Journal of Applied Ecology

British Ecological Society

Journal of Applied Ecology 2015, **52**, 851–860 doi: 10.1111/1365-2664.12461

Safeguarding Sumatran tigers: evaluating effectiveness of law enforcement patrols and local informant networks

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Summary

1. The United Nations recently listed illegal wildlife trade as a serious crime because of the escalating demand for highly prized species, such as tiger and rhinoceros, and the failure to effectively control the trade. In turn, this places greater urgency on reducing supply by securing source populations of these species. Yet, whether law enforcement strategies designed to mitigate poaching are succeeding remains poorly understood, despite the millions of dollars invested annually in this mainstay conservation strategy.

2. Here, we assess the performance of one of Asia's longest running law enforcement programmes, from Kerinci Seblat National Park in Sumatra, by investigating whether forest ranger patrols reduced the occurrence of snare traps set for tiger and its ungulate prey base; local informant reports on poaching influenced ranger patrol success; and the resulting population trends of target species changed in response to these conservation actions.

3. A total of 4433 snare traps were removed during 642 foot patrols conducted from 2000 to 2010. Controlling for the influence of varying detection probabilities, as well as accessibility and other possible determinants of illegal hunting, revealed that sites with a greater frequency of patrols, rather than the combined distance walked, had a lower occurrence of snare traps in succeeding years.

4. Patrols conducted on the basis of local informant 'tip-offs' were significantly more likely to detect snare traps than routine patrols, with reports increasing detections by over 40%.

5. There were no significant changes in the occupancy status of the tiger prey base from 2004 to 2011, suggesting that it remained stable during this period. The relatively good condition of prey and predator populations in Kerinci Seblat National Park was further supported by the results of an independent survey conducted in 2008–2009 which revealed a widespread tiger occurrence.

6. *Synthesis and applications*. Our results not only demonstrate the effectiveness of the Kerinci Seblat law enforcement strategy in protecting wildlife, but highlight the benefits from cultivating a network of reliable informants. The study also represents a critical step in helping these urgently needed conservation assessments to become common place in the fight to save flagship species.

Key-words: conservation evidence, illegal wildlife trade, informant network, large carnivore conservation, law enforcement, occupancy, snare trap, sumatran tiger

Introduction

Unregulated and unsustainable killing of wildlife has pushed many of the world's most charismatic and lavishly funded species to the edge of extinction (Bennett 2011). Indeed, the term 'empty forest' was coined to indicate seemingly intact forests that had lost large-bodied mammals from their resident fauna (Redford 1992; Harrison 2011). To prevent further losses, it is crucial to understand the effectiveness of interventions that aim to stop such killings,

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and adapt them if necessary (Balmford 2012). Nevertheless, rigorous quantitative assessments of the impact of conservation interventions are rare, even though in many cases the target species continue to decline and protected areas fail (Ferraro & Pattanayak 2006; Laurance *et al.* 2012).

Law enforcement patrolling guided by reports from local informants underpins the management strategies of many protected areas. Understanding the ability of these strategies to influence patterns of illegal activity over space and time is therefore of fundamental importance to conservation managers, policymakers and donors. However, law enforcement programmes are often implemented by conservation practitioners who prioritize field-based actions over quantitative analyses of operational outcomes. Furthermore, even where evaluations of the effectiveness of law enforcement patrol performance have been undertaken (Leader-Williams, Albon & Berry 1990; Jachmann & Billiouw 1997), they have been unable to control for unequal detection probabilities between patrol areas and the possible influence of confounding factors, such as accessibility, on poaching patterns (Wibisono *et al.* 2011). Studies on species distribution modelling demonstrate how accounting for imperfect detections leads to significantly different management decisions being made (Lahoz-Monfort, Guillera-Arroita & Wintle 2014; Hayward *et al.* 2015).

These same limitations are also highly relevant for tiger conservation. Over the past decade, more than US$20 million has been directly invested into tiger law enforcement activities (Gratwicke *et al.* 2007), mainly to support forest ranger patrols. A further US$190 million has been pledged to support frontline law enforcement activities for the implementation of the Global Tiger Recovery Plan that aims to double the number of wild tigers by 2022 (Global Tiger Initiative Secretariat, 2013). Yet, to date, no rigorous assessment of the effectiveness of law enforcement interventions in conserving tigers has been conducted. This is critical to prevent the implementation of well-intended but ineffective strategies and ongoing losses of tigers. Complementary standardized statistical sampling techniques to enable on-site and comparative range-wide analyses have yet to be developed, to mirror the significant advances made in the science of monitoring tigers (Karanth & Nichols 1998; Karanth *et al.* 2011; Wibisono *et al.* 2011).

In this study, we analyse a decade of law enforcement patrol data within a robust capture–mark–recapture statistical framework to assess the effectiveness of law enforcement interventions in one of Asia's largest tiger landscapes (Dinerstein *et al.* 2007). Firstly, we assess the influence of different types of law enforcement intervention on reducing the occurrence of snare traps set for tigers and their prey; secondly, we examine whether local informant reports significantly influence the success of forest ranger patrols in detecting snare traps. In both analyses, we control for the influence of varying detection probabilities, as well as accessibility and other possible determinants of illegal hunting. Finally, we investigate the spatiotemporal population trends of the prey base of tigers, comprising sambar, muntjac and wild boar.

