



COLLABORATIVE GOVERNANCE SUPPORTS BANTENG HABITAT RECOVERY IN THAILAND'S WORLD HERITAGE BUFFER ZONES

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ABSTRACT

Managing human–wildlife interactions in buffer zones is essential for megafauna conservation where conservation objectives overlap with local livelihoods. We evaluated management interventions in Thailand's Huai Kha Khaeng World Heritage landscape after livestock removal by comparing endangered banteng (*Bos javanicus*) responses under unregulated access (Year 1) and daytime-only access through registration (Year 2). Using operating cameras at 99 locations, we assessed banteng relative abundance, diel activity and habitat use in relation to human activity. Banteng activity shifted from primarily nocturnal in Year 1 to less nocturnal in Year 2, with wider distribution including areas with less canopy cover and better forage near the reservoir edge. Banteng activity peaked during the dry season when villagers were less likely to forage for mushrooms. Banteng activity was negatively associated with human activity and more likely further from the village. Despite daytime ranger patrols, villagers were less active at a distance from patrol routes and continued night activities during mushroom harvesting. These findings indicate that regulated access, community agreement and meaningful incentives can support behavioural recovery and habitat use by threatened wildlife. Collaborative governance, supported by community-based wildlife tourism, offers a pathway for balancing conservation, livelihoods and long-term stewardship in World Heritage buffer landscapes.

Key words: *Bos javanicus*; camera-trap surveys; relative abundance index; ranger patrols; human–wildlife coexistence; buffer-zone management

INTRODUCTION

Huai Kha Khaeng and Thung Yai Naresuan Wildlife Sanctuaries were inscribed on the UNESCO World Heritage List in 1991 (IUCN, 2025; UNESCO, 1991). The most recent IUCN Conservation Outlook Assessment describes the property as “good with some concerns”, recognising improvements in law enforcement while highlighting continuing risks from boundary pressures, potential development and renewed illegal offtake (IUCN, 2025). Safeguarding the property's Outstanding Universal Value (OUV) therefore depends not only on effective protection within the core zone, but also on how human access and ecological processes are governed across the wider buffer landscape (Martin & Piatti, 2008; UNESCO, 2023). In Huai Kha Khaeng Wildlife Sanctuary (HKK), these pressures are particularly evident along the periphery, where forest product collection and human–

wildlife conflict continue to challenge protected area management (IUCN, 2025).

The HKK buffer zone is a critical landscape for examining how management can balance conservation objectives with local livelihood use. Management effectiveness in such areas should be assessed not only through law enforcement, but also through the capacity of interventions to reduce disturbance, maintain ecological functions and support local participation. The mainland banteng (*Bos javanicus birmanicus*) is a useful indicator species for evaluating these outcomes (Jornburom et al., 2020; Phumsathan et al., 2024; Phumsathan, Pongpattananurak et al., 2022). Banteng populations have declined substantially across Southeast Asia due to habitat loss, agricultural expansion, poaching and human disturbance (Gardner et al., 2016; Gray et al., 2012), leaving the species critically endangered (Groenenberg &

Gray, 2025). HKK and its buffer landscape remain Thailand's primary banteng stronghold (Chaiyarat et al., 2024; Simcharoen et al., 2014). Although recent studies report positive trends for ungulates following strengthened patrolling within the sanctuary (Saisamorn et al., 2024), human pressures persist in the wider landscape (IUCN, 2025). Understanding how specific management interventions influence banteng behaviour and habitat use is therefore important for adaptive management and for demonstrating that OUV is supported beyond the protected core.

In the north-eastern buffer of HKK, non-timber forest product (NTFP) collection and livestock grazing have long been major sources of disturbance in large-herbivore habitats (Jornburom et al., 2020; Phumsathan et al., 2024; Phumsathan, Pongpattananurak et al., 2022). The Huai Thap Salao–Huai Kok Kwai National Forest (HTSHKK) experiences intense seasonal mushroom harvesting, mainly between May and November, alongside a history of livestock grazing (Phumsathan, Pongpattananurak et al., 2022). Livestock infrastructure, including pens, camps and trails, creates persistent localised disturbance that overlaps with open foraging habitats used by banteng (Chookaew et al., 2026; Phumsathan et al., 2024). Previous studies have therefore recommended regulating high-impact activities without eliminating livelihood access (Chookaew et al., 2026; Jornburom et al., 2020; Phumsathan, Daonurai et al., 2022; Phumsathan et al., 2024; Pongpattananurak, 2020). Unregulated access involving motor vehicles, multiple entry routes and day-and-night activity can increase noise, artificial lighting and human–wildlife encounters near critical resources. Such chronic disturbance may trigger avoidance behaviour, alter banteng habitat use and diel activity, and weaken the buffer's function as a seasonal refuge and movement corridor (Gaynor et al., 2018).

