Identifying priority areas for the conservation of the Critically Endangered northern white-cheeked gibbon *Nomascus leucogenys* in northern Lao

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Abstract All gibbon species are declining throughout South and South-east Asia because of habitat loss and human activities such as hunting. Lao still contains a relatively large area of forest habitat suitable for gibbons, but their status in the country remains poorly known. Here we present the first density estimate of the Critically Endangered northern white-cheeked gibbon *Nomascus leucogenys* in Nam Et-Phou Louey National Protected Area, northern Lao. We conducted gibbon surveys using an auditory sampling technique during May–August 2014 and May 2015, at 40 sites, covering 125.6 km². We applied N-mixture models to analyse group counts, investigating which landscape and human disturbance covariates influenced the spatial variation of gibbon abundance across the study area. We estimated the average gibbon density to be 0.4 groups/km². Gibbon density was higher in mixed deciduous forest (0.74 groups/km²) than in evergreen forest (0.09 groups/km²), which could be a result of long-term hunting in evergreen forest areas. Thus, future gibbon protection plans should consider not only evergreen forest as priority habitat, but also deciduous forest, which tends to receive less attention in conservation planning. We also highlight key areas containing gibbons where law enforcement patrols should be focussed, to limit threats such as poaching. Future forest management plans should aim to maximize the size and connectivity of suitable gibbon habitat, to enable exchange between subpopulations.

Keywords Density estimation, Lao, Nam Et-Phou Louey National Protected Area, N-mixture model, *Nomascus leucogenys*, northern white-cheeked gibbon

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Introduction

South-east Asia's biodiversity is under serious threat because of habitat loss and degradation, and overexploitation of animal populations for bush meat and pet trade (Hughes, 2017). The region has one of the highest deforestation rates in the tropics (Stibig et al., 2014), and forest cover has declined by c. 11% since 1990 (Sodhi et al., 2004). The area is considered a biodiversity hotspot with numerous threatened and endemic species, where future land-use changes are expected to cause extinctions across a wide range of taxa (Sodhi et al., 2010).

The gibbons of the tropical forests of South-east Asia are important seed dispersers (McConkey, 1999) but their numbers are declining because of habitat loss and hunting (Geissmann, 2007). Of the 16 extant gibbon species and 12 subspecies, four species and four subspecies are categorized as Critically Endangered on the IUCN Red List, and 12 species and six subspecies as Endangered (IUCN, 2016). The northern white-cheeked gibbon *Nomascus leucogenys*, native to the forests of Lao, Viet Nam and southern China (Harding, 2012), is categorized as Critically Endangered because its populations may have declined by $>$ 80% since 1990; i.e. over the course of c. three gibbon generations (Bleisch et al., 2008). The species has been affected by deforestation caused by agricultural encroachment into montane areas, and by fuelwood and timber extraction from remaining forests, particularly in China and Viet Nam. In addition, it is hunted for food and traditional medicine (Geissmann et al., 2000). In China a small population in Xishuangbanna, southern Yunnan (Hu et al., 1989), may be on the edge of extinction (Fan & Huo, 2009), leaving the forests of Viet Nam and Lao as the species' major remaining habitats. In Viet Nam, gibbon habitat is particularly fragmented, with only small residual forest patches (Geissmann et al., 2000), and Pu Mat National Park is one of the few sites where the species has not been extirpated, with an estimated 130 groups remaining (Bach & Rawson, 2011).

The range of *N. leucogenys* in Lao stretches from the north-east (Phou Den Din and Nam Et-Phou Louey National Protected Areas) to the central region (Nam Kading National Protected Area; Duckworth, 2008; Hallam et al., 2015). The country still harbours a sizeable population of *N. leucogenys* because large areas of forest are difficult to access for humans and remain intact

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(Duckworth, 2008). Thus, Nam Et-Phou Louey National Protected Area represents the best opportunity for the long-term survival of this species. However, its status is poorly known; reliable national population estimates are not available because most remaining habitat patches have not yet been surveyed.

Reliable population estimates are important for determining threat levels and prioritizing conservation actions (Rawson, 2010). Understanding the relationship between gibbons and their habitats is essential for effective conservation planning (Hamard et al., 2010). As gibbons are strictly arboreal and mainly frugivorous, their abundance and density in a particular area have typically been associated with ecological characteristics that support feeding, vocalizing, sleeping and sheltering (Hamard et al., 2010). Many gibbon species inhabit primary tropical forests (Geissmann, 2007; Gray et al., 2014) containing a high density of flowering and fruiting food plants (Wich & Van Schaik, 2000). Although they are typically associated with evergreen forests, they can also be observed in deciduous and mosaic forest patches (Phoonjampa et al., 2011; Light, 2016). Gibbons tend to be sensitive to human presence, preferring undisturbed habitats with a continuous canopy of tall trees (Phoonjampa et al., 2011).

The aims of this study were to estimate the abundance and density of *N. leucogenys* and identify the variables influencing the species' spatial distribution in Nam Et-Phou Louey National Protected Area, Lao. Our findings will provide managers with the baseline data on gibbon status necessary for designing priority conservation areas and improving the management of suitable forests, ensuring that gibbon habitat stays intact and that connectivity is maintained, and will support more effective patrol planning.

Study area

The 5,950 km² Nam Et-Phou Louey National Protected Area of north-eastern Lao (Fig. 1) is one of the country's largest National Protected Areas. The 3,000 km² core area forms a totally protected zone in which access and harvest are prohibited. The remaining 2,950 km² are in a management zone in which sustainable harvest of specified animals and plants for local subsistence is permitted (Johnson et al., 2012). Altitude is 400–2,257 m, with > 60% of the area above 1,000 m and 91% on slopes of > 12% incline. The temperature ranges from < 5 °C (December–January) to 30 °C (May–June). Annual rainfall is 1,400–1,800 mm (Vieng Xai weather station data from 2003), with a rainy season (May–October), a cold dry season (November–January), and a hot dry season (February–April). The landscape of the Protected Area has a long history of human settlement, resulting in many patches of secondary forest, bamboo stands, and anthropogenic grasslands traditionally burned for hunting and cattle grazing (Johnson, 2012). The majority (72%) of the Protected Area is covered by mixed evergreen and deciduous forests up to 1,500 m, transitioning into evergreen forest at 1,500–1,800 m that is interspersed with Fagaceae (primarily *Castanopsis* and *Lithocarpus*) and *Rhododendron* species above 1,800 m (Davidson, 1999). These forested areas are embedded in a mosaic of old shifting cultivation fallow and bamboo groves (Johnson, 2012). Approximately 50 species of mammals and 290 species of birds have been recorded (Davidson, 1999).

Methods

Field survey

We used an auditory sampling survey to count the number of gibbon groups within a defined area, utilizing fixed radius point counts of gibbon vocalization. We focused on duets, the species' most distinctive vocalization, during which the bonded adult male and female sing simultaneously. We surveyed 34 sites during May–August 2014 and six sites in May 2015, totalling 157 days and covering 125.6 km². We set up listening points in 40 locations separated by at least 2,000 m, in four of the Protected Area's management sectors (Fig. 1), covering moist evergreen (18 sites) and mixed deciduous forest areas (22 sites). To maximize gibbon audio detection, we preselected listening points using a topographical map, placing them at high altitude on mountain ridges or tops, where the gibbons' calls can be heard from a greater distance. The field survey was conducted simultaneously by two teams working separately at different listening points, with each team consisting of a main observer and two or three assistants trained in gibbon survey techniques. At a given listening point, the team surveyed gibbons for four consecutive days, starting from c. 5.00 until c. 10.00, or until gibbons had ceased vocalizing for at least 30 min (Cheyne, 2008; Hamard et al., 2010; Coudrat et al., 2015). Gibbon duets can be heard from a distance of up to 2 km under favourable conditions (Brockelman & Srikosamatara, 1993). However, to avoid counting the same group multiple times simultaneously from different listening points, and to minimize errors in groups singing beyond the typically audible distance, only groups detected within a 1-km radius from the listening point (as determined by estimated distance and triangulation) were included for estimating abundance (Brockelman & Ali, 1987). Thus, we defined the area within a 1-km radius (3.14 km²) around each listening point as the effective listening area for calculating gibbon density (number of groups per km²). To count the number of groups on any day at each point, observers recorded all duets. We considered duet start and end times, as well as compass angles and distance between the observer and the calling gibbon, to determine the location of calling animals and thus avoid double counting. We regarded duets with different start and end times, and plotted at locations > 500 m apart, as different groups.

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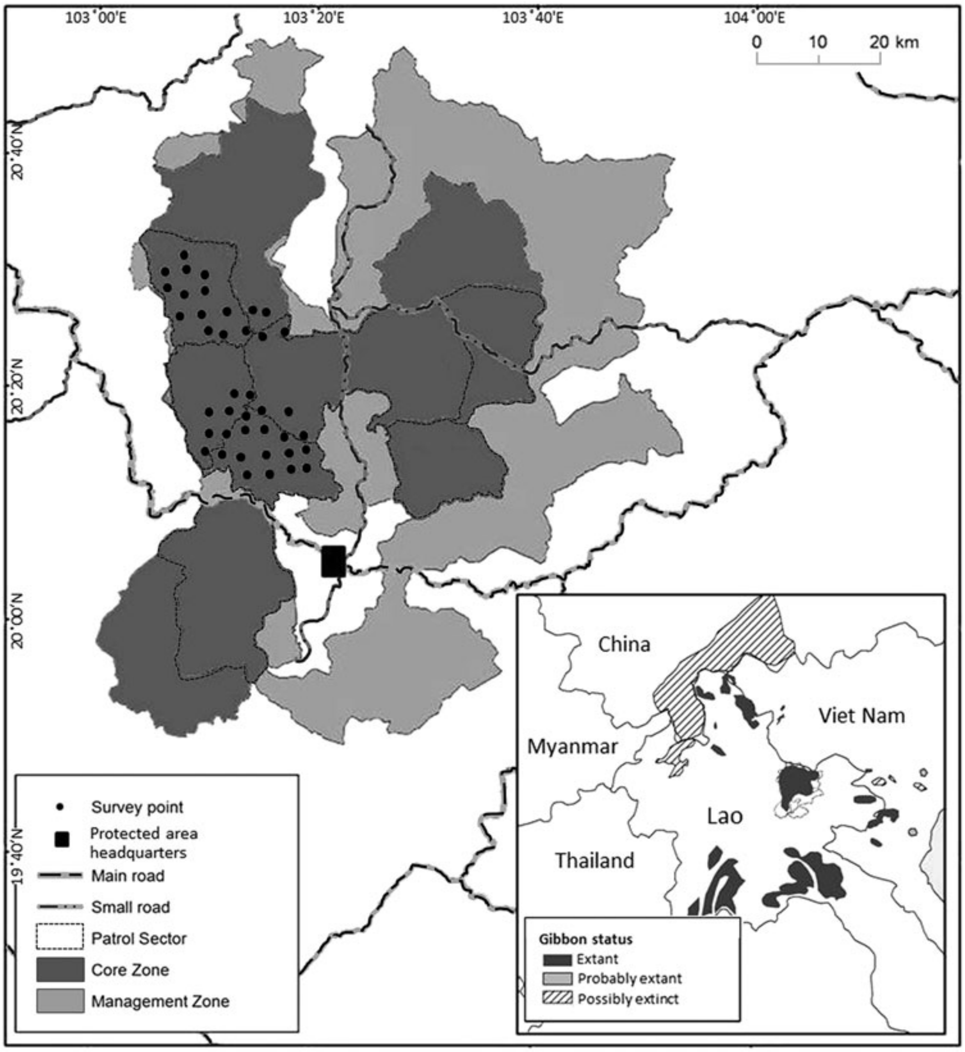

FIG. 1 Map of Nam Et-Phou Louey National Protected Area in Lao, showing gibbon survey sites on four management sectors (patrol sectors) and regional ranges of the northern white-cheeked gibbon *Nomascus leucogenys*.

Gibbons may not perform duets every day and their calling can be affected by factors such as weather conditions and season (Cheyne et al., 2008; Coudrat et al., 2015). We therefore recorded weather conditions (i.e. presence of direct sunlight, wind, cloud or fog) at the beginning of each survey to assess their possible influence on gibbon detection probability. Weather conditions were recorded as binary values (e.g. any presence of direct sunlight was coded as 1 and complete absence as 0).

We recorded five landscape and human disturbance variables as potential predictors of gibbon group abundance: area of mixed deciduous forest (%), altitude (m) measured at the centre of the sampled area, standard deviation of slope (ruggedness; Riley et al., 1999; Dawrueng et al., 2017), distance (m) from the centre of the sampled area to the boundary of the totally protected zone, and a hunting pressure index (Table 1). We selected these variables because gibbon distribution is associated with forest type (Geissmann et al., 2000), altitude and terrain ruggedness (Kim et al., 2011), distance to forest edge or road (Phoonjampa et al., 2011; Akers et al., 2013), and level of human disturbance (Phoonjampa et al., 2011). We obtained all variables from the databases of the Protected Area headquarters and the records of the Wildlife Conservation Society Lao Programme. We calculated

TABLE 1 Description of the site covariates collected and calculated within a 1-km radius around each survey site.

Covariate code	Description	Mean (range)
deciduous	Area of mixed deciduous forest (km)	2.23 (0.16–3.14)
elevation	Mean elevation (m)	1,369 (1,095–1,978)
slope	Standard deviation of slope (ruggedness) (°)	9.02 (6.95–11.51)
distance	Distance to the boundary of Totally Protected Zone (km)	4.68 (0.00–10.44)
hunting	Hunting pressure index (hunting signs per patrol effort)	0.04 (0.00–0.24)

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these five variables within the 1-km buffer radius of each listening point using *ArcGIS 10.1*.

Because the proportions of evergreen forest and mixed deciduous forest were highly correlated ($r = -0.97$), we selected only mixed deciduous for modelling as this forest type is present across the entire Protected Area (Fig. 3a). To estimate levels of illegal hunting in the area, we recorded the locations of signs such as direct sightings of poachers, camps and snares, with a GPS. Prior to 2014, ranger patrols were recorded using a database in which details were difficult to access. Ranger patrolling started to improve during 2014–2016, but effectiveness was still low. Since 2016, patrols have been conducted from eight ranger stations, with six rangers per station and each patrol lasting c. 18 days per month, resulting in a more systematic monitoring (see Eshoo et al., 2018 for details). To estimate patrolling effort, we recorded the geographical coordinates of patrol movements in the area and number of visits by rangers over the study period (2007–2015). We used the number of visits to represent patrolling effort, because patrolling distance was not recorded prior to 2014.

To determine hunting pressure we created a 1 × 1 km grid of the study area. For each 1 km^2 grid cell, we assigned a value for hunting evidence (number of observed signs of illegal hunting in the grid cell area) and patrolling effort (number of ranger visits to the grid cell from 2014 onwards). We then calculated the hunting pressure index by dividing hunting evidence by patrolling effort for each grid cell. At each survey site the effective listening area may cover multiple cells and therefore multiple hunting pressure index values; thus, we weighted the overall pressure index of one site by summing up the proportional hunting pressure value (i.e. the cell value multiplied by the proportion of the cell's area that fell inside the effective listening area; Fig. 3b).

Data analysis

We used an N-mixture model to estimate the abundance of gibbon groups from four replicate counts; i.e. four consecutive survey days at each listening point (Royle, 2004). This hierarchical method accounts for the imperfect detection of gibbon groups using auditory surveys through repeated counts (i.e. multiple visits to the same location). N-mixture models facilitate the investigation of the relationship between environmental variables and estimated abundance λ while accounting for detection probability p (Royle, 2004; Joseph et al., 2009; Fiske & Chandler, 2011). We conducted data analysis using function *pcount* in the *R* package *unmarked* (Fiske & Chandler, 2011; R Core Team, 2017). All landscape variables were standardized before fitting the models, and autocorrelated variables ($r > 0.7$) were not incorporated within the same model. We first determined which variables affected gibbon detection probability (sampling covariates) by fitting five models with different weather conditions and incorporating global covariates (Table 1) for abundance (Adams et al., 2010; Harihar & Pandav, 2012; Kamjing et al., 2017). We then used the weather variables of the best detection models together with an ecologically plausible combination of landscape and anthropogenic variables to predict gibbon abundance. We compared the fitted models using Akaike's information criterion (AIC) by considering a list of candidate models with $\Delta AIC < 2$ (Akaike, 1973). We assessed goodness-of-fit of the best fitted model based on Pearson χ^2 P-value by using the function *Nmix.gof.test* in the *R* package *AICcmodavg* with 1,000 simulations (Mazerolle, 2016).

We calculated mean density (groups/km^2) for the entire study area by using the mean abundance λ from the best model divided by the site effective listening area (3.14 km^2; Chandler et al., 2011; Dawrueng et al., 2017). To compare density estimates between the two forest types, we employed the *predict* function in the *R* package *unmarked* by using the maximum value of mixed deciduous forest (3.14 km^2) to predict density in the mixed deciduous forest, and the minimum value of mixed deciduous (0 km^2, i.e. evergreen forest) to estimate density in evergreen forest. We estimated total gibbon group abundance over the 40 sites by summing the estimated site-specific abundance along with uncertainty of confidence intervals, after 1,000 replicate bootstrap samplings (Chandler et al., 2011).

Results

During our survey we detected gibbon groups at 24 of 40 listening sites. Duet start times ranged from 05.14 to 09.22, with the majority of calls (71%) starting before 06.00, 16% between 06.00 and 07.00, 7% between 07.00 and 08.00, 4% between 08.00 and 09.00, and 2% after 09.00 (n = 128 calls). Mean call length was 11 min (range 2–30 min).

The best fitting detection model incorporated global abundance covariates and sun as a function of detection (λ(global)p(sun)), with a lowest AIC score of 213.93 and an Akaike weight of 0.63 (the second best fitting model had an AIC score of 216.99; Table 2). The best model, with $\beta = 1.08$, suggested that detection probability was positively related to sunny weather.

Amongst the landscape variables assessed, area of mixed deciduous forest had the strongest effect on the variability of gibbon group abundance (Fig. 2). Although three of the models had a $\Delta AIC < 2$, the model using *deciduous* only had more support than models with a higher number of variables. Because these variables did not provide any effect in addition to forest type, λ(deciduous)p(sun) was selected as the best fitted model, with abundance positively associated with area of mixed deciduous forest ($log(\lambda) = 0.23 + 0.56*deciduous$) and detection probability ($logit(p) = -1.63 + 1.03*sun$). The goodness-of-fit test lends credibility to the selected model with a Pearson χ^2 P of 0.55.

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TABLE 2 Model ranking by Akaike information criterion (AIC) for gibbon counts at Nam Et-Phou Louey National Protected Area, Lao, during May 2014–May 2015, showing model parameters, AIC, difference of AIC from best-performing model (ΔAIC) and Akaike weight.

Model	No. of parameters	AIC	ΔAIC	Akaike weight
λ *(deciduous) p(sun)*	4	209.65	0.00	0.29
λ *(deciduous+hunting) p(sun)*	5	210.37	0.72	0.20
λ *(deciduous+slope) p(sun)*	5	211.32	1.67	0.13
λ *(deciduous+distance) p(sun)*	5	211.33	1.69	0.13
λ *(deciduous+elevation) p(sun)*	5	211.59	1.95	0.11
λ *(hunting) p(sun)*	4	213.36	3.71	0.05
λ *(global) p(sun)*	8	213.93	4.28	0.03
λ *(slope) p(sun)*	4	214.77	5.12	0.02
λ *(distance) p(sun)*	4	215.35	5.70	0.02
λ *(elevation) p(sun)*	4	215.60	5.96	0.01
λ *(.) p(.)*	2	218.73	9.09	0.00

Gibbon group abundance varied across listening points, ranging from 0.15 to 3.60 groups per km². The mean abundance of gibbon groups per site (λ) estimated with the best model was 1.26 (95% CI 0.54–2.93), giving a density estimate of 0.4 groups/km² (95% CI 0.17–0.93) with a detection probability of 0.35 (95% CI 0.17–0.60) on sunny days. The density estimate was 0.74 groups/km² (95% CI 0.32–1.74) for mixed deciduous forest, and 0.09 groups/km² (95% CI 0.02–0.54) for evergreen forest. The estimated number of gibbon groups for the entire study area was 57 (95% CI 32–261).

On rare occasions we located additional gibbon groups outside the surveyed area, but no inference could be made about these groups from our dataset because the threat level was unknown, and could be relatively high (KS, pers. obs.). We also found solitary males both inside and outside the surveyed area; their presence could not be used for density estimate analyses.

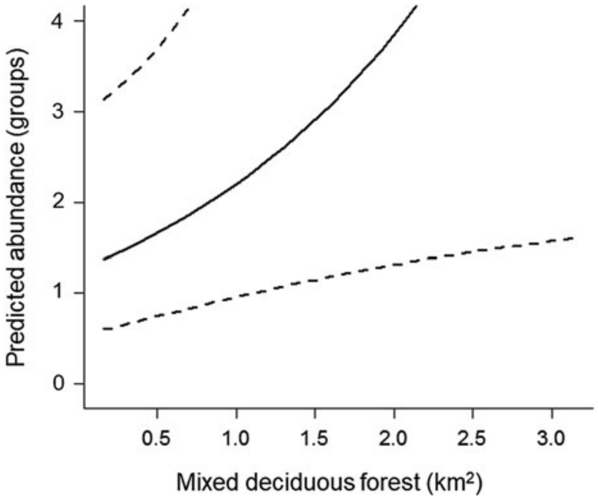

FIG. 2 Relationship between predicted gibbon abundance (solid line) and area of mixed deciduous forest in 1-km radius around the survey point. Dashed lines represent the 95% confidence interval.

Discussion

Our northern white-cheeked gibbon density estimates are low compared to other populations of the genus (Table 3). These low numbers may reflect a high level of human disturbance, at least over the last two decades, and are associated with the poor habitat quality across the range of the genus (Bleisch et al., 2008). A history of logging, followed by relatively dry conditions in secondary forest, has been associated with low gibbon food availability and low group density (Phoonjampa et al., 2011), because the animals need to maintain larger home ranges for securing sufficient food in dry habitats (Savini et al., 2008; Light, 2016).

The way density is calculated, particularly the choice of an effective listening area, is critical for accurate measurement. It is likely that the effective listening distance in the rugged terrain of Nam Et-Phou Louey National Protected Area varied between listening points. For example, Chanthalaphone (2013) used two independent effective listening distances in the same study site, yielding different density estimates. The degree to which this possibility has been accounted for in other published estimates from the region is inconsistent (Gilhooly et al., 2015). Despite this possible methodological bias, an undisturbed habitat should have a carrying capacity for most gibbon species of c. 4–5 groups/km² (Brockelman et al., 2009), which is much higher than our estimates for the northern white-cheeked gibbon.

According to the best model, gibbon abundance was positively related to the proportion of deciduous forest area, with gibbon groups being unexpectedly less numerous in evergreen forest. As gibbons are exclusively arboreal and mostly frugivorous (Geissmann et al., 2000), they are primarily found in mature forests with dense canopy cover, which is mostly associated with evergreen forests (Hamard et al., 2010). Thus, we presume that gibbons do not prefer mixed deciduous forest over evergreen forest but that there has been more intense poaching in the latter, because species

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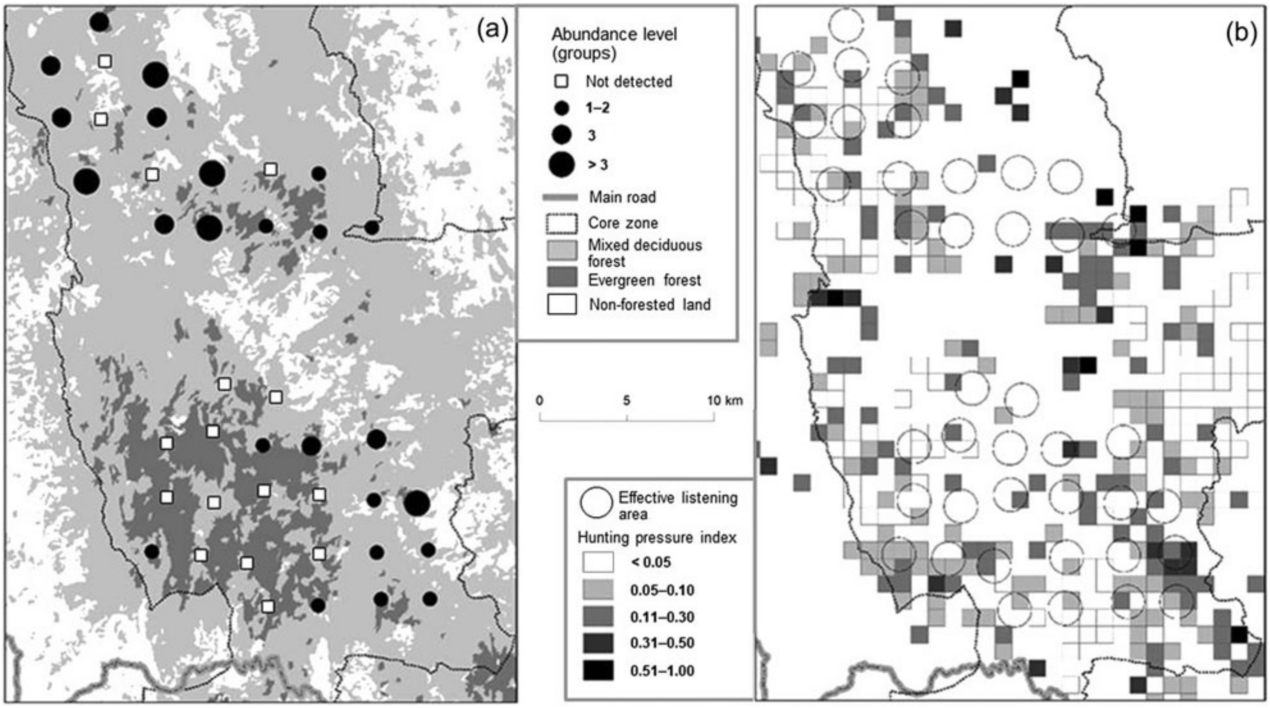

FIG. 3 (a) Abundance of gibbons across survey areas and (b) spatial distribution of forest types and hunting pressure (hunting signs per patrol effort, in 1 × 1 km grid cells) level at Nam Et-Phou Louy National Protected Area, Lao. Effective listening areas are defined as the area within a 1-km radius around each survey point.

typically targeted by poachers tend to occur there (KS, pers. obs. and pers. comm. with local residents). Recent work elsewhere in the region has found viable, breeding lar gibbon *Hylobates lar* groups in a mosaic of mixed deciduous and dry dipterocarp forest (Phiphatsuwannachai et al., 2017), demonstrating that gibbons can adapt to dry habitats with low fruit availability.

Most of the remaining large patches of evergreen forest are in the southern part of the study area, closer to the main road and human settlement, compared to the areas dominated by deciduous forest in the north (Fig. 3). Roads divide wildlife populations, restrict their movements (Laurance et al., 2014), and drastically increase hunting pressure by providing access to forested areas (Jackson, 2000). Accordingly, gibbons in Nam Kading National Protected Area, central Lao, were more abundant in areas away from roads and human settlements (Hallam et al., 2015). The long-term presence of a road through the southern part of Nam Et-Phou Louey National Protected Area suggests that this entire area has a history of persistent anthropogenic disturbance. Although gazetted as a protected area in 1993, ranger patrolling in Nam Et-Phou Louey National Protected Area only started in 2003, and full enforcement by systematic patrols (WCS Smart Patrolling Program) in 2006–2007. Full protection has been in place only since 2004, 10 years before the start of this study. A

TABLE 3 Comparison of *Nomascus* gibbon densities in various locations.

Location	Species	Group density (per km^2)	Method	Reference
Nam Et-Phou Louey, Lao	*Nomascus leucogenys*	0.40	N-mixture	This study
Nam Kading National Protected Area, Lao	*N. leucogenys* & *Nomascus siki*	0.21	Royle–Nichols	Hallam et al. (2015)
Nakai-Nam Thuen National Protected Area, Lao	*N. siki*	0.13	Triangulation	Chanthalaphone (2013)
Nakai-Nam Thuen National Protected Area, Lao	*N. siki*	2.68	N-mixture	Chanthalaphone (2013)
Pu Mat National Park, Viet Nam	*N. leucogenys*	0.16	Point count	Bach & Rawson (2011)
Phnom Prich, Cambodia	*Nomascus gabriellae*	0.12–0.19	Triangulation	Channa & Gray (2009)
Seima, Cambodia	*N. gabriellae*	0.71	Triangulation	Rawson et al. (2009)
Seima, Cambodia	*N. gabriellae*	0.73	Line transect	Rawson et al. (2009)

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decade is a brief period in the life history of gibbons. They reach sexual maturity, and thus dispersal age, at the age of 10 years (Reichard & Barelli, 2008) with males dispersing mostly into neighbouring groups (Matsudaira et al., 2018). Thus, as gibbon home ranges are relatively small (c. 25 ha; Bartlett et al., 2015) it is unlikely that suitable habitat is rapidly colonized. This probably makes gibbon populations slow to recolonize the entire Protected Area, which may take at least 20–30 years if there is no further disturbance (Caldecott & Miles, 2005). This slow population recovery could be the reason why we did not find a significant link between hunting pressure and distance to the core zone boundary, although hunting is widespread over the entire Protected Area (Fig. 3b).

Although apparently suboptimal, the large continuous areas of deciduous forest could be adequate for gibbon persistence, as indicated by Phiphatsuwannachai et al. (2017) for lar gibbons. These authors observed that deciduous trees in this forest type often carry flowers or fruit sufficient to support low density gibbon populations. Future studies should examine whether northern white-cheeked gibbons maintain larger home ranges in less productive habitats as observed elsewhere for lar gibbons (Savini et al., 2008; Phiphatsuwannachai et al., 2017). A study of *Nomascus gabriellae* in Seima Biodiversity Conservation Area, Cambodia, found no significant differences in group densities across evergreen, semi-evergreen and deciduous forest, supporting the view that gibbons are more flexible than previously thought with regard to habitat usage (Rawson et al., 2009). Such flexibility could support gibbon resilience in the face of moderate habitat degradation and thus, under appropriate circumstances, open the possibility of conserving other habitat types for gibbons.

Despite not covering the entire Protected Area, our findings confirm that Nam Et-Phou Louey National Protected Area holds a significant, albeit small, population of northern white-cheeked gibbons. The results are fundamental for understanding the regional status of this Critically Endangered species and for protecting its habitat. Although the population in the study area is widely dispersed, it tends to be more abundant in deciduous forest. This indicates that both evergreen and deciduous forests should be considered as priority habitat for protecting this species. We recommend that the gibbon population at the Protected Area should be surveyed every 5 years to investigate evidence for the species' recovery and monitor the effectiveness of the current protection plan. Moreover, sociodemographic changes in selected family groups should be monitored annually to estimate population viability in both evergreen and deciduous forests. A study determining whether the density of gibbon territories increases in evergreen forest habitat as a result of inward migration would be of value. Law enforcement patrols should continue in the key areas containing gibbons, to reduce threats. This should preserve the existing population, with particular attention to the northern part of the study area, where more groups live (Fig. 3a). A forest management plan is required to maximize quality habitat and ensure habitat connectivity. Finally, public awareness is also needed to ensure relevant stakeholders are involved in gibbon protection, and to contribute towards a more sustainable management of the Protected Area.

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Author contributions Study design: KS and TS; data collection: KS; data analysis: KS, DN, and TS; writing: all authors.

Conflict of interest None.

Ethical standards This research abided by the *Oryx* guidelines on ethical standards and was carried out in accordance with the laws of Lao PDR.

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