Materials and methods

STUDY AREA

The 13 800-km^2 Kerinci Seblat National Park spans the Indonesian provinces of West Sumatra, Jambi, Bengkulu and South Sumatra. Its forests and wildlife are managed by a single agency under the Ministry of Forestry. The elongated shape of, and the enclave within, Kerinci Seblat creates a long permeable edge that is predominantly bordered by lower elevation smallholder farms. Its interior runs along the backbone of the Sumatra-long Barisan mountain chain that is rugged, remote and should therefore be less vulnerable to poaching than its edges. The National Park is recognized as a UNESCO World Heritage Site for its rich biodiversity and a global priority for the long-term survival of wild tigers (Dinerstein *et al.* 2007). Indeed, field surveys conducted in 2009 found that 83% of Kerinci Seblat and its surrounding forests were still occupied by tigers (Wibisono *et al.* 2011).

To protect tigers and their principal prey, the National Park authority and the international NGO Fauna & Flora International (FFI) established two Tiger Protection and Conservation Units, hereafter referred to as 'patrol teams', in 2000. The number of patrol teams increased to six by 2005, each with its own distinct area of operation. One team was discontinued in 2006 due to resource limitations. The mandate of the five operational patrol teams remains to secure the population of wild tigers inside the National Park and its adjacent forests through reducing the threats from poaching, domestic trade and conflicts with forest-edge communities. Strategic guidance and liaison with the park's neighbours is provided by FFI, whereas operational field command is provided by National Park staff who are assigned to the teams and work in partnership with community members, who are recognized as honorary park officers. This means that ranger units have full powers of arrest in remote situations where it is not possible for a third party, such as the police, to respond in a timely manner.

MEASURING PATROL TEAM EFFORT

Field data were compiled using information recorded in ranger patrol logbooks and ranger data sheets collected by two teams covering two districts in 2000 and up to five teams covering eight districts in 2010. Two main types of field patrols were conducted by the teams. Routine foot patrols were carried out most frequently. These typically focussed on covering entry points and interior forest routes where people were most likely to hunt wildlife. However, routes were alternated to avoid patrol patterns becoming too predictable for poachers. Given the dense forest understorey in Kerinci Seblat, these routes are located on the ridges and forest trails that are used by tigers and their prey (Linkie *et al.* 2006, 2008). On patrol, a team of four rangers would record its route using a GPS unit and compass on a paper topographic map. Key signs of encounters were also recorded in logbooks and might include indications of snaring or other forms of poaching, whether for mammals or birds, as were the presence of threats to habitats, such as illegal logging. Tiger signs tended only to be recorded upon first encounter along each trail, thereby precluding their use for biological monitoring in this study. Any forest camps that were found were intimately checked to assess their purpose. Two types of snare trap type were recognized and these were primarily differentiated by the construction of the snare anchor, its strength and the material used. Heavy duty, flexible nylon or metal cable indicated a snare trap set for a tiger, whereas a nylon rope was set for a deer.

The second patrol type is intelligence based and was triggered by reports from local informants operating as part of a network spanning most of the National Park border. The network is primarily managed by the community ranger members of the patrol team. Informants typically live in villages close to the forest edge and will contact their handler, the ranger with whom they are most familiar, when they either see or hear of a suspicious person entering the forest. There are approximately 30 'open' informants, comprising family and friends of the rangers, and another 30 'closed' informants, with whom the project staff are friendly but have not revealed their identity to the informant. These latter informants tend to be individuals who are known to associate with hunters and traders and are actively involved in lower grade hunting and forest resource extraction. Upon receiving a report, the patrol team will verify it with other field staff or field contacts and, if deemed valid, will rapidly mobilize and patrol in the approximate location. Informants who advise of a suspicious person entering the forest or those monitoring known or suspected poacher movements using sympathetic village informants will receive a small reward for their information, typically mobile phone credit or money for cigarettes. Further, unsolicited information advising of strangers entering the forest will not always receive a small tip-off fee so as to deter disingenuous reporting.

SPATIAL DATA BASE CONSTRUCTION

The sampling unit used for this study was a grid cell of $8{\cdot}5 \times 8{\cdot}5$ km, considered to be the average distance that a hunter or a patrol team might cover in a day. In total, there were 464 forested grid cells in and around Kerinci Seblat, of which 146 were patrolled by the teams from 2000 to 2010. Spatial covariates for accessibility that have been shown to influence hunting patterns from elsewhere in the tropics were extracted for each grid cell (Wibisono *et al.* 2011). These factors comprised the following: elevation, slope, proximity to nearest road, proximity to forest edge, proximity to nearest village and protected area status (Blom *et al.* 2005; Mockrin *et al.* 2011).

The topographic covariates of elevation and slope were obtained from the Shuttle Radar Topography Mission (Rabus *et al.* 2003) with elevation data at 90-m resolution, from which the slope layer was subsequently derived. Data on the roads and villages were obtained from the Indonesian National Coordination Agency for Surveys and Mapping for Sumatra and converted into individual distance coverage maps. Data on the forest edge and protected area boundary were obtained from the Kerinci Seblat National Park GIS data centre, from which was constructed a distance to forest edge layer and distance from the Kerinci Seblat National Park border to the exterior forest.

A preliminary analysis was performed to investigate whether collinearity existed amongst two or more of the independent continuous covariates. Several parameters were found to be highly correlated (Pearson's $r > 0{\cdot}50$, $P < 0{\cdot}05$), and a principal component analysis (PCA) was performed to create a single composite covariate for accessibility that explained 75·4% of the total variance. Loadings of the original variables on the principal component were −0·723 (distance to roads), −0·552 (distance to village), 0·708 (distance to forest edge) and −0·582 (distance to the national park boundary from outside). The final data set consisted of three covariates (i.e. elevation 'Access 1', slope 'Access 2' and the PCA composite 'Access 3'). These were standardized using a z-transformation and then reassessed for collinearity, of which Access 3 was not found to be strongly correlated (Pearson's $r < 0{\cdot}45$ amongst all pairs, $P > 0{\cdot}05$), whereas Access 1 and Access 2 were but only analysed separately within the subsequent analyses. The mean value of the three accessibility covariates was extracted for each grid cell.

Spatial information on law enforcement patrol effort was compiled from all field patrol sheets completed from 2000 to 2010. A patrol sheet consisted of a 1 : 50 000 topographic map that a team used to mark its forest patrol route using a GPS and compass. The hard copy maps were scanned and then georeferenced to match the datum for that area (WGS1984 and either UTM-47s or UTM-48s) using ArcGIS v9·2 software (ESRI Inc., Redlands, CA). These data were corrected for topographic variations by overlaying digitized patrol routes on a digital elevation model, from which the three-dimensional distance travelled for each grid cell was extracted.

To assess the influence of law enforcement patrols on the location of snare traps, four management intervention covariates were constructed at the neighbourhood scale for each site. This covered the focal grid cell ($8{\cdot}5 \times 8{\cdot}5$ km) and then up to eight adjacent cells, if they were also patrolled and contained forest habitat (collectively defined as the sampling unit), because patrols in a single cell were likely to have a wider influence. Two types of intervention were measured over two time periods, comprising patrol frequency (number of times a sampling unit was visited by a team in the previous year and then the previous 2 years) and patrol effort (number of kilometres patrolled in a sampling unit in the previous year and then the previous 2 years).

For 2009 and 2010, information on whether a patrol was conducted based on an informant report ('tip-off') was compiled using a binary variable (routine patrol = 0 and informant-based patrol = 1) for each grid cell covered by that particular patrol. Prior to 2009, an unknown number of patrols were conducted based on informant reports, but this information could not be reconstructed either by the patrol teams or from their monthly patrol summary reports. Therefore, for all patrols conducted from 2000 to 2008, it was not possible to account for the influence of informant reports, which would have been expected to increase snare trap detection probability.

Camera-trap data collected from repeat surveys (2004–2006 and 2009–2011) in four study areas were used for the biological monitoring component of this study (Linkie *et al.* 2006, 2008; Wong, Leader-Williams & Linkie 2013). These studies deployed camera traps in a similar manner, with placements set on ridge and animal trails. To standardize sampling effort and minimize the likelihood of violating an assumption that the population was demographically closed over K sampling occasions (Otis *et al.* 1978), data from 90-day sampling periods were compiled for each study area and period. Photographic records of the principal prey species of Sumatran tigers, comprising sambar, muntjac and wild boar, were aggregated to create a single prey base data set. Data were aggregated because the snare traps are indiscriminate towards species, and the main point of interest was the overall prey population. To measure occupancy, data from a camera trap (the sampling unit) spaced at least 4 km from its nearest neighbour were used, with camera traps randomly removed if closer. The size of the sampling unit was based on the putative home range size of an individual prey species. Next, the site covariates of elevation and nearest distance to roads, logging roads, settlements, rivers and forest edge from the interior were obtained from the same sources as the ranger patrol analyses. All continuous data were logarithmically transformed.

STATISTICAL ANALYSES

The statistical analysis was based on the logic that the conservation intervention of law enforcement patrols could influence the amount of illegal activity through removing snare traps, which in turn could influence the status of tiger prey and ultimately of tigers. However, poachers were very rarely encountered in person by a patrol team. Therefore, the effectiveness of law enforcement patrolling was assessed using an occupancy framework that accounts for imperfect detections (MacKenzie *et al.* 2002). This framework modelled deterrence rather than the immediate act of patrol staff removing snare traps. It is based on the rationale that the continuous presence of patrol teams could increase the opportunity costs of poaching by reducing the success of snare traps, through their ongoing removal. In turn, this could increase the chance of a poacher being caught, or their perception of the likelihood of being caught, as the poachers would know that patrol teams were present based on finding that their snare traps had been removed.

To generate detection histories, each patrol route within its unique grid cell was divided into 1-km segments (spatial sampling occasions). Snare trap detection (1) or non-detection (0) was then determined for each occasion. Given the spatial dependence in detecting snares along consecutive occasions, a first-order Markov process model was used to estimate the probability of snare trap occurrence ($\hat{\Psi}_{\text{snare}}$; Hines *et al.* 2010). This formulation explicitly decomposes the detection process by estimating two segment-level occupancy parameters ($\hat{\theta}$ and $\hat{\theta}'$) and the probability of detecting snares ($\hat{p}_t$) conditional on segment-level occupancy.

Analyses were individually performed for each patrol year under the single-season formulation of the Hines *et al.* (2010) model using program PRESENCE v4·7. For each annual data set, a two-step modelling approach was used. Initially, the probability of detecting a snare trap, where $\hat{p}_t$ (was either assumed to be constant or allowed to vary with individual or additively combined covariates, was modelled. To minimize unmodelled sources of heterogeneity in $\hat{p}_t$ (by patrol teams from 2000 to 2008, the effects of forest accessibility (using Access 1, Access 2 and Access 3 covariates) was modelled. For 2009 and 2010, the influence of intelligence-based patrolling was analysed in addition to the three accessibility covariates, by introducing the 'tip-off' covariate. Following the recommendations of MacKenzie *et al.* (2006), $\hat{\Psi}_{\text{snare}}$was held in a general form for each $\hat{p}_t$model. Candidate models were compared using Akaike's Information Criterion (AIC; Burnham & Anderson 2002).

Upon incorporating covariates influencing detection probability with Akaike weight (w_i) >90%, the influence of spatial covariates on occupancy in the second step of the analysis was modelled. As the study specifically aimed to examine the effects of historical law enforcement investment (either patrol_frq or patrol_km over a 1 or 2 year preceding period) on the probability of snare trap occurrence, it was necessary to first control for the possible influence of confounding effects from accessibility. In all models, segment-level occupancy parameters ($\hat{\theta}$ and $\hat{\theta}'$) were modelled without the influence of covariates. The relative strength of associations of covariates on the $\hat{\Psi}_{\text{snare}}$ and $\hat{p}_t$ was assessed by basing interpretations on the summed Akaike weights across all models for each year. In addition, model-averaged estimates of parameters were computed by considering all of the candidate occupancy models.

Next, prey base occupancy was estimated for all survey periods and sites using a likelihood-based method (MacKenzie *et al.* 2002). From field surveys, the detection (1) or non-detection (0) sequence of tiger prey base over six consecutive 15-day sampling occasions per study area was recorded and used to construct a detection history. Detection histories were produced for each of the four study areas and entered into PRESENCE. Single-species, single-season analyses were run for the data sets collected from 2004 to 2006 and 2009 to 2011 to compare occupancy estimates between the two periods. Occupancy and detection probability were modelled first as if constant across sites and samples, $\psi(.)$ $p(.)$, and second as functions of the covariates, either individually or for two non-collinear covariates. Candidate models were ranked based on their delta second-order information criterion (ΔAIC_c) values, adjusted for small sample sizes, and their Akaike weights (Burnham & Anderson 2002). The top-ranked model from each study area for each sampling occasion was used for calculating prey base occupancy. To investigate whether there was a significant change in prey base occupancy between the two survey periods for the individual study areas, non-overlap of 95% confidence intervals were first used. A Wald test was then performed to provide an independent and robust measure of change, with the $P < 0{\cdot}05$ considered to be significant (i.e. $Z > 1{\cdot}96$).

Results

From 2000 to 2010, the patrol teams conducted 642 forest patrols and covered a combined distance of 8885 km. These teams removed 122 snare traps set specifically for tiger and 4311 traps set for its ungulate prey. The overall trend in snare trap occurrence in the study area revealed a non-significant decline of 24% from 2000 to 2010 (Fig. 1). However, this preliminary analysis did not control for the possible spatial effect created from establishing new teams in previously unprotected forest patches with unmitigated poaching pressures. Conducting new patrols in these under threat areas would likely have contributed to increasing the overall poaching result for the entire study area, thereby confirming the importance of measuring local level (individual patrol team) area effects through the subsequent spatiotemporal analyses.

The factors influencing snare trap detectability for the different patrol teams varied considerably across years, but illustrated the importance of controlling for the effects of unequal detection probabilities and confounding variables, as well as highlighting the limitations associated with the use of relative abundance indices that do not (Fig. 2, Table 1 & Table S1 in Supporting Information). Overall, more snare traps were recovered in sites that were located at a lower elevation (Access 1), on flatter terrain

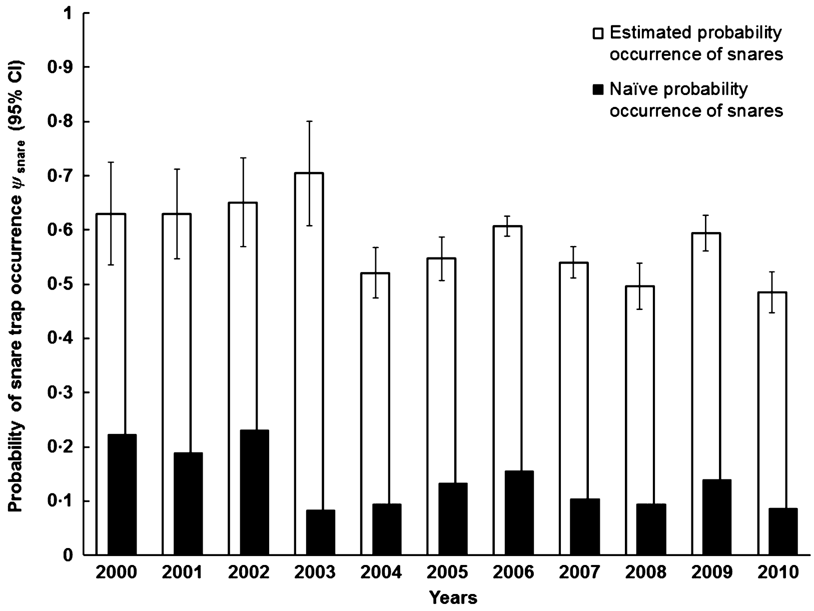

Fig. 1. Naïve and model-averaged probability of snare trap occurrence ($\hat{\Psi}$) from 2000 to 2010. [Correction added on 8 July 2015 after first online publication: Fig. 1 and text citation updated.]

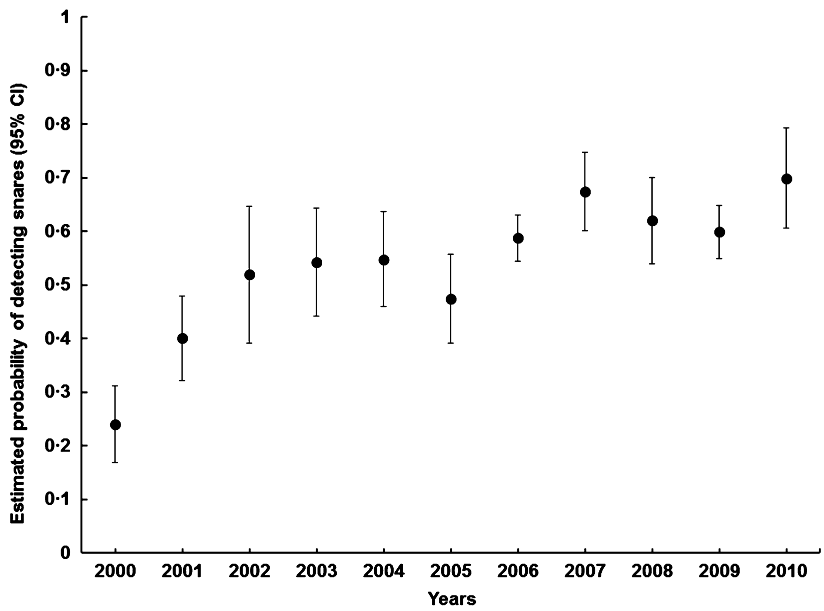

Fig. 2. Estimated probability of snare detection ($\hat{p}$) from 2000 to 2010. [Correction added on 8 July 2015 after first online publication: Fig. 2 and text citation updated.]

(Access 2) and/or generally more accessible to the patrol teams and poachers (Access 3; Tables 1 & S1).

The patrol teams appeared to gain experience in detecting snares as shown by the average annual increases in detection probability from 0·24 ± 0·08 [$\hat{p}$ (±SE)] in 2000 to 0·58 ± 0·05 in 2006, after which these probabilities plateaued at 0·59–0·70 (Table 2, Fig. 2). Informant tip-offs significantly increased patrol effectiveness (Table 1, Fig. 3). Compared with routine foot patrols conducted in 2009 (n = 166) and 2010 (n = 117), intelligence-based patrols had detection probabilities that were 48% higher in 2009 (n = 96) and 41% higher (n = 40) in 2010 (Fig. 3). The spatiotemporal analysis confirmed the importance of accounting for accessibility when evaluating patrol team performance. Across all years, forest with greater accessibility to poachers had higher snare occurrence (Table 1). Controlling for this influence enabled the law enforcement parameter to be explicitly modelled.

Differences in the four law enforcement scenarios suggested a shift in the impact of patrol strategies over time, measured as the reduction in snare trap occurrence in the succeeding years (Table 1). From 2000 to 2003, increasing law enforcement effort through the number of kilometres walked (or area covered within a sampling unit) was predicted to have the greatest impact. From 2004 to 2010, the patrol teams were well-established in the Kerinci Seblat landscape and allocating patrol effort to increasing detections in the forest, through increasing the number of visits to a sampling unit, was predicted to yield greater benefits (Table 1 & see Table S1). From 2000 to 2010,

Table 1. Relative strength of association of (a) accessibility covariates and different types of law enforcement intervention (frequency: fq, and kilometres walked: km) for one year (1 year) or two years (2 yr) preceding and their influence on the probability of snare trap occurrence ($\hat{\Psi}$) and (b) accessibility covariates and information from an informant network in influencing snare trap detection ($\hat{p}$) from 2000 to 2010

Year	(a) Influencing the probability snare trap occurrence*							(b) Influencing snare trap detection			
	Access1	Access2	Access3	km-1 year	km-2 year	fq-1 year	fq-2 year	Access 1	Access 2	Access 3	Tip-Off
2000	0·099	0·05	0·881	0·189	0·189	0·158	0·158	0·158	0·363	0·074	–
2001	0·032	0·957	0·967	0·239	0·233	0·142	0·138	0·155	0·453	0·642	–
2002	0·124	0·134	0·981	0·057	0·12	0·12	0·12	0·798	0·088	0·528	–
2003	0·96	0·024	0·945	0·029	0·022	0·032	0·798	0·038	0·45	0·789	–
2004	0·003	0·995	0·996	0·005	0·357	0·168	0·454	0·102	0·589	0·637	–
2005	0·977	0·017	0·011	0·095	0·116	0·062	0·634	0·69	0·195	0·701	–
2006	0·841	0·095	0·943	0·155	0·142	0·187	0·211	0·998	0·002	0·983	–
2007	0·861	0·135	0·864	0·145	0·099	0·194	0·106	0·281	0·186	0·564	–
2008	0	0·999	0·999	0·071	0·112	0·068	0·746	0·911	0·083	0·994	–
2009	0·011	0·006	0·998	0·088	0·031	0·823	0·019	0·938	0·038	0·344	0·257
2010	0·12	0·095	0·951	0·066	0·092	0·127	0·066	0·131	0·59	0·555	0·54

*Cells shaded in grey denote management interventions with the greatest relative strength of association on reducing snare trap occurrence.

Table 2. Model-averaged estimates of model parameters from law enforcement patrols from 2000 to 2010

Year	Description of patrols				Model-averaged parameter estimates			
	Number of patrol teams	Overall patrol frequency*	Overall patrol effort†	Naïve occupancy	$\hat{\Psi}$ (SE)	$\hat{\theta}$ (SE)	$\hat{\theta}'$ (SE)	$\hat{p}$ (SE)
2000	2	25	179	0·222	0·631 (0·10)	0·159 (0·048)	0·557 (0·279)	0·240 (0·08)
2001	2	43	555	0·188	0·630 (0·09)	0·155 (0·050)	0·796 (0·239)	0·401 (0·08)
2002	3	33	371	0·231	0·651 (0·09)	0·103 (0·056)	0·188 (0·076)	0·519 (0·13)
2003	3	37	562	0·083	0·705 (0·10)	0·092 (0·035)	0·745 (0·224)	0·543 (0·11)
2004	5	60	519	0·093	0·522 (0·05)	0·112 (0·066)	0·894 (0·447)	0·549 (0·09)
2005	6	63	902	0·132	0·548 (0·05)	0·03 (0·016)	0·720 (0·220)	0·475 (0·09)
2006	5	80	1712	0·155	0·607 (0·02)	0·213 (0·139)	0·491 (0·113)	0·588 (0·05)
2007	5	69	964	0·104	0·541 (0·03)	0·044 (0·030)	0·492 (0·266)	0·674 (0·08)
2008	5	70	1018	0·094	0·497 (0·05)	0·490 (0·157)	0·815 (0·461)	0·620 (0·09)
2009	5	81	1227	0·138	0·594 (0·04)	0·081 (0·053)	0·612 (0·141)	0·599 (0·05)
2010	5	81	876	0·085	0·486 (0·04)	0·054 (0·014)	0·761 (0·175)	0·700 (0·10)

*Number of patrols.
†Effort in km of walk.

law enforcement patrol frequency with a longer historical investment (i.e. 2 years) had the greatest impact, as judged by the respective AIC weight (w_i) summed over all years, where patrol frequency over 2 years (w_i = 0·314) >frequency over 1 year (0·189) >kilometres walked over 2 years (0·137) >kilometres walked over 1 year (0·104; Table 1).

From a combined 8190 trap nights in 2004–2006 and 7778 trap nights in 2009–2011, study area-specific occupancy values for the prey base population increased by 35·3% in RKE, 16·7% in Bungo, 15·0% in Sipurak and 36·8% in Ipuh. However, these trends were not significant because the 95% CIs between the two survey periods overlapped (Fig. 4, see Table S2). This was further supported by the Wald test (RKE, Z = 0·43, *P* = 0·71; Sipurak, Z = 0·99, *P* = 0·36; Bungo, Z = 0·85, *P* = 0·42; Ipuh, Z = 1·08, *P* = 0·34). The occupancy estimates for tiger prey species at each study area were not affected by spatial autocorrelation (Moran's *I* = 0·04, 0·05, 0·03, 0·03, respectively, *P* > 0·1).

Discussion

The recent loss of viable tiger populations from Vietnam, Cambodia and Laos due to the unyielding threat of poaching provides a sobering reminder of the present-day pressures facing tigers across their range (Thompson 2010; Gray *et al.* 2012). The Kerinci Seblat findings are therefore encouraging in this context. They provide information on the first rigorous assessment of a law

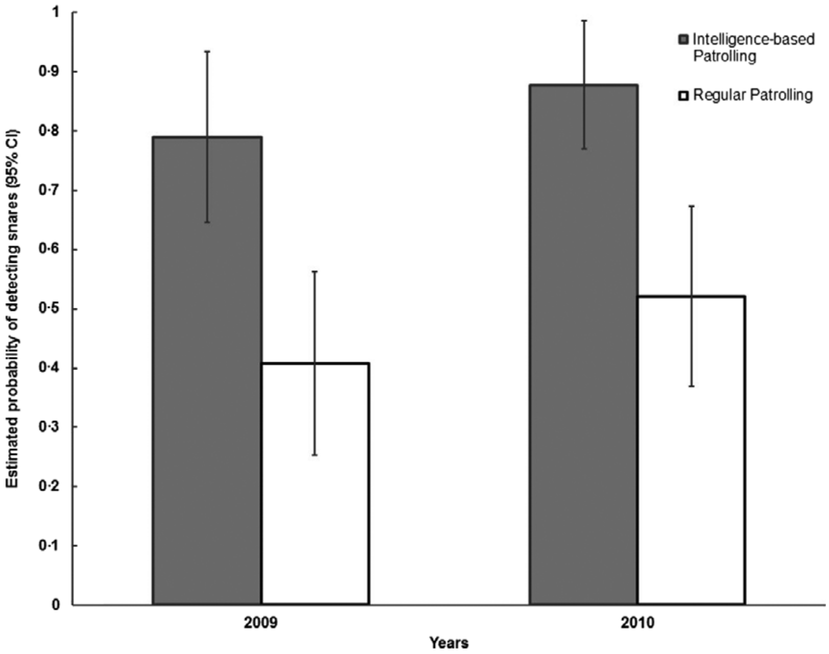

Fig. 3. Estimated probability of detecting snares ($\hat{p}$) under routine patrols and intelligence-based patrols.

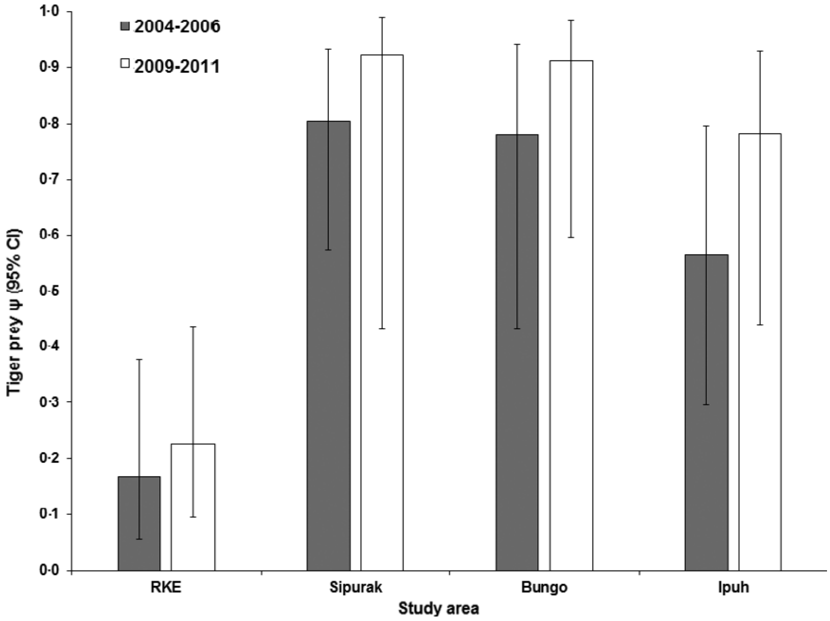

Fig. 4. Temporal change in tiger prey base occupancy ($\hat{\Psi}$) across the Kerinci Seblat landscape from four study areas conducted over a first (2004–2006) and a second (2009–2011) survey period.

enforcement intervention strategy explicitly aiming to mitigate poaching of tigers and their prey. Although poaching remained an omnipresent threat in the Kerinci Seblat landscape, the law enforcement strategy in place locally deterred illegal hunting in the sections targeted, thereby creating the enabling conditions for a stable prey base. Our study stresses the importance of expanding patrol coverage and augmenting this with a carefully cultivated and widespread informant network. The analytical techniques and sampling framework used in this study have wide application for evaluating wildlife law enforcement interventions elsewhere. However, the techniques we used are not without their limitations as discussed below, and future studies are still required to assist in their ongoing refinement and standardization.

The monitoring of law enforcement patrols requires a different approach to strictly standardized wildlife monitoring. For example, the latter requires strict adherence to a predefined sampling protocol to ensure, for example, that similar sampling effort is achieved in uniform-sized sampling units. The law enforcement data set constructed for our study was not originally designed for the regression-based analyses that were subsequently performed. We sought to overcome the associated limitations with a *post hoc* sampling design by reformatting records from patrol team field books so that three-dimensional annual detection and non-detection data sets could be constructed through aggregating multiple snare recoveries within 1-km segments (which became the sampling occasions). This then allowed for us to explicitly account for unequal detection probabilities and spatial non-independence in snare encounters along patrol routes.

Another limitation typical to most law enforcement strategies, including ours, is that the area of influence of patrol teams inside the forest is unknown. In addition, the arrest of tiger traders and poachers that occurred outside the forest during this study might also have exerted a deterrent effect across a wider – yet difficult to quantify – area, especially where the traders and poachers arrested are well known and have a wide sphere of influence. In the analysis, we sought to control for the first effect, by estimating historical law enforcement effort through the inclusion of neighbouring grid cells to patrol areas. Our prior field experience suggests that this may be sufficient given the size of the cells and that poaching teams setting snares only operate on foot, do not cover great distances and only have a localized impact.

The competing demands for limited budgets and the large size of the Kerinci Seblat landscape meant that the ranger patrol areas lacked complementary annual or biannual biological monitoring data. Using ranger team patrol data on species records would have introduced an uncontrollable bias associated with unmodelled detection probability because information on tiger and prey sign was not recorded consistently as was the case for the threats. Nevertheless, a tiger survey conducted in 2008–2009 revealed that tigers had wide coverage (83%) in the Kerinci Seblat landscape (Wibisono *et al*. 2011). Furthermore, our camera-trap data provided reassuring results of a stable prey base across four distinct study areas with wide spatial coverage across the national park. Future studies should plan to measure prey abundance or, better still, biomass metric, instead of occupancy, as this has been shown to be a reliable predictor of tiger density (Karanth *et al*. 2004). However, it was not possible to confidently monitor prey abundance from camera-trap records as individual animals lacking distinguishing marking could not be identified, thereby precluding a capture–recapture analysis, and distance sampling which typically relies on the direct sighting of individuals was not possible in the dense and rugged rain forest.

Future research to evaluate the performance of law enforcement strategies might investigate the applicability of zero-inflated models for analysing patrol team data sets; presence of a poaching displacement effect caused by increasing protection in adjacent areas; influence of different measures of law enforcement investment (such as individual patrol teams and team leaders); and benefits provided by informant networks, such as individual informant performance and the response time to act upon intelligence reports. This type of research should build on studies that have investigated conservation investment prioritization schemes, such as the trade-offs associated with allocating finite conservation funds between monitoring and managing threatened and difficult to detect species, such as tiger (McDonald-Madden *et al*. 2011; Chadès *et al*. 2008). A key outcome is that conservation science influences on the ground action (Rayan & Linkie 2015).

The introduction of SMART standards (http://www.smartconservationsoftware.org/) for law enforcement patrolling and the wide replication of the Tigers Forever protocol (Goodrich, Smith & Rabinowitz 2013) provide a new framework for establishing rigorous adaptive management systems in tiger landscapes. This involves the deployment of forest ranger teams, analysis of patrol data (including the changing patterns of threat, target species and patrol effort) and strategic planning for subsequent interventions based on these patterns. With this introduction, single-site or multiple site scientific assessments of project intervention performance should become common practice. While the Kerinci Seblat project did not conduct detailed statistical analyses of past poaching patterns as done in our study, team debriefings did discuss the current threat levels based on recent patrol information and these were used to identify subsequent patrol locations.

Despite the positive outcomes in our study, tigers and their prey continue to be poached in the Kerinci Seblat landscape. In 2013–2014, Kerinci Seblat experienced a spike in poaching, with the highest annual number of snare traps being removed for a patrol effort similar to previous years (D. Martyr, unpublished data). This follows part of a species and range-wide trend (Stoner & Pervushina 2013), and emphasizes the need to conduct frequent analyses to enable ongoing adaptive management of the situation. For Kerinci Seblat, this should include increasing the number of patrol teams to cover a wider area and strengthening actions to identify and arrest traders who are often based in cities far from the protected area but, nevertheless, form the local source of demand. Equally important will be maintaining a minimum level of routine law enforcement in the well-established patrol areas, to ensure that levels of deterrence do not drop and poachers return. From our models, the frequency rather than intensity of law enforcement patrols yielded greatest benefits in reducing future snare trap occurrence. This is consistent with findings from other studies that have identified poacher detection in the field as being important (Leader-Williams & Milner-Gulland 1993; Milner-Gulland & Leader-Williams 1992; Rowcliffe, de Merode & Cowlishaw 2004). Overall, these types of natural resource violations are predicted to decrease where there is a high probability that a rule breaker will be caught and then punished with a sufficiently high sentence (Karanth *et al*. 2011).

During our study period, 30 tiger poachers and traders (including district government, parliament and army personnel) were arrested with direct support from the teams. Of these, 90% were successfully prosecuted and sentenced to 3–36 months in prison, with an average sentence length of 13 months (D. Martyr unpublished data). To progress this, a milestone was achieved in the signing of a Memorandum of Understanding between four provincial police forces and the Kerinci Seblat National Park authority to improve intelligence reports for patrolling and evidence gathering for prosecutions. Still, the realities confronting conservation managers remain complex, demanding and typically depend upon strong national park leadership with an equally strong commitment to tackle threats, without fear of local reprisals (Linkie *et al.* 2014).

Priority tiger conservation landscapes and source sites have been identified for high-level conservation investment (Dinerstein *et al.* 2007; Walston *et al.* 2010). Many of these landscapes have long-established law enforcement systems in place, and evaluations of their performance are critical for collective efforts in advancing tiger conservation. Our study provides the first evidence on how a principal threat to tiger survival in forest landscapes is being tackled and offers wide benefits to other highly threatened flagship species, thereby enabling range states to not only meet their tiger commitments but also their wider biodiversity targets (CBD 2013, GTI).

Acknowledgements

We are grateful to the Indonesian Ministry of Forestry for assisting us in this project, especially the management and staff of Kerinci Seblat National Park; Ir Wandoyo, Ir. Listya, Ir. Soewartono, Ir Suyanto, Ir Luhut Sihombing and Ir Arief. The Kerinci Seblat law enforcement programme is indebted to the long-term support and commitment of the US Fish and Wildlife Service, Save the Tiger Fund, 21st Century Tiger, Dreamworld, Australia Zoo and Panthera. We thank Y. Dinata for help with prey data collection and J. Lahoz-Monfort and G. Guillera-Arroita for their earlier input on the study design. W-MW collected camera data while based at the University of Kent (2008–2011) and analysed these data in 2014 while working for Panthera, which began partially funding FFI's Kerinci Seblat project in 2012.

Data accessibility

The data in the present study have not been archived because they contain sensitive information about law enforcement patrols, informants and a protected species listed as endangered (EN) on the IUCN Red List.

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Received 4 February 2015; accepted 6 May 2015
Handling Editor: Matt Hayward

Supporting Information

Additional Supporting Information may be found in the online version of this article.

Table S1. Model averaged estimates of coefficients influencing the probability of snare trap occurrence and influencing the probability of snare trap detection from 2000 to 2010.

Table S2. Estimated tiger prey base occupancy and detection probability from the top-ranked models for four study areas from the Kerinci Seblat landscape for survey periods 2004–2006 and 2009–2011.