To address these challenges, a stepwise, community-supported management response was implemented in the Huai Thap Salao buffer. Following public engagement in 2020, villagers agreed to remove livestock and pens from HTSHKK and to support the Department of National Parks, Wildlife and Plant Conservation (DNP) in establishing a new non-hunting area. The long-term goal was to reduce high-impact extractive use and develop community-participatory wildlife tourism (Phumsathan et al., 2025; Phumsathan, Pongpattananurak et al., 2022; Pongpattananurak, 2020). The DNP subsequently designated the Huai Thap Salao–Huai Rabam Non-Hunting Area (HTSHR) under Thailand's Wildlife Preservation and Protection Act B.E. 2562 (Royal Gazette, 2019). HTSHR functions as an IUCN Category IV protected area where resource use is

actively regulated (Dudley, 2008). Management was phased: livestock grazing was prohibited in late 2020, leading to the removal of thousands of domestic animals and associated infrastructure (Chookaew et al., 2026; Phumsathan, Daonurai et al., 2022; Pongpattananurak, 2020). An initial DNP patrolling programme followed in 2021–2022, but was constrained by limited budgets and largely unregistered NTFP entry. By 2022–2023, increased funding supported more systematic patrol coverage and the introduction of a formal registration system that restricted forest resource collection to daytime hours.

This study evaluates the early effectiveness of this management transition by analysing banteng responses before and after management intensification in HTSHR. Using camera-trap data collected between March 2021 and April 2023, we: (1) examined whether banteng occurrence and diel activity shifted in response to human activity, including NTFP collectors, researchers and patrol operations; (2) quantified banteng relative abundance and habitat use across environmental covariates and seasons; and (3) compared spatial and temporal patterns between the pre- and post-intensification phases to assess whether standardised patrolling, NTFP registration and daytime-only access reduced disturbance at sensitive times and improved conditions for banteng to use buffer-zone habitats. The findings provide practical guidance for patrol timing and access regulation during peak NTFP periods, and offer early evidence of whether HTSHR is functioning as an effective buffer zone that supports participatory wildlife tourism, local livelihoods and the protection of OUV.

METHODS

Study area

This study was conducted in the HTSHR establishment area in Lan Sak District, Uthai Thani Province, western Thailand. The area adjoins the north-eastern boundary of Huai Kha Khaeng Wildlife Sanctuary and includes part of the Huai Thap Salao Reservoir (Figure 1). Field data were collected between March 2021 and April 2023, during a transitional phase in buffer-zone management. Key management interventions during this period included livestock removal, the removal of associated infrastructure, the initiation of ranger patrolling and the subsequent implementation of a formal registration system that restricted forest resource collection to daytime hours, from 6.00 am to 6.00 pm (Phumsathan, Pongpattananurak et al., 2022; Pongpattananurak, 2020). Additional details on the study area and management history are provided in the Supplementary Online Material.

Environmental and anthropogenic covariates

Environmental and accessibility covariates were extracted from the landscape raster database developed by Pongpattananurak (2020). These included vegetation structure, slope and distances to water, villages and patrol roads. Survey month represented seasonality. Variable definitions and data sources are detailed in the Supplementary Online Material under Methods and Table S1.

Data collection and statistical analysis

We monitored banteng and human activity using 99 continuously operating camera traps on a 500 × 500 m grid during Year 1 (March 2021–March 2022) and Year 2 (April 2022–April 2023). Camera deployment followed standard protocols (Chutipong et al., 2014; TEAM, 2008); detection criteria and human-activity classification are detailed in the Supplementary Online Material. Monthly relative abundance indices (RAIs) were calculated as independent detections per 100 trap nights (Azlan & Sharma, 2006; Kawanishi et al., 1999). Diel periods were daytime (6:00 am–6:00 pm) and night-time (6:00 pm–6:00 am). Overall and diel RAIs were compared between phases using Multi-Response Permutation Procedures (MRPP). Station-level RAI maps provided descriptive spatial context.

