABLE 1 Species-level inputs: initial population, group size, territory size, years to reproductive maturity, reproduction rate (surviving young per reproductive female per year) and daily probability of being caught in snares or through direct poaching methods when in the same cell as snares or poachers (Pr_{snare}, Pr_{direct})

Species	Initial population	Group size	Territory (km²)	Years to maturity	Rep. rate	Pr_{snare}	Pr_{direct}
Annamite striped rabbit	5	1	0.1	0.115	1	0.006	0.004
Asiatic black bear	114	1	70	6	1	0.008	0.006
Bengal slow loris	111	1	5	0.58	0.5	0.002	0.004
Pygmy slow loris	16	1	5	0.58	0.5	0.002	0.004
Chinese pangolin	2	1	8	7	0.75	0.002	0.010
Sunda pangolin	13	1	0.45	7	0.5	0.002	0.010
Clouded leopard	5	1	35	2	1	0.004	0.002
Douc langur	450	15	6	3	0.5	0.002	0.010
Large-antlered muntjac	10	1	70	0.71	0.5	0.006	0.008
Large-spotted civet	5	1	2	1	1	0.006	0.006
Owston's civet	8	1	2	1	1	0.006	0.006
Northern pig-tailed macaque	5	15	1	4	0.5	0.004	0.010
Stump-tailed macaque	25	15	1	4	0.5	0.004	0.010
Northern white-cheeked gibbon	33	4	0.17	10	0.63	0.002	0.010
Rufous-necked hornbill	111	5	10	19	1	0.000	0.004
Sambar	223	1	15	2	0.5	0.004	0.008
Saola	5	2	50	6	0.5	0.006	0.008
Southern Serow	15	1	5	2.5	0.34	0.002	0.008
Tiger	2	1	200	7	0.5	0.006	0.002

Note: Additional information about each species and data sources is provided in Appendix S2.

led by Dr C. Vongkhamheng in June 2015 confirmed the occurrence of the species in our study area. However, very limited documented species' abundance data exist for Lao PDR (MoNRE-IUCN, 2016).

The model we developed accounts for the fact that some species live and travel in small groups or family groups, while other species live and move individually (Table 1). Each animal (group) is assigned a territory area of the defined home range size for that species within the simulated PCV PPA area.

For each animal, the actual cells of its territory are selected at random from all cells within the protected area, with a preference for cells with higher habitat quality (each cell j has a weighted probability of selection equal to Q_j). Cells are selected independently for each animal (group), meaning that territories can overlap. Animals (groups) are assumed to be within one cell within their territory at any given moment, but to move around between cells within the territory over time. Movement of animals is not represented explicitly, but rather by assuming that the probability of an animal being in a particular cell at any given moment is equal to the inverse of the total number of cells in its territory.

Years to maturity captures the time from birth to sexual maturity of a species when it is able to produce offspring. Half of all individuals are assumed to be female. Any female that has reached reproductive maturity may produce young in any given month. Annual reproduction rate, i.e. the annual average number of offspring per sexually mature female, is used to predict the number of new offspring at each time step. The maximum number of individuals of a species is constrained by its territory size. If the total territory size for a species exceeds the total protected area, no further reproduction is possible. Species dispersal and recruitment beyond protected area boundaries are assumed to be zero as we are interested in numbers of animals saved within the protected area.

The Pr_{snare} and Pr_{direct} values in Table 1 were estimated by local experts and are based on how common the species is, how likely it is to be seen by poachers, the animal's behaviour (nocturnal, elusive, avoids humans etc.), and group size. For species that live in groups, the model assumes that all individuals in the group are killed if the group is snared/shot/hunted/collected (Fan, Fei, & Luo, 2014; Johnson, Singh, Duangdala, & Hedemark, 2005), but the Pr_{snare} and Pr_{direct} values are set to account for the fact that in reality some individuals may survive.[2] Model testing showed modelling as a group in

[2]For example, if expert input told us that a group has a 0.5 probability of being seen by hunters, and that on average half of the individuals are killed after the group is seen, we use a probability in the model of 0.5 × 0.5 = 0.25 of being detected and killed.

this way versus modelling as independent individuals had negligible effect on results.

2.5 | Poaching component

A maximum of three poacher groups are assumed to operate at any given time. Each poacher group is assumed to target a fixed poaching territory of 20 cells in a given month. The 20 poaching territory cells for each poacher group are selected randomly from all cells within the boundary of the PCV PPA protected area, with a cell probability weight equal to the cell's accessibility value. The first of these cells is assumed to be the poachers' base camp. The weighting by accessibility reflects the facts that observed snare densities are the greatest near human infrastructure (Watson, Becker, McRobb, & Kanyembo, 2013) and that high forest density, with groundcover close to 100% and impenetrable bamboo thickets, prevents poacher access (Tsechalicha, Pangxang, Phoyduangsy, & Kyophilavong, 2014).

At each monthly time step, poaching groups can be apprehended and new teams of poachers may enter the area with probability $Pr_{\text{newpoachers}}$ = 0.4. The relatively low likelihood of occurrence of 0.4 simulates the effects of enforcement, assuming that once poachers know that patrols are operating, they are less likely to enter the area. Existing teams of poachers may move their base and targeted areas each month with probability $Pr_{\text{poachermove}}$ = 0.6. This movement, if it occurs, can result in new areas being poached. The value of 0.6 assumes that poachers are relatively mobile and likely to change their targeted area reasonably frequently. Poachers are assumed to actively hunt (i.e. shoot or kill animals directly) for 15 days every month. At each time step, poachers are also assumed to set a snare line in each cell within their poaching territory, with a density of 100 snares per km^2 (following field data on snaring methods; (Nguyen, 2009).

Illegal hunting and poaching in this region occurs by snaring and direct methods. The model simulates the possibility of an animal being snared or killed directly at each time step based on the assumption that both animals and poachers move around between the cells in their territory. Whether the animal is actually killed in that month or not is determined stochastically in the simulation based on the monthly probability of death due to snaring or direct poaching ($Pr_{\text{monthly.death}}$ Appendix S3).

2.6 | Patrolling components

Anti-poaching patrols are assumed to move throughout the specified patrolled cells each month. Similarly to the modelling of poachers encountering animals, the probability that a patrol is in the same cell as a poacher group on any given day is assumed to be equal to the number of cells common to the patrolled area and the poachers' territory, divided by the product of the total number of cells in the poachers' territory and the total number of cells patrolled. If the anti-poaching patrols are in the same cell as poachers, there is a probability $Pr_{\text{apprehend}}$ that those poachers are apprehended. This could be set to zero if a patrol has no legal powers of apprehension. There is also a possibility of anti-poaching patrols finding and removing an existing poacher group base at some time during the month. If the patrolled cells include a poacher base, it is assumed that it will be discovered and removed according to a user-specified probability $Pr_{\text{removebase}}$.

At each time step, anti-poaching patrols find and remove any snares in each patrolled cell with a probability of $Pr_{\text{snarefind}}$. This probability reflects that a patrol may fail to find the snare line within a cell when one is present, and can be varied according to the assumed likelihood of snare detection, which is unlikely to ever be 100% (Becker et al., 2013). It is assumed that if the snare line is found, then all snares within a cell are removed or at least rendered ineffective.

2.7 | Model scenarios

We simulated four different model scenarios of two patrol teams operating in the area each month. The scenarios are designed to represent the most likely patrol structures that will initially be implemented in the PES scheme. The definition of the scenarios are informed by previous studies on species monitoring and patrolling (Becker et al., 2013; Vongkhamheng et al., 2013). All parameters are available in Appendix S3 and are described below.

1. Base case (Base) = The base case scenario represents the current situation with poachers and no anti-poaching patrols. As such, it provides the worst-case scenario for biodiversity in the region. The base scenario was calibrated based upon expert predictions and observations of current biodiversity decline in the Lao PDR.
2. Low-effort patrols (SC1) = In this scenario, 100 of the 223 km^2 cells are patrolled each month, the probability that patrols apprehend poachers is moderate (0.6) and the probability that patrols remove poacher camps is low (0.1). Patrols remove snare lines as they move through grid cells at 60% efficiency (Chanthavy Vongkhamheng, 2015, personal communication, 9 May). The moderate probability of poacher apprehension and low probability of camp removal mimic the minimum effects of patrols on poachers; even if patrols do not directly confront poachers, the presence of patrols in the area may abate poaching pressure to some degree.
3. Medium-effort patrols (SC2) = This third scenario is designed to mimic the most likely patrol scheme that will initially be implemented under the PES scheme. Again, 100 grid cells are patrolled each month, but there is a higher likelihood (0.8) that poachers are apprehended if encountered by a patrol, and a 0.6 likelihood that a poacher camp is removed if intercepted. Patrols still remove snare lines at 60% efficiency. This scenario is designed to represent patrols having some authority, operating at reasonable efficiency.
4. High-effort patrols (SC3) = All 223 cells are patrolled at higher efficiency than other scenarios: 90% of poachers are apprehended and all camps are removed if they are intercepted. The snare line removal efficiency is increased to 80%. SC3 demonstrates how many animals may survive when the whole area is patrolled on a monthly basis.

This represents a high-cost patrol scheme that should be more effective for mitigating poaching in the area. There is still some stochasticity in the model, regarding contact between patrols and poachers, poacher-targeted grid cells, or poacher camps. This is realistic since it is unlikely that all poaching activities can be removed completely. This high-effort scenario would require members of the police or militia to be part of the patrol to ensure apprehension of poachers.

The four management scenarios were run over a 10-year period (120 months) to capture long-term trends in populations. This period can readily be adjusted to suit specific temporal scales (e.g. the duration of a PES contract). We expect populations to recover to some degree under some of the patrol schemes. For each scenario, 100 replicate model runs were used to account for the internal model stochasticity, which resulted in variance within the results for each individual scenario. Subsequent consideration of standard errors on mean model predictions indicated that 100 replicates was sufficient (see figures in Section 3).

Note that any of the parameter values that define landscape features, species-level inputs, poacher and patrol activities can be readily altered in the model if better information becomes available, or to use the model in other regions (see Appendix S3 for the full model code and associated input files). Our model was used to test the impacts of different patrolling and poaching scenarios as defined in discussions with experts and local villagers who would be undertaking the patrols. When the model is used to determine the impact of different patrolling schemes, one can change the number of cells patrolled, and the number of days that anti-poaching patrols operate each month to reflect different patrolling scheme scenarios. The model allows various options for selecting exactly which cells within the protected area are patrolled, based on accessibility (the cells with the highest accessibility values, or random selection with probability weighted by a cell's accessibility value), habitat quality (cells having a weighted probability based on Q), or purely random (all cells have an equal probability). These various options are important because they allow the model user to match the specific patrolling strategies that villagers are engaged in through the PES scheme. It is also possible to specify exactly which cells are patrolled to match specific patrol plans or records. Furthermore, it is possible for some cells to be patrolled more than once in a month, which in turn means that it is possible to patrol more cells than the total number of cells in the protected area in a given month.

3 | RESULTS

Each scenario provides estimates of (a) the number of animals surviving in the PCV PPA and (b) the number of species protected. These results allow us to evaluate the most effective patrolling approach to poaching management in terms of biodiversity conservation, and provide direct information into the PES scheme.

Results show that increasing anti-poaching patrol effort leads to higher numbers of individual animals (Figure 2), and to higher

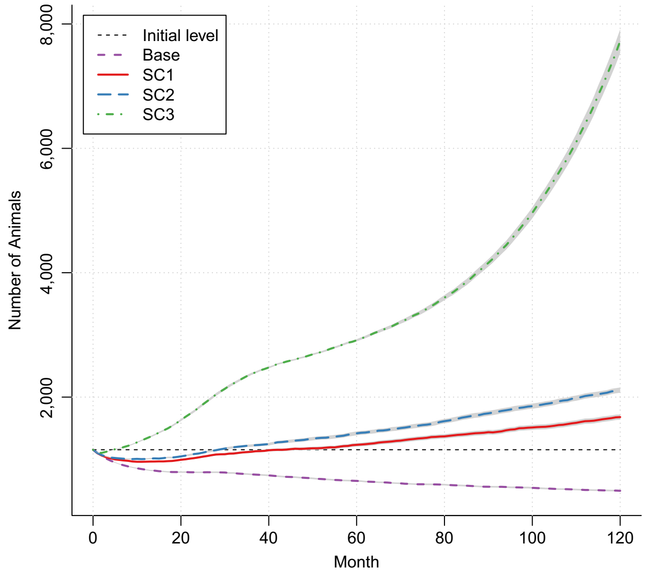

FIGURE 2 Number of animals surviving in the Phou Chom Voy Provincial Protected Area study area under different poaching-patrol management scenarios over a 10-year modelling period (Dotted lines show the mean over 100 replicate runs, and grey shaded ribbons indicate standard error of the mean)

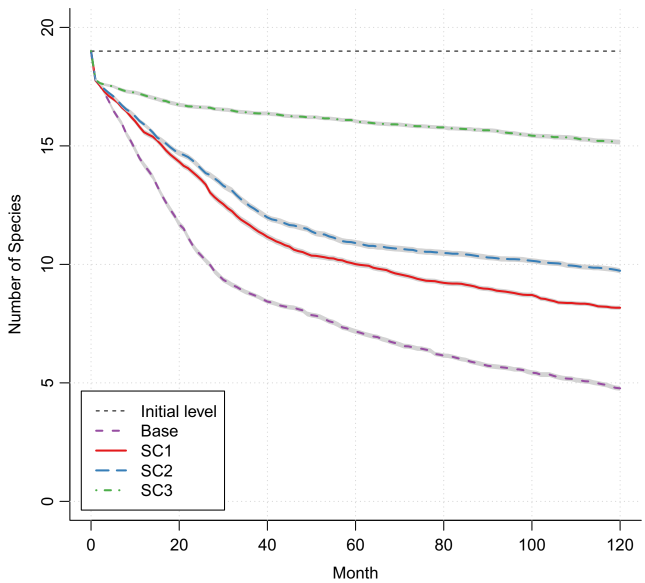

FIGURE 3 Number of species remaining in the Phou Chom Voy Provincial Protected Area study area under different poaching-patrol management scenarios over a 10-year modelling period. (Lines show the mean over 100 replicate runs, and grey shaded ribbons indicate standard error of the mean)

numbers of species surviving (Figure 3). Without any patrol effort (Base case), approximately 494 animals and less than five species would survive in the PCV PPA after 10 years (standard error = 13 and 0.10 respectively). Increasing patrol effort (scenarios SC1, SC2 and SC3) has a marked effect on the number of animals protected and on species survival, compared to the Base (Table 2). These results

TABLE 2 Mean number of animals and of species surviving at t = 120 months for each management scenario

Scenario	Average number of animals remaining at t = 120	Average number of species remaining at t = 120
Current (t = 0)	1,154	19
Base case	493 (12.92)	4.8 (0.10)
SC1	1,678 (42.61)	8.2 (0.09)
SC2	2,112 (42.42)	9.7 (0.11)
SC3	7,724 (191.05)	15.2 (0.10)

Note: Standard errors in parentheses.

suggest that even the most basic patrol scheme SC1 will have an impact on preserving species diversity in the region.

Two species; the Bengal Slow Loris & Rufous-necked Hornbill, are predicted to survive under all poaching-patrol scenarios (Figure 4). This is because these species are smaller, harder to see, and not impacted by snares on the ground. The Loris spp. have a higher survival chance than other species considered in this study because of their high initial populations and their small range—which makes them less likely to encounter poachers. Species that are very rare, with low initial population counts, and high probability of capture (Pr_{snare} and Pr_{direct}) could go extinct even under higher effort patrolling scenarios (SC2 and SC3). Such high risk species include the Northern Pig-Tailed Macaque, Tiger, Saola, Asiatic Black Bear, Large-Antlered Muntjac, and Clouded Leopard (Figure 4).

3.1 | Sensitivity and scenario analysis

Sensitivity analyses were conducted to test how uncertainty in the species' input parameters and patrol-poaching characteristics would influence the model outcomes. The sensitivity analyses were run for scenario SC2 (which was the most likely community-led patrol scheme to be implemented under the PES scheme), with model results showing the total number of animals and total number of species surviving after 120 months. In this section, results are presented for changes in the poaching and patrol characteristics. Further

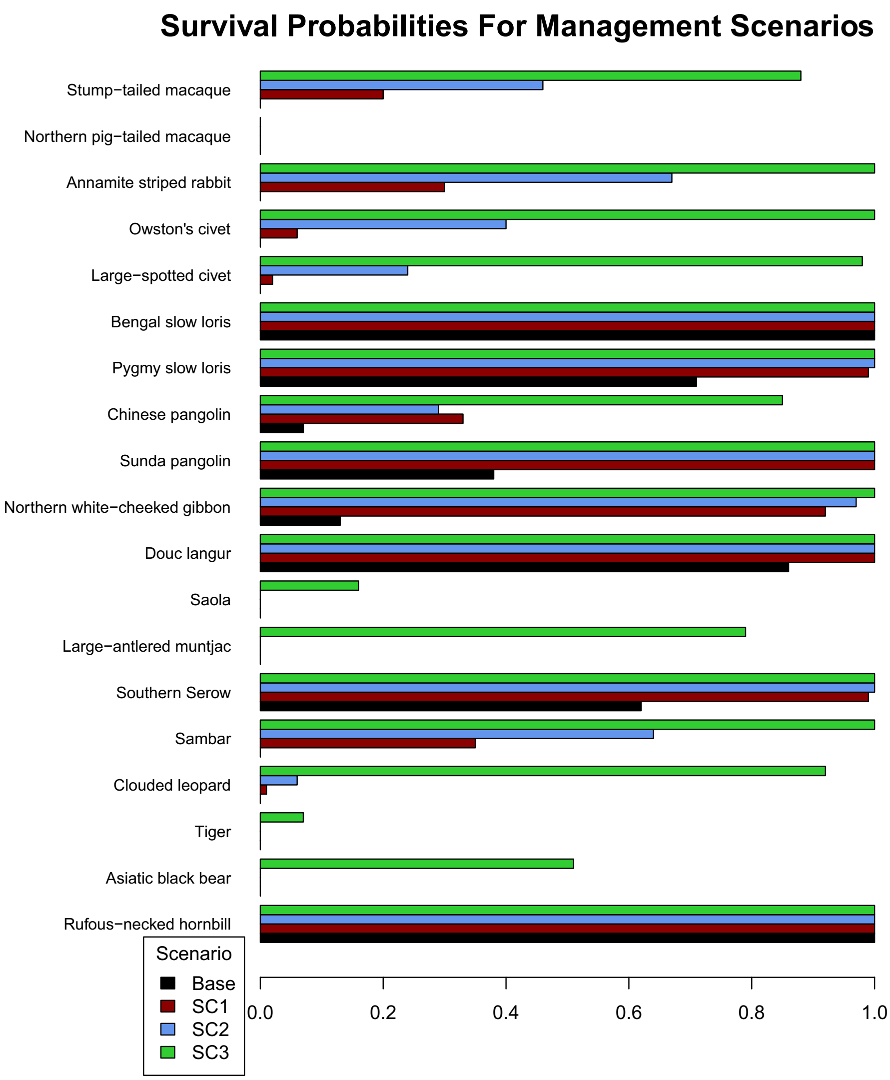

FIGURE 4 Probability of survival for each species at t = 120 months under alternative management scenarios

TABLE 3 Values of poaching and patrol parameters used in the sensitivity analysis

	SC2 base values	High	Low
# Cells patrolled	100	125	75
Accessibility constant	0.1	0.05	0.15
# Poacher groups	3	4	2
# Cells poached	20	25	15
$Pr_{newpoachers}$	0.4	0.6	0.2

results of the sensitivity analyses to variations in species' input data are included in Appendix S4.

The values of poaching and patrol parameters were varied to assess how model output would change under different poaching/patrolling strategies ('High' and 'Low': Table 3). Results show that the number of cells patrolled had the highest impact on model outputs: increasing the number of cells patrolled from the base value of 100 to a high value of 125 (a 25% increase) increased the average number of animals surviving by 32.5% relative to the base in SC2 (Figure 5 and Table 4). This shows that patrols are an effective means to increase animal survival, even with only a moderate increase in area patrolled.

The model output was only marginally sensitive to the other parameter changes. Altering the accessibility constant resulted in a +3% change in animal count, and a 0%–2% change in the number of species surviving (Table 4). These changes are within the variability caused by the model's stochasticity itself and can hence not be uniquely attributed to the accessibility parameter.

The poaching inputs parameters 'number of cells targeted by poacher groups' and 'number of poacher groups' have limited influence on model outputs. Reducing/increasing the number of poacher groups did not affect the number of animals or number of species surviving beyond the model's internal variability (Figures 5 and 6). Increasing/decreasing poacher effort by changing the number of cells they target, reduces/increases the number of animals surviving by about 4%–5% (Figure 5). Our findings are as expected: higher poacher effort (# of cells poached and # of poacher groups) results in fewer animals surviving. Model outputs were only moderately sensitive to the probability of new poacher groups ($Pr_{newpoacher}$). A higher chance of poacher incursion negatively impacted animal survival and species counts. Changes in the probability of new poacher groups had a larger effect on the total number of animals surviving (approximately ±6%; Figure 5) than on species survival (Figure 6).

4 | DISCUSSION

Poaching has a negative impact on the populations of endangered species in the Lao PDR's Phou Chomvoy Provincial Protected Area (PCV PPA). Despite the significant threats placed by poaching on Lao's biodiversity, there is currently limited knowledge on the impacts of poaching in Southeast Asia (Gray et al., 2018). We present a model that allows us to estimate the impact of community-led anti-poaching patrols on threatened species populations in the PCV PPA. No other studies have tried to predict the interaction of wildlife patrols and poachers with populations of endangered species. The model was developed as part of a Payment for Environmental Services (PES) scheme that pays local villagers for anti-poaching patrols in the area. Villagers are paid for different levels of patrolling effort, with payments determined by the potential biodiversity benefits as predicted in the model.

The model development process is generic and flexible enough to incorporate knowledge from a range of data sources, including local expert knowledge as well as scientific data—an essential feature in this region where limited scientific data are available. Our study demonstrates how a model can be built to integrate available information in a data-limited situation, which was essential given the requirement for a transparent evidence-based predictive framework to act as the basis of the PES project. The modelling framework is sufficiently flexible to be applied in other regions and can readily be parameterized for other species and poaching-patrol scenarios.

The data and assumptions underlying the model were based upon the best available information and expertise at the time, and can be

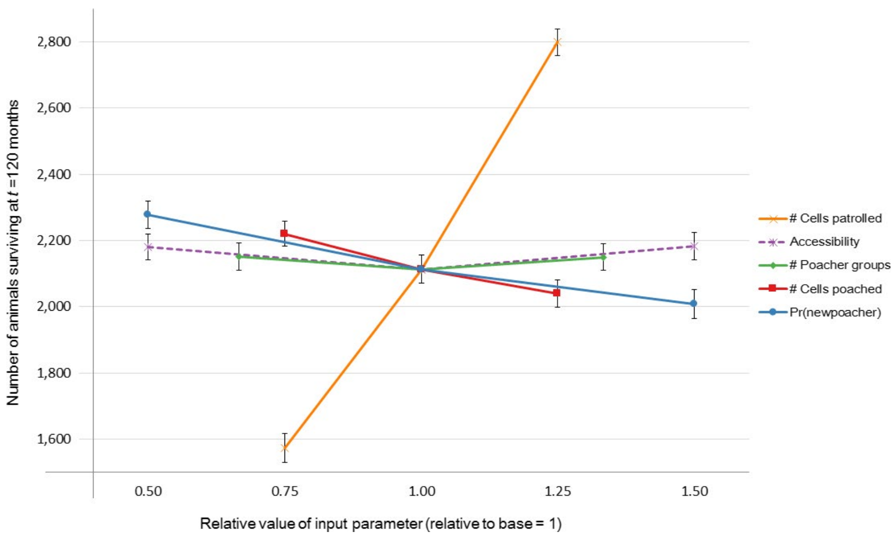

FIGURE 5 Sensitivity of predicted mean number of animals surviving at t = 120 months. Patrol and poaching input variables are varied relative to their base input values

TABLE 4 Sensitivity analysis results when varying poaching and patrolling parameters

Number of animals	Input parameters HIGH # Animals surviving	Standard error	% Change	Input parameters LOW # Animals surviving	Standard error	% Change
Base result at 100 runs[a]	2,154	38.2	2	2,125	43.3	1
# Cells patrolled	2,798	40.7	32	1,573	43.2	−26
Accessibility constant	2,181	39.2	3	2,183	40.2	3
# Poacher groups	2,149	39.7	2	2,150	41.2	2
# Cells poached	2,039	41.2	−4	2,220	37.8	5
$Pr_{newpoachers}$	2,008	43.6	−5	2,277	40.3	8
Number of species	**# Species surviving**	**Standard error**	**% Change**	**# Species surviving**	**Standard error**	**% Change**
Base result at 100 runs[a]	9.7	0.1	−1	10.0	0.1	2
# Cells patrolled	11.0	0.1	13	8.8	0.1	−10
Accessibility constant	9.7	0.1	0	9.9	0.1	2
# Poacher groups	9.6	0.1	−1	9.8	0.1	1
# Cells poached	9.7	0.1	−1	10.0	0.1	2
$Pr_{newpoachers}$	9.4	0.1	−4	10.0	0.1	2

[a]This value captures the stochasticity in the model with means varying over 100 runs.

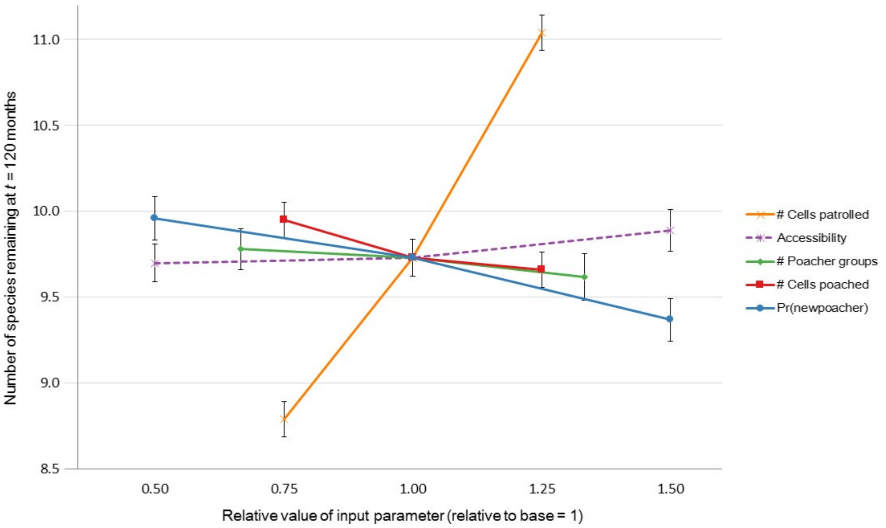

FIGURE 6 Sensitivity of predicted mean number of species surviving at t = 120 months. Patrolling and poaching input variables are varied relative to their base input values

readily updated when additional data becomes available. Note that data collection is anticipated through a monitoring system built into the PES project. As the patrol scheme progresses, additional data on input variables such as species counts, population sizes, poacher movements, and snare densities are expected to become available. These data can be used to refine and improve the accuracy of the model predictions. Like all models, our model is a simplified representation of reality, and to avoid over-complicating and to meet the requirements of the PES scheme we had to make various simplifying assumptions. In the future, it would be interesting to test the implications of these assumptions and possibly improve them if additional data is collected through the PES project.

The results presented in this paper are consistent with current knowledge of the damaging effects of poaching in protected areas (Pratt et al., 2004; Vongkhamheng et al., 2013). The management scenarios investigated (SC1–SC3) are example scenarios that are based on current understanding of anti-poaching patrols and poaching techniques. They demonstrate the effectiveness of different types of anti-poaching patrolling scenarios. We show that, in the absence of anti-poaching patrols, the number of species and individual animals are predicted to decrease to about 494 animals and less than five species, compared to an estimated 1,154 animals and 19 species that are currently present. Results demonstrate that management of poachers through wildlife patrol teams (even in low patrolling efforts scenarios—SC1) will protect the number of animals in the PCV. However, we demonstrate that poaching will always reduce the number of species, even if 'high patrol effort' scenarios (SC3) are implemented. This means that some of the most endangered species may not be saved from local extinction. For example, the Northern Pig-Tailed Macaque lives in large groups that are easy for poachers to find. Our results demonstrate that there is a limit to the effectiveness of protecting species through anti-poaching patrols. Patrols move through the area, but are restricted by, for example, their walking speeds and thus the area they can cover; the fact that snares will not always be found even when a grid-cell is entered; and the limited accessibility due to rough terrain and dense forests. These are real-world challenges that will need to be considered when rewarding local villagers for their poaching-mitigating patrolling efforts.

The sensitivity analysis indicates that a 25% increase in patrolling efforts (i.e. the # of cells patrolled) can have a significantly positive effect on the number of animals protected (+32%) and species surviving (+13%), demonstrating the benefits of the proposed community patrolling scheme. An increase in poaching effort (through a higher # of poacher groups or higher # of cells poached), is shown to reduce the number of animals and species although not as much as expected. This is because the region has limited accessibility, and thus new poacher groups will not be able to reach many more locations. Also, competition for locations will become relevant if more poachers access the area, which would reduce the new poachers' effectiveness. We also assessed the model's sensitivity to a change in an animal's probability of being killed by poachers (Pr_{snare} and Pr_{direct}; Supporting Information). This showed that a 20% increase in Pr_{snare} significantly reduces the number of surviving animals (−37%). This is because the snares are laid throughout the PCV, which means that animals have a much higher chance of being caught when moving though their territory. Given the sensitivity of the results to species' characteristics like Pr_{snare}, reproduction rate, and territory size, future research should concentrate on improving our knowledge of those input parameters.

An important challenge for anti-poaching patrols in this region is the potential risk associated with the task. We assume that patrols are able to remove snares (SC1) without incident or undue personal risk. However, there will be a risk associated when patrols confront poachers and remove poacher camps (SC2). Poachers are armed with weapons and approaching them could be dangerous for an unarmed patrol group. Ergo for SC2 with camp removal, we must assume that patrols have some legal mandate to undertake their task. Enforcement of such a mandate is enhanced if a local policeman or military official accompanies the patrol to handle apprehension of illegal poachers (a realistic possibility in this region), which will be necessary in scenario SC3 where patrols always arrest poachers when encountered. With increasing patrol effort, there is increased patrol–poacher confrontation which may be dangerous, and the compensation received by patrols through the PES pilot scheme should reflect the scenario which they are to work by.

As a key component of the PES scheme, it was important that the model input parameters could be readily changed by the user to reflect the different levels of patrol effort proposed by the local villagers involved in the PES scheme. Patrol frequency, percentage of snares collected, or the number of cells patrolled per month can be altered to analyse the effects of improving patrol effectiveness or efficiency. Our research only provides a starting point to understand and quantify the effects of poaching and anti-poaching patrol effort on biodiversity in Lao PDR, which has not been attempted previously. We demonstrate that wildlife patrols can be an appropriate conservation strategy.

ACKNOWLEDGEMENTS

This work was funded by the Australian Centre for International Agricultural Research (ACIAR), project "Effective Implementation of Payments for Environmental Services in Lao PDR", project number FST/2011/003. Dr Kragt received funding from the Australian Government as an Australian Research Council Discover Early Career Award (DE160101306) while writing this paper. We are grateful to Dr Chanthavy Vongkhamheng, Dr Phouphet Kyophilavong and Mr Xiong Tsechalicha for their help in data collection and navigating the systems in Lao PDR.

AUTHORS' CONTRIBUTIONS

M.E.K., M.R., G.S. and J.B. conceived the study; M.E.K. and E.H. collected the data; M.R. and E.H. developed the model; M.R., G.S., M.E.K. and E.H. contributed to the design and interpretation of the model; M.E.K. and M.R. led the writing of the manuscript. All authors gave approval for publication and agree to be accountable for the aspects of the work that they conducted.

DATA AVAILABILITY STATEMENT

The full model code, as well as the associated input data, is available through the UWA Research Repository https://doi.org/10.26182/5dad0224ed548 (Kragt & Renton, 2019).

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REFERENCES

Becker, M., McRobb, R., Watson, F., Droge, E., Kanyembo, B., Murdoch, J., & Kakumbi, C. (2013). Evaluating wire-snare poaching trends and the impacts of by-catch on elephants and large carnivores. *Biological Conservation*, *158*, 26–36. https://doi.org/10.1016/j.biocon.2012.08.017

Burkholder, D. A., Heithaus, M. R., Fourqurean, J. W., Wirsing, A., & Dill, L. M. (2013). Patterns of top-down control in a seagrass ecosystem: Could a roving apex predator induce a behaviour-mediated trophic cascade? *Journal of Animal Ecology*, *82*(6), https://doi.org/10.1111/1365-2656.12097

Colman, N. J., Gordon, C. E., Crowther, M. S., & Letnic, M. (2014). Lethal control of an apex predator has unintended cascading effects on forest mammal assemblages. *Proceedings. Biological Sciences*, *281*(1782), 20133094. https://doi.org/10.1098/rspb.2013.3094

Conservation International. (2017). *International biodiversity hotspots*. Arlington, VA: Conservation International. Retrieved from www.biodiversityhotspots.org

Conteh, A., Gavin, M. C., & Solomon, J. (2015). Quantifying illegal hunting: A novel application of the quantitative randomised response technique. *Biological Conservation*, *189*, 16–23. https://doi.org/10.1016/j.biocon.2015.02.002

Duckworth, J. W., Batters, G., Belant, J. L., Bennett, E. L., Brunner, J., Burton, J., … Wirth, R. (2012). Why South-east Asia should be the world's priority for averting imminent species extinctions, and a call to join a developing cross-institutional programme to tackle this urgent issue. *Sapiens*, *5*(2), 77–95.

Duckworth, J. W., Salter, R. E., & Khounbline, K. (1999). *Wildlife in Lao PDR: 1999 Status Report*. Vientiane, Laos: IUCN.

Fan, P. F., Fei, H. L., & Luo, A. D. (2014). Ecological extinction of the Critically Endangered northern white-cheeked gibbon Nomascus leucogenys in China. *Oryx*, *48*(1), 52–55. https://doi.org/10.1017/S0030605312001305

Gray, T. N. E., Hughes, A. C., Laurance, W. F., Long, B., Lynam, A. J., O'Kelly, H., … Wilkinson, N. M. (2018). The wildlife snaring crisis: An insidious and pervasive threat to biodiversity in Southeast Asia. *Biodiversity and Conservation*, *27*(4), 1031–1037. https://doi.org/10.1007/s10531-017-1450-5

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

IUCN. (2016). IUCN red list of threatened species. Version 2014.3. International Union for Conservation of Nature and Natural Resources. Retrieved from http://www.iucnredlist.org

Johannesen, A. B., & Skonhoft, A. (2005). Tourism, poaching and wildlife conservation: What can integrated conservation and development projects accomplish? *Resource and Energy Economics*, *27*(3), 208–226. https://doi.org/10.1016/j.reseneeco.2004.10.001

Johnson, A., Singh, M., Dongdala, M., & Vongsa, O. (2003). *Wildlife hunting and use in the Nam Ha National Protected Area: Implications for rural livelihoods and biodiversity conservation*. Vientiane: Wildlife Conservation Society.

Johnson, A., Singh, S., Duangdala, M., & Hedemark, M. (2005). The western black crested gibbon Nomascus concolor in Laos: new records and conservation status. *Oryx*, *39*(3), 311–317. https://doi.org/10.1017/S0030605305000906

Kimanzi, J. K., Sanderson, R. A., Rushton, S. P., & Mugo, M. J. (2014). Spatial distribution of snares in Ruma National Park, Kenya, with implications for management of the roan antelope Hippotragus equinus langheldi and other wildlife. *Oryx*, *49*(2), 295–302. https://doi.org/10.1017/S0030605313000689

Kragt, M. E., & Renton, M. (2019). Data input files for Lao PDR anti-poaching patrol model. The University of Western Australia, https://doi.org/10.26182/5dad0224ed548

MoNRE-IUCN. (2016). *Fifth national report to the United Nations convention on biological diversity* (110 pp). Vientiane: Ministry of Natural Resources and Environment. Retrieved from https://www.cbd.int/doc/world/la/la-nr-105-en.pdf

Moore, J. F., Mulindahabi, F., Masozera, M. K., Nichols, J. D., Hines, J. E., Turikunkiko, E., & Oli, M. K. (2018). Are ranger patrols effective in reducing poaching-related threats within protected areas? *Journal of Applied Ecology*, *55*(1), 99–107. https://doi.org/10.1111/1365-2664.12965

Morgera, E., & Wingard, J. (2009). *Principles for developing sustainable wildlife management laws* (p. 90). Budapest: Joint publication of FAO and CIC.

Newton, P., Van Thai, N., Roberton, S., & Bell, D. (2008). Pangolins in peril: Using local hunters' knowledge to conserve elusive species in Vietnam. *Endangered Species Research*, *6*(1), 41–53. https://doi.org/10.3354/esr00127

Nguyen, M. H. (2009). The status of Vulnerable gaur *Bos gaurus* and Endangered banteng *Bos javanicus* in Ea So Nature Reserve and Yok Don and Cat Tien National Parks, Vietnam. *Oryx*, *43*(1), 129–135. https://doi.org/10.1017/S0030605307000440

Pratt, D. G., Macmillan, D. C., & Gordon, I. J. (2004). Local community attitudes to wildlife utilisation in the changing economic and social context of Mongolia. *Biodiversity & Conservation*, *13*(3), 591–613. https://doi.org/10.1023/B:BIOC.0000009492.56373.cc

Provincial Agriculture and Forestry Office. (2010). Phou Chom Voy provincial protected area management plan 2011–2015. Provincial Conservation Division – Provincial Agriculture and Forestry Office of Bolikhamxay, Lao People'sDemocratic Republic.

R Core Team. (2017). *R: A language and environment for statistical computing*. Vienna, Austria: R Foundation for Statistical Computing. Retrieved from http://www.R-project.org/

Robbins, P., McSweeney, K., Waite, T., & Rice, J. (2006). Even Conservation rules are made to be broken: Implications for biodiversity. *Environmental Management*, *37*(2), 162–169. https://doi.org/10.1007/s00267-005-0009-5

Scheufele, G., Bennett, J., & Kyophilavong, P. (2018). Pricing biodiversity protection: Payments for environmental services schemes in Lao PDR. *Land Use Policy*, *75*, 284–291. https://doi.org/10.1016/j.landusepol.2018.03.023

Steinmetz, R., Srirattanaporn, S., Mor-Tip, J., & Seuaturien, N. (2014). Can community outreach alleviate poaching pressure and recover wildlife in South-East Asian protected areas? *Journal of Applied Ecology*, *51*(6), 1469–1478. https://doi.org/10.1111/1365-2664.12239

Timmins, R. J. (1996). A preliminary wildlife and habitat survey of the Dong Khanthung Area, Champasak Province, Lao PDR. Final Report to the Centre for Protected Areas and Watershed Management of the Department of Forestry, Ministry of Agriculture and Forestry, Lao Peoples' Democratic Republic. Wildlife Conservation Society, New York.

Timmins, R. J., Evans, T. D., Khounboline, K., & Sisomphone, C. (1998). Status and conservation of the giant muntjac *Megamuntiacus vuquangensis*, and notes on other muntjac species in Laos. *Oryx*, *32*(1), 59–67. https://doi.org/10.1046/j.1365-3008.1998.00018.x

Timmins, R. J., & Khounboline, K. (1996). *A preliminary wildlife and habitat survey of Hin Namno National Biodiversity Conservation Area, Khammouane Province, Laos*. Vientiane: Wildlife Conservation Society.

Tizard, R. J. (1996). *A preliminary wildlife and habitat survey of the proposed northern extension to the Nakai-Nam Theun National Biodiversity Conservation Area and the adjacent Nam Gnouang area, Bolikhamsai Province, Laos*. Vientiane: Wildlife Conservation Society.

Tsechalicha, X., Pangxang, Y., Phoyduangsy, S., & Kyophilavong, P. (2014). The environmental, economic and social condition of the Nam Mouane – Nam Gnouang Catchment. Australian National University, Effective Implementation of Payments for Environmental Services in Lao PDR, Canberra.

Turvey, S. T., Trung, C. T., Quyet, V. D., Nhu, H. V., Thoai, D. V., Tuan, V. C. A., … Wilkinson, N. M. (2015). Interview-based sighting histories can inform regional conservation prioritization for highly threatened cryptic species. *Journal of Applied Ecology*, *52*(2), 422–433. https://doi.org/10.1111/1365-2664.12382

Vongkhamheng, C., Johnson, A., & Sunquist, M. (2013). A baseline survey of ungulate abundance and distribution in northern Lao: Implications for conservation. *Oryx*, *47*(4), 544–552. https://doi.org/10.1017/S0030605312000233

Watson, F., Becker, M. S., McRobb, R., & Kanyembo, B. (2013). Spatial patterns of wire-snare poaching: Implications for community conservation in buffer zones around National Parks. *Biological Conservation*, *168*(C), 1–9. https://doi.org/10.1016/j.biocon.2013.09.003

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

How to cite this article: Kragt ME, Hay E, Scheufele G, Bennett J, Renton M. Predicting the effectiveness of community anti-poaching patrols for conserving threatened wildlife in the Lao PDR. *J Appl Ecol*. 2020;57:320–330. https://doi.org/10.1111/1365-2664.13527