Jurnal Biologi Tropis

Original Research Paper

Predominantly Diurnal, Bimodal-Crepuscular Activity Patterns of Sun Bears (*Helarctos malayanus*) in Bukit Tiga Puluh National Park, Sumatera, Indonesia

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Article History
Received : July 15th, 2026
Revised : July 26th, 2026
Accepted : July 29th, 2026

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Abstract: The sun bear (*Helarctos malayanus*) is a vulnerable species listed on the IUCN Red List, whose behavioral ecology is critically shaped by habitat conditions. Increasing deforestation pressure in and around Bukit Tiga Puluh National Park (BTNP), Sumatra, highlights the urgency of understanding the spatiotemporal activity patterns of this species to support evidence-based conservation. This study analyzes the diel activity patterns of sun bears using secondary (bycatch) camera trap data collected by PKHS from 103 stations in BTNP between 2017 and 2022. From a total of 35,619 trap-days, 647 independent video detections were obtained. Kernel Density Estimation (KDE) analysis revealed a predominantly diurnal (62.44%) and strongly bimodal activity pattern. Activity peaks were recorded in the morning (06:00–09:00 WIB) and late afternoon (16:00–19:00 WIB), with a marked reduction during midday (11:00–14:00 WIB). This bimodal pattern indicates crepuscular characteristics, likely reflecting thermoregulatory adaptation and foraging strategies. The persistence of a strong diurnal signal suggests that BTNP continues to function as a relatively potential refuge from anthropogenic disturbance, although this inference is indirect, as human disturbance intensity was not measured directly. These findings provide a temporal basis for designing more effective anti-poaching patrol schedules and human–wildlife conflict mitigation strategies.

Keywords: Activity Pattern; Bukit Tiga Puluh National Park; Crepuscular; Camera Trap; *Helarctos malayanus*.

Introduction

Primary forest loss in Indonesia remains a major global conservation concern. Satellite-based land-cover monitoring has documented extensive deforestation across Sumatra driven by plantation expansion, extractive industries, and agricultural conversion (Margono et al., 2016). Within and around Bukit Tiga Puluh National Park (BTNP), Sumatra, mounting pressure on intact forest ecosystems threatens the long-term persistence of species dependent on closed-canopy habitat, including the sun bear (*Helarctos malayanus*). Within BTNP itself, encroachment for oil-palm and rubber cultivation, illegal logging, and road development along the park boundary have progressively fragmented lowland forest blocks, intensifying edge effects and human access into areas historically used by sun bears.

The sun bear is the smallest member of the family Ursidae and is formally classified as Vulnerable (VU) on the IUCN Red List, with population estimates indicating a decline exceeding 30% over three generations, primarily attributable to habitat loss and illegal hunting (Scotson et al., 2017). The species plays a functionally important role as a seed disperser and invertebrate regulator particularly of termites and wood-boring beetles in the lowland

rainforest ecosystems of Southeast Asia (Fredriksson et al., 2006; Steinmetz et al., 2011). Continued forest loss directly affects the availability of food resources and resting sites, with cascading consequences for activity budgets and population persistence. In Sumatran lowland forests specifically, sun bears disperse the seeds of numerous fleshy-fruited tree species through frugivory and, by excavating decaying wood and termite mounds in search of invertebrate prey, contribute to nutrient cycling and deadwood decomposition processes that shape forest regeneration dynamics.

Earlier research has documented variation in sun bear diel activity across different landscapes. Studies using bycatch camera trap data from Bukit Barisan Selatan National Park demonstrated that detection rates varied significantly with altitude and the degree of area protection (Sibarani et al., 2024). In landscapes subject to elevated human disturbance, sun bears have been reported to shift their activity towards nocturnal periods, an adaptive response documented globally across mammal taxa as a consequence of the 'landscape of fear' generated by human presence (Gaynor et al., 2018). Research in Tabin Wildlife Reserve, Sabah, further showed that habitat selection by sun bears was strongly mediated by proximity to forest edges and the intensity of anthropogenic disturbance (Tee et al., 2021).

Despite a growing body of literature on sun bear occupancy and habitat use in Sumatra, detailed analyses of diel activity patterns specifically within BTNP remain scarce. Prior mammal inventories in the Bukit Tiga Puluh landscape have focused primarily on species occurrence without providing fine-scale temporal resolution (Mossbrucker 2020). Accordingly, a knowledge gap persists regarding the daily rhythms of sun bears in BTNP, including the influence of microhabitat characteristics and human disturbance intensity on temporal activity variation. It is important to distinguish this temporal knowledge gap from the spatial questions of occupancy (whether a site is used at all) and habitat use (which environmental features are selected) addressed by prior studies; diel activity analysis instead asks when, within the 24-hour cycle, a site already known to be used is actually active, a dimension that spatial occupancy and habitat-selection models do not capture.

This study addresses that gap by analysing the diel activity patterns of sun bears at BTNP using a six-year (2017–2022) camera trap dataset accumulated by PKHS. Specifically, the study aims to: (1) quantify the proportion of diurnal versus nocturnal activity; (2) identify daily activity peaks using Kernel Density Estimation (KDE); and (3) discuss the conservation implications of the observed activity patterns for sun bear management in BTNP. A rigorous understanding of the species' daily rhythms is essential for designing effective anti-poaching patrol schedules, informing the delineation of core and buffer zones, and developing temporally targeted human–wildlife conflict mitigation programs. Based on evidence that human disturbance shifts mammalian activity toward nocturnality (Gaynor et al. 2018), we hypothesised that, if current anthropogenic pressure within BTNP remains comparatively low, sun bear activity would retain a predominantly diurnal signal rather than shifting toward nocturnal or strictly cathemeral patterns.

Materials and Methods

Study Site

Bukit Tiga Puluh National Park is located between 0°40'–1°25' S and 102°10'–102°50' E, covering a total area of 144,223 ha. Administratively, the park spans two provinces: Riau Province (Indragiri Hulu District, 81,223 ha; Indragiri Hilir District, 30,000 ha) and Jambi Province (Tanjung Jabung Barat District, 10,000 ha; Tebo District, 23,000 ha) (Balai Taman Nasional Bukit Tiga Puluh, 2007). The park was gazetted as a national park in 1995 and its boundaries were formally delimited in 2002 (Departemen Kehutanan, 2002). Camera stations were deployed across a mosaic of primary and selectively logged lowland dipterocarp forest, spanning an elevation range broadly comparable to that of the park as a whole (approximately 60–734 m a.s.l.), and included stations both within intact forest interior and in forest closer to park boundaries and access roads that show greater signs of anthropogenic degradation.

Bukit Tiga Puluh National Park represents one of the largest remaining lowland tropical rainforest blocks in central Sumatra, with elevations ranging from approximately 60 to 734 m a.s.l. The park harbours at least 198 bird species and 59 mammal species, including three globally threatened megafauna: the sumatran

tiger (*Panthera tigris sumatrae*), the sumatran orangutan (*Pongo abelii*), and the sumatran elephant (*Elephas maximus sumatranus*). The landscape also supports communities of the indigenous Talang Mamak and Melayu Tua peoples, whose livelihoods are closely tied to forest resources.

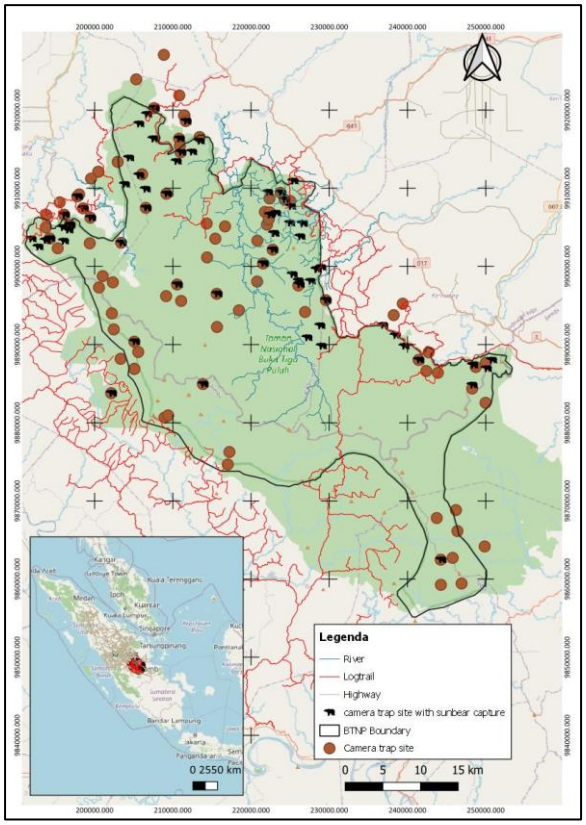


Figure 1. Map of Bukit Tiga Puluh National Park, Riau and Jambi provinces, Indonesia, showing the spatial distribution of PKHS camera trap stations deployed between 2017 and 2022

Survey Design and Camera Deployment

Camera trap data used in this study were secondary (bycatch) data derived from Sumatran tiger monitoring surveys conducted by PKHS within and adjacent to BTNP during 2017–2022. A total of 103 camera stations (various commercial models) were deployed across the landscape using a systematic grid approach. Individual cameras were positioned at locations expected to maximise wildlife detection probability including active wildlife trails, near fruiting trees, and in proximity to water sources following established wildlife monitoring protocols (Rovero & Marshall, 2009). Because station placement was optimised to maximise detection of Sumatran tigers rather than sun bears, this bycatch design may bias estimated activity patterns if tiger-favoured microsites (e.g., trails and ridgelines) differ systematically from locations most frequently used by sun bears; this potential placement bias is treated as a limitation of the present analysis and is revisited in the Discussion.

The number of active stations, and the specific stations sampled, varied among years (Table 1), reflecting the rotational deployment schedule of the underlying tiger-monitoring programme; individual stations were typically operated for two-to-three month intervals between servicing visits, and the same physical locations were not necessarily resurveyed in consecutive years, so year-to-year comparisons should be interpreted with this uneven and non-fixed sampling design in mind. This study was conducted using secondary (bycatch) camera trap data collected under the research and monitoring permits held by PKHS from the Bukit Tiga Puluh National Park Management Authority, and the data were made available for this analysis with PKHS's permission.

Each camera was mounted on a tree at a height of 40–50 cm above the ground and programmed to operate continuously for 24 hours. Cameras were configured to record a video clip whenever the passive infrared (PIR) motion sensor was triggered, with a minimum inter-trigger interval of one minute to limit multiple detections of the same individual. Batteries and memory cards were checked and replaced at approximately two-to-three month intervals. Video clips were recorded at a fixed duration of 10–15 seconds per trigger, with PIR sensitivity set to the manufacturer's default (medium) setting across units. Because the 103 stations comprised several commercial camera models, differences in PIR sensitivity and trigger speed among models cannot be fully ruled out as a source of detection heterogeneity; this is noted as a methodological caveat rather than a factor explicitly modelled in the present analysis.

Data Management and Classification

All video recordings were reviewed and identified to species level. Footage that was too blurred or otherwise inadequate for positive species identification was excluded from analysis. To avoid pseudoreplication, an "independent photographic event" was defined as a detection of a given species at the same camera station with an interval of more than 30 minutes from the preceding detection, following

conventions widely adopted in Southeast Asian camera trap studies (O'Brien et al., 2010; Rowcliffe et al., 2014). The timestamp (hour and minute) of each independent sun bear video event was extracted from the recording metadata for temporal activity analysis. The 30-minute threshold was adopted for consistency with regional camera trap conventions rather than derived from a formal sensitivity analysis on this dataset; because sun bears can linger at fruiting trees or feeding sites, this convention may occasionally split or merge bouts belonging to the same visit, and we treat the resulting event counts as indices of detection frequency rather than exact counts of individual visits.

Activity Pattern Analysis

Diel activity patterns of sun bears were analysed using circular nonparametric Kernel Density Estimation (KDE). This method is well-suited to camera trap data because it models the distribution of activity across the 24-hour cycle without imposing assumptions about the underlying distribution (Ridout & Linkie, 2009). Event timestamps were converted to radians to permit visualisation in circular coordinates. The KDE procedure yields a smoothed probability density curve representing the relative probability of activity at each time point throughout the day. Kernel bandwidth was selected using the default likelihood cross-validation procedure implemented in the fitact function of the activity package, rather than a fixed, user-specified value. All timestamps were recorded and analysed in local Western Indonesia Time (WIB, UTC+7); camera clocks were set to WIB at deployment and checked against a reference time at each servicing visit to limit clock drift.

Activity peaks were identified as local maxima on the density curve. Ninety-five per cent confidence intervals were estimated by bootstrap resampling (1,000 iterations). All statistical analyses were performed using the activity package in R version 4.4.0.0. Results are presented as circular plots and linear density graphs displaying the 24-hour activity distribution, with shaded areas representing 95% confidence intervals and grey bands indicating nocturnal periods.

Results and Discussion

Summary of Camera Trap Data

The 103 camera trap stations deployed across BTNP accumulated a total of 35,619 trap-days over the six-year survey period (2017–2022). Cameras recorded 20,926 independent events in total, comprising 12,758 wildlife events (60.97%) and 8,168 non-wildlife triggers (39.03%). Among wildlife detections, 647 events were identified as independent sun bear records, yielding a Relative Abundance Index (RAI) of 1.82 independent events per 100 trap-days. This value indicates that, for every 100 days a camera was active in the field, approximately 1.82 independent sun bear video events were recorded. Interpreted with caution, the RAI provides a cost-effective index for monitoring relative detection frequency, rather than a direct measure of population abundance, over time in cryptic species such as the sun bear (O'Brien et al., 2010).

Table 1. Summary of camera trap survey effort and sun bear (*Helarctos malayanus*) detections at Bukit Tiga Puluh National Park, Sumatra, Indonesia, 2017–2022

Variable	Survey Year						
	2017	2018	2019	2020	2021	2022	Total
Camera trap active days (trap-days)	621	12,229	17,510	1,824	2,421	1,014	35,619
Number of camera trap stations	6	38	55	3	9	7	103
Stations with sun bear detections	4	33	42	2	5	4	-
Total sun bear video detections	4	369	368	26	13	57	837
Independent sun bear video events	4	320	281	20	12	10	647
RAI (independent events per 100 trap-days)	0.64	2.62	1.61	1.10	0.50	0.99	1.82

The temporal distribution of survey effort and detections is summarised in Table 1. Survey effort was strongly uneven across years, with 2018 and 2019 alone contributing 29,739 of the 35,619 trap-days (83.5%) and the corresponding majority of independent sun bear detections; consequently, the pooled activity pattern reported below is necessarily weighted toward these two years, and year-specific RAI values (Table 1) are presented to allow this

imbalance to be assessed transparently. As RAI is a detection-rate index rather than a direct estimate of abundance or density, it is not interpreted here as a population trend without accounting for imperfect and possibly year-varying detection probability, which was not explicitly modelled in this bycatch dataset.

Diel Activity Distribution

Detection events were classified into two primary temporal categories: diurnal (daytime, 06:01–18:00 local time) and nocturnal (night-time, 18:01–06:00 local time), following the local civil clock; because BTNP lies close to the equator, sunrise and sunset times vary by less than approximately 30 minutes across the year, so this fixed threshold closely approximates a solar-time definition of day and night. Crepuscular activity was defined operationally as the intervals within two hours of nominal sunrise and sunset (approximately 05:00–08:00 and 16:00–19:00 local time), corresponding to the morning and afternoon peaks identified by the KDE analysis (Figure 3b). Of the 647 independent sun bear events, 404 (62.44%) were recorded during daylight hours, while 243 (37.56%) were recorded at night. These proportions demonstrate a clear predominance of diurnal activity relative to nocturnal activity in the study population.

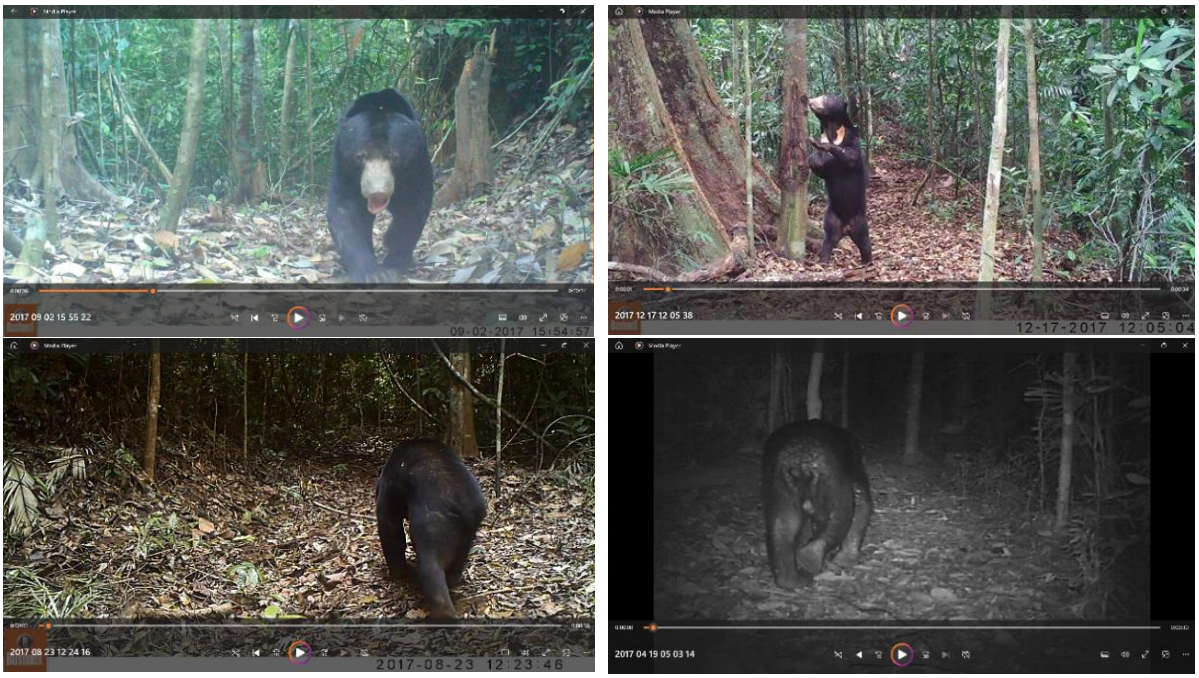
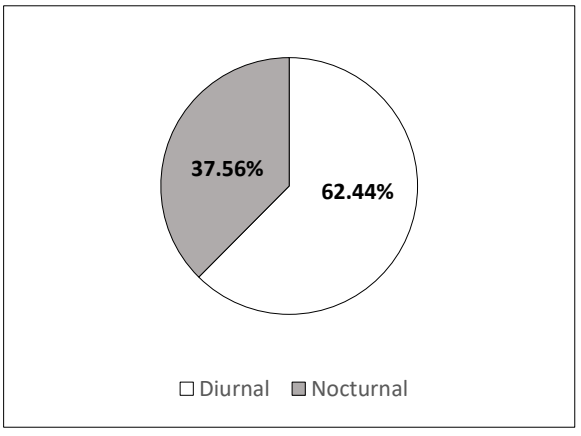


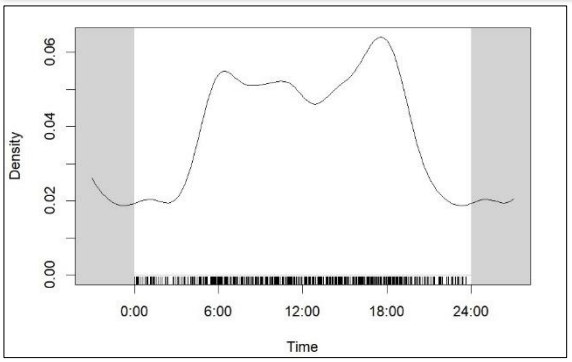
Figure 2. Representative camera trap video stills of sun bears (*Helarctos malayanus*) recorded at BTNP during 2017–2022, illustrating detections during both diurnal (a, b) and nocturnal (d, e) periods (Photo credit: PKHS, 2022)

Temporal Activity Pattern

Kernel Density Estimation visualised the diel activity pattern of sun bears at fine temporal resolution (Figure 3). The density curve revealed a distinctly bimodal distribution, indicative of strong crepuscular tendencies in the study population. The first activity peak (morning peak) was identified between 06:00 and 09:00 local time, with the highest density around 07:00. A second, prominent activity peak (afternoon peak) was recorded between 16:00 and 19:00, with a notable elevation immediately before and shortly after sunset.



(a)



(b)

Figure 3. (a) Proportion of sun bear activity during diurnal (62.44%) and nocturnal (37.56%) periods based on independent camera trap detections at BTNP, 2017–2022; (b) Diel activity pattern of sun bears estimated by Kernel Density Estimation (n = 647 independent events). The x-axis represents the 24-hour time cycle; the y-axis represents activity density; grey shading indicates nocturnal periods. Shaded bands around the density curve represent 95% bootstrapped confidence intervals.

Activity declined markedly during midday (11:00–14:00), representing the lowest detection frequency within the diurnal window. Within the nocturnal period, a secondary reduction was observed around midnight (01:00–04:00), likely corresponding to a putative rest period. Taken together, these patterns confirm a crepuscular signature superimposed on a broadly diurnal activity rhythm.

Discussion

This study provides detailed quantitative evidence of the diel activity patterns of sun bears in BTNP, revealing a predominantly diurnal regime with strong crepuscular characteristics. The observed bimodal activity, peaking in the morning and late afternoon and declining markedly at midday is consistent with thermoregulatory adaptation and foraging optimisation under equatorial conditions, and is further interpreted in the context of the relative anthropogenic disturbance regime within the study landscape.

The 62.44% diurnal activity proportion is consistent with earlier findings from relatively undisturbed forest landscapes. Radio-collar studies in lowland Sabah, Malaysia, established that sun bears are predominantly diurnal, with mean daily travel distances of 1.45 ± 0.24 km closely linked to fruit availability particularly Ficus spp. (Te Wong et al., 2004). Diurnal activity has historically been considered the species' baseline behavioural mode, allowing efficient exploitation of daytime fruiting events and social cues, and distinguishing the sun bear from many larger sympatric carnivores that show stronger nocturnal tendencies (Sunarto et al., 2015).

These findings stand in contrast to studies from landscapes with elevated anthropogenic pressure, where sun bears shift toward predominantly nocturnal schedules. This phenomenon aligns with the global meta-analysis of (Gaynor et al., 2018), which synthesised 76 studies spanning 62 species across six continents and demonstrated that mammals increase nocturnality by a factor of 1.36 on average in response to human disturbance, irrespective of continent, habitat type, or taxonomic group. Importantly, (Gaynor et al., 2018) cautioned that temporal shifts while facilitating coexistence with humans may carry long-term costs for individual fitness and population persistence. The retention of a strong diurnal signal in the BTNP population is consistent with, but does not on its own demonstrate, relatively low anthropogenic disturbance within the surveyed zone; because this study did not directly measure human activity, distance to roads or settlements, or poaching pressure at camera stations, the interpretation that BTNP currently functions as a favourable refuge should be regarded as a tentative hypothesis pending corroboration with explicit disturbance covariates, rather than an established conclusion.

The bimodal pattern, with peaks in the early morning (06:00–09:00) and late afternoon (16:00–19:00), is most parsimoniously explained by thermoregulation. Comparative studies of thermoregulation in sun bears indicate that the species' morphological traits including short pelage and a relatively small body mass interact with the high ambient temperatures and humidity characteristic of equatorial lowland rainforests to constrain the thermal comfort window for intense physical activity (Schneider, 2015). By curtailing locomotion during peak midday heat (11:00–14:00), sun bears likely reduce hyperthermia risk and conserve water balance, a pattern documented in other tropical mammals that exhibit bimodal crepuscular activity. The morning and late-afternoon peaks may additionally coincide with heightened foraging opportunities, as fallen and fermenting fruit accumulates overnight and invertebrate activity

intensifies during transitional light conditions. We emphasise that this thermoregulatory explanation remains a plausible working hypothesis rather than a directly tested mechanism, as the present study did not collect microhabitat temperature data, ambient temperature at the time of each detection, or species-specific thermal-tolerance measurements for BTNP; targeted microclimate monitoring alongside future camera surveys would allow this hypothesis to be tested more directly.

Foraging ecology reinforces the thermoregulatory interpretation. Sun bears in Borneo are highly frugivorous, with dietary studies documenting a strong reliance on Ficus spp. fruits and invertebrates such as termites and wood-boring beetle larvae (Wong et al., 2002). Morning activity peaks likely reflect opportunistic consumption of fruit that has fallen during the night, as well as exploitation of invertebrates whose activity increases with rising ambient temperatures. The afternoon peak may represent a final concentrated foraging effort before the overnight rest period, maximising daily energy acquisition. Such temporal partitioning of foraging effort is consistent with the findings of (Steinmetz et al., 2011), who documented niche partitioning between Asiatic black bears and sun bears in Thai mixed tropical forests partly structured by temporal resource use. We note that this foraging-based explanation is inferential: local data on fruiting phenology, seasonal food availability, or invertebrate abundance in BTNP were not collected as part of the present study, and the proposed link between activity peaks and food availability should be regarded as a hypothesis for future testing rather than a demonstrated causal mechanism.

The 37.56% nocturnal activity proportion confirms a degree of cathemeral flexibility in the BTNP sun bear population. This behavioural plasticity the capacity to be active across both temporal partitions represents an important adaptive trait that enables exploitation of resources whenever available and facilitates adjustment to dynamically changing ecological conditions. The cathemeral component may also reflect individual variation, reproductive state, or opportunistic responses to localised food pulses. Nocturnal activity has been noted as a potential indicator of heightened human avoidance in disturbed landscapes (Scotson et al., 2017), but its magnitude (37.56%) in the present study does not exceed what would be expected in a largely intact forest setting. However, in the absence of direct human-disturbance covariates, we do not conclude that this nocturnal component reflects an absence of stress; rather, we treat the 37.56% nocturnal proportion as evidence of behavioural plasticity whose relationship to disturbance remains to be tested directly.

The RAI of 1.82 independent events per 100 trap-days constitutes a quantitative baseline for long-term population monitoring of sun bears in BTNP. Although RAI does not yield absolute density estimates, it represents a cost-effective and widely applicable monitoring metric for cryptic species (O'Brien et al., 2010). Systematic tracking of RAI across annual survey cycles, in conjunction with the temporal activity patterns documented here,can serve as an early-warning indicator of detection-level responses to changes in hunting pressure, habitat quality, or management intervention.

Several limitations merit acknowledgement. The camera stations were positioned to optimise detection of Sumatran tigers, not sun bears; placement bias may therefore influence detection frequencies. Nevertheless, the broad spatial coverage (103 stations) and extended temporal scope (six years) provide sufficient statistical power to characterise the population-level activity pattern. Future research would benefit from integrating GPS-collar telemetry with the camera trap dataset to elucidate individual movement trajectories and home range dynamics, and from examining correlations between temporal activity and environmental covariates such as seasonal fruit availability and spatial variation in anthropogenic disturbance intensity. Additional limitations include the absence of quantitative human-disturbance covariates (e.g., distance to roads, villages, or documented poaching incidents), the lack of local fruiting-phenology or seasonal data to test foraging-based explanations directly, and the absence of a formal occupancy or detection-probability model, which means that RAI and derived activity proportions should be interpreted as detection-based indices rather than bias-corrected estimates of true abundance or activity.

Conclusions

This study demonstrates that sun bears in Bukit Tiga Puluh National Park exhibit a

predominantly diurnal activity pattern characterised by a strong bimodal, crepuscular rhythm. Activity peaks in the early morning (06:00–09:00) and late afternoon (16:00–19:00) are consistent with thermoregulatory avoidance of midday heat and temporally optimised foraging behaviour. The retention of a robust diurnal signal, despite documented cathemeral flexibility, may suggest that BTNP currently provides relatively favourable conditions for sun bears, with anthropogenic disturbance levels not yet sufficient to drive a complete shift toward nocturnality; this interpretation remains indirect in the absence of measured disturbance covariates and should be treated as a hypothesis for future confirmation.

The RAI of 1.82 detections per 100 trap-days and the detailed temporal activity profile reported here constitute a quantitative scientific basis for evidence-based conservation management. Specifically, these results can directly inform the scheduling of anti-poaching patrols to consider both peak sun bear activity periods and periods of elevated human-access risk, the spatial designation of core and buffer zones, and the development of temporally targeted human–wildlife conflict mitigation strategies, thereby contributing to the long-term conservation of the sun bear in Sumatra. We stress that patrol timing should be guided primarily by known or suspected poaching and human-access risk rather than by sun bear activity peaks alone, so that management interventions reduce threats to the species without inadvertently concentrating human presence in periods and locations of highest bear activity.

Acknowledgements

The authors extend sincere thanks to the Bukit Tiga Puluh National Park Management Authority for research permits and logistical support. We gratefully acknowledge the Foundation for Sumatran Tiger Conservation (PKHS) as the primary implementer of the monitoring project in BTNP, and for granting access to the secondary (bycatch) camera trap dataset that underpins this analysis. The monitoring project was supported by funding from Bioparc de Doué-la-Fontaine (France) and the Tropical Forest Conservation Action for Sumatra (TFCA-Sumatra). We also thank all field personnel, PKHS staff, and local communities surrounding the park for their cooperation and dedication

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