Generalised Linear Mixed Models (GLMMs) with a Tweedie distribution and log link evaluated banteng habitat use and villager intrusion. Banteng models included environmental, accessibility and anthropogenic covariates, survey month and a station random effect. Interactions among NTFP collection, research and ranger activity were evaluated to account for potentially interdependent associations with habitat use. Villager-intrusion models included distance to patrol roads and seasonal variables. Final banteng habitat-use models were selected through backward elimination using likelihood ratio tests ($\alpha = 0.10$). Akaike information criterion (AIC) values were reported to compare model performance. Full statistical procedures, including model diagnostics, effect-size estimation and R packages, are provided in the Supplementary Online Material.

RESULTS

We obtained 3,798 independent detections of banteng and 3,158 detections of human activity across 27,723 trap nights. Domestic livestock were not recorded by camera traps during the study period. Comparison of relative abundance index (RAI) values between the pre-intensification phase (Year 1) and post-intensification phase (Year 2) using MRPP showed distinct temporal shifts (Table 1). Overall banteng RAI decreased from 14.8 ± 0.61 in Year 1 to 12.7 ± 0.63 in Year 2. In contrast, overall human activity remained consistently high across

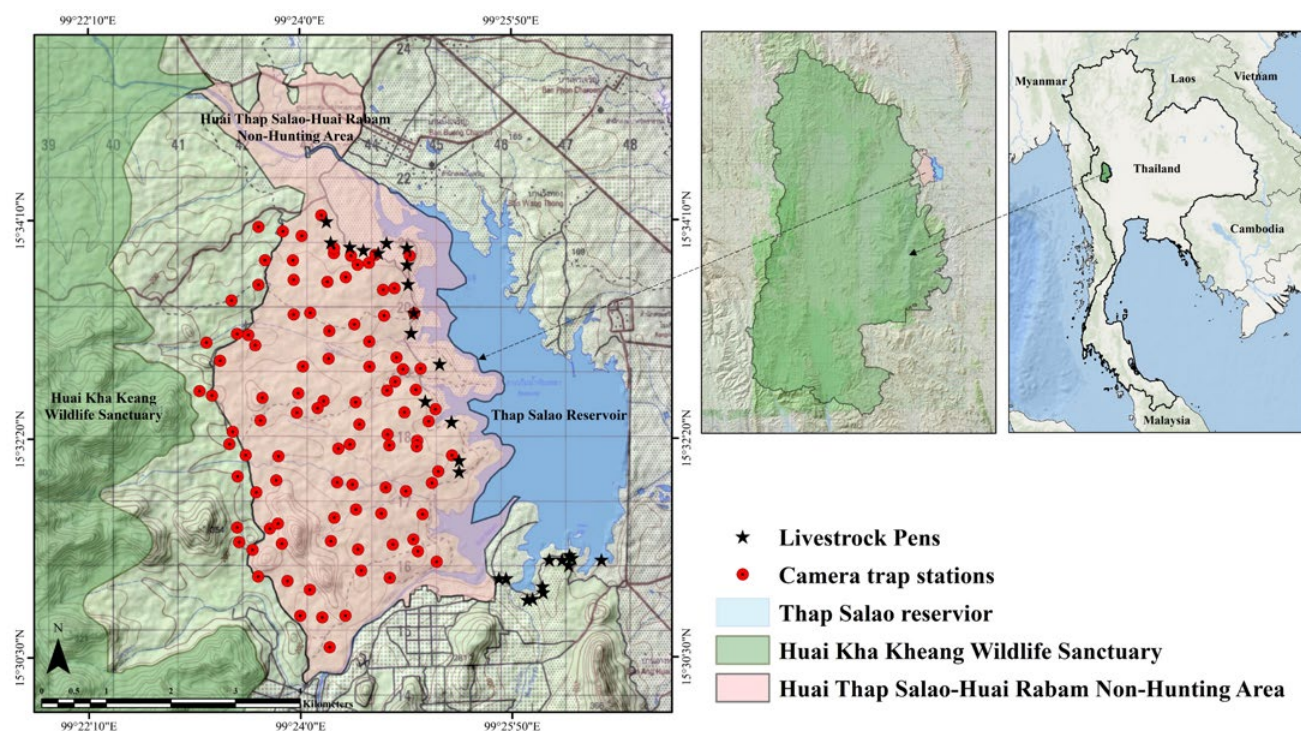


Figure 1. Study area and locations of camera trap stations ($n = 99$) within the Huai Thap Salao–Huai Rabam Non-Hunting Area, western Thailand.

Table 1. Comparison of banteng relative abundance, diel activity and human activity between the pre-intensification management phase (Year 1) and post-intensification management phase (Year 2).

Activity type	Time period	Year 1 (mean $\pm$ SE)	Year 2 (mean $\pm$ SE)	MRPP p-value
Banteng	Total (24 h)	14.8 $\pm$ 0.61	12.7 $\pm$ 0.63	0.01
	Day-time	5.84 $\pm$ 0.29	6.05 $\pm$ 0.36	0.66
	Night-time	9.01 $\pm$ 0.44	6.61 $\pm$ 0.42	< 0.01
Human activity overall	Total (24 h)	11.9 $\pm$ 0.62	11.9 $\pm$ 0.69	0.20
	Day-time	11.4 $\pm$ 0.60	11.5 $\pm$ 0.66	0.14
	Night-time	0.45 $\pm$ 0.06	0.39 $\pm$ 0.08	0.30
NTFP collection	Total (24 h)	4.42 $\pm$ 0.40	4.63 $\pm$ 0.49	0.76
	Day-time	4.02 $\pm$ 0.37	4.34 $\pm$ 0.44	0.45
	Night-time	0.40 $\pm$ 0.06	0.29 $\pm$ 0.07	0.06
Ranger patrol	Total (24 h)	3.28 $\pm$ 0.34	3.35 $\pm$ 0.38	0.55
	Day-time	3.22 $\pm$ 0.34	3.27 $\pm$ 0.37	0.53
	Night-time	0.06 $\pm$ 0.02	0.08 $\pm$ 0.02	0.24
Research activity	Total (24 h)	4.17 $\pm$ 0.19	3.96 $\pm$ 0.24	< 0.01
	Day-time	4.17 $\pm$ 0.19	3.96 $\pm$ 0.24	< 0.01
	Night-time	0.00 $\pm$ 0.00	0.01 $\pm$ 0.01	0.08

Note: SE = standard error; MRPP = Multi-Response Permutation Procedure; NTFP = non-timber forest product, Daytime: 6.00 am–6.00 pm; Night-time: 6.00 pm–6.00 am.

both phases, with similar mean RAI values in Year 1 and Year 2 (11.9 $\pm$ 0.62 vs. 11.9 $\pm$ 0.69; p = 0.20). Night-time NTFP collection decreased from 0.40 $\pm$ 0.06 in Year 1 to 0.29 $\pm$ 0.07 in Year 2, although this difference was marginal (p -value = 0.06). Banteng night-time activity declined significantly from 9.01 $\pm$ 0.44 to 6.61 $\pm$ 0.42 (p -value < 0.01). In Year 1, banteng night-time RAI was significantly higher than daytime RAI (5.84 $\pm$ 0.29; p -value < 0.01), indicating a strongly nocturnal activity pattern. In Year 2, this difference disappeared: daytime RAI remained stable (6.05 $\pm$ 0.36), while lower night-time activity resulted in no significant difference between daytime and night-time RAI (p -value = 0.40). Ranger patrol activity remained similar across the two years (3.28 $\pm$ 0.34 vs. 3.35 $\pm$ 0.38; p -value = 0.55), whereas research activity declined significantly from 4.17 $\pm$ 0.19 to 3.96 $\pm$ 0.24 (p -value < 0.01).

Temporal patterns of monthly activity

Analysis of monthly activity patterns showed an inverse relationship between banteng and human activity across the two study years (Figure 2). Banteng RAI was highest during the dry season (December–April), when human activity in the landscape was lowest. In contrast, banteng RAI declined between September and November,

coinciding with the period of highest daytime anthropogenic activity. However, the magnitude of this seasonal decline differed between years. In Year 1, banteng RAI reached its lowest level during the peak human-activity months. In Year 2, banteng RAI also declined during the same period, but the reduction was less severe and remained higher than in Year 1. This suggests that banteng continued to respond to seasonal human disturbance, but the post-intensification management phase may have reduced the extent of avoidance.

Spatial distribution patterns

Visualisation of station-level RAI suggested differences in the spatial distribution of banteng between the two management phases, including more detections near the reservoir edge in Year 2 (Figure 3). In Year 1, banteng RAI was relatively evenly distributed across the central and western parts of the study site (Figure 3a), while human activity was concentrated along the eastern forest edge and reservoir boundary (Figure 3c). In Year 2, banteng distribution became more widespread across the northern, central and southern areas, with high-intensity clusters emerging along the eastern boundary, particularly near the Thap Salao Reservoir (Figure 3b).

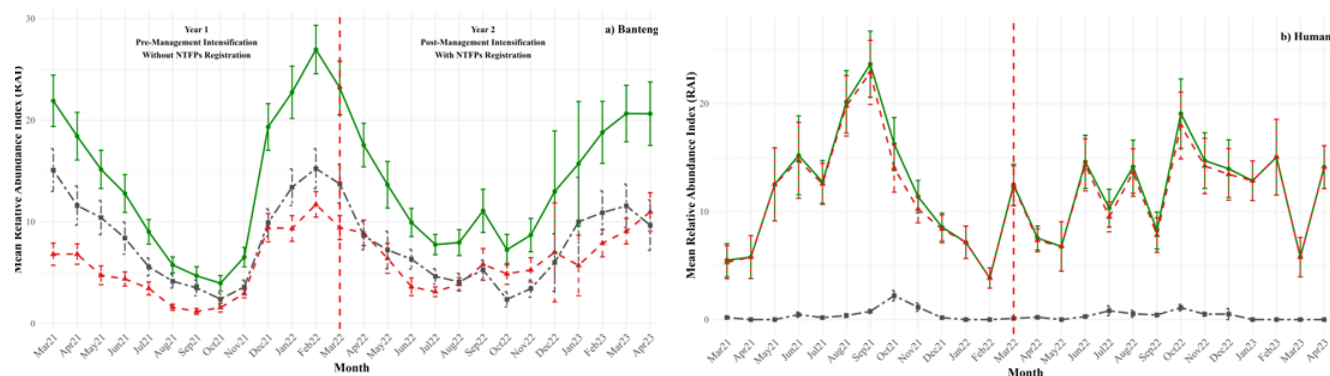


Figure 2. Monthly diel activity patterns based on mean relative abundance index (RAI) during the pre-intensification management phase (Year 1) and post-intensification management phase (Year 2) for (a) banteng and (b) human activity.

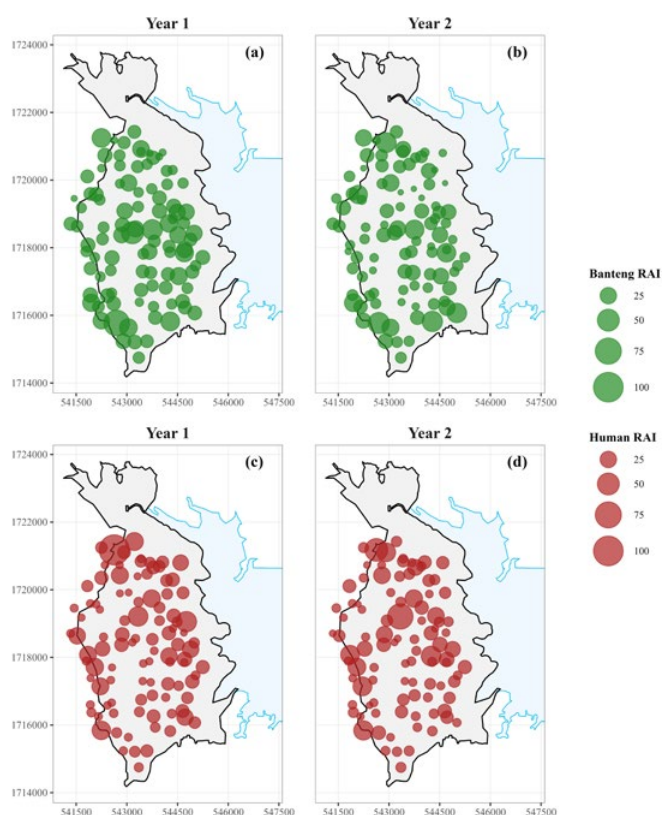


Figure 3. Spatial distribution of banteng and human activity (RAI) in the Huai Thap Salao-Huai Rabam Non-Hunting Area for banteng in the pre-intensification management phase (Year 1) (a) and post-intensification management phase (Year 2) (b), and human activity in Year 1 (c) and Year 2 (d).

This clustering occurred despite the continued presence of human activity in the same eastern areas (Figure 3d). These visual patterns provide landscape context for the subsequent model-based assessment of habitat use.

Factors influencing habitat use

GLMMs and AIC-based model selection were used to identify predictors of banteng habitat use (Table 2). In both years, models based only on static environmental variables performed poorly and did not improve model

fit relative to the null model (Year 1: $\Delta\text{AIC}_{\text{null}} = 7.1$; Year 2: $\Delta\text{AIC}_{\text{null}} = 5.8$). Among the single-category anthropogenic disturbance models, the NTFP activity model showed the greatest improvement over the null model in both Year 1 ($\Delta\text{AIC}_{\text{null}} = -109.8$) and Year 2 ($\Delta\text{AIC}_{\text{null}} = -27.3$). The top-ranked models had the lowest AIC values among the candidate models in both phases, although their predictor structures differed. In Year 1, the top-ranked model ($\text{AIC} = 6412.9$) included seasonal factors and anthropogenic variables, and improved model fit compared with the seasonal model alone ($\text{AIC} = 6455.4$). Banteng RAI was negatively associated with NTFP collector activity, researcher activity and the three-way interaction among NTFP collector activity, researcher activity and ranger patrols. In contrast, distance from the nearest village and the two-way interaction between NTFP collector activity and researcher activity were positively associated with banteng RAI. Both interaction terms retained in the Year 1 top-ranked model were statistically significant ($p < 0.01$ for each; Table 2), indicating that the associations between human activities and banteng RAI depended on the levels of other activities.

In Year 2, the top-ranked model had the lowest AIC among the candidate models ($\text{AIC} = 4350.7$), but the two-way and three-way interaction terms were no longer retained. The Year 2 top-ranked model therefore represented anthropogenic activities through additive terms, in contrast to the interaction terms retained in Year 1. The model included forest basal area alongside seasonal and anthropogenic variables, indicating that habitat structure became a more important predictor in the post-intensification phase. The $\Delta\text{AIC}_{\text{null}}$ difference between the top-ranked and seasonal models was also smaller in Year 2 than in Year 1, suggesting that seasonal variation remained important, but anthropogenic interactions were less influential after access regulation. However, these differences in the selected models do not constitute



a formal test of between-year differences in interaction effects or establish that access regulation caused those effects to weaken. Detailed parameter estimates for the top-ranked models are provided in Tables S2 and S3.

Drivers of villager intrusion

Modelling the drivers of NTFP collection (Table S3) showed that active ranger patrols were not significantly associated with reduced villager activity in either Year 1 or Year 2 (p-value = 0.49 and p-value = 0.69, respectively). However, the spatial distribution of villager activity was significantly associated with distance to patrol roads in both years. In Year 1, villager activity was concentrated closer to patrol roads (estimated coefficient = -1.82, p-value < 0.01) and was negatively associated with researcher activity (p-value < 0.01). In Year 2, the negative relationship with distance to patrol roads remained significant (estimated coefficient = -1.32, p-value = 0.04), while the association with researcher activity was no longer significant (p-value = 0.16). Villager activity also showed strong seasonal variation in both phases, peaking between September and November. The magnitude of this seasonal effect was higher in Year 2, with estimated coefficients ranging from 2.92 to 4.21, compared with 1.27 to 2.08 in Year 1. These results suggest that ranger patrols alone did not substantially reduce livelihood-driven forest entry, particularly during the peak NTFP collection season.

DISCUSSION

This study provides empirical evidence that regulated access and collaborative governance can improve conditions for threatened wildlife in a World Heritage buffer landscape where conservation objectives overlap with local livelihood use. The establishment and management of the Huai Thap Salao–Huai Rabam Non-Hunting Area (HTSHR) created a practical mechanism for reducing high-impact disturbance while maintaining negotiated access for local communities. Our findings extend the baseline established by Chookaew et al. (2026), who documented seasonal banteng displacement associated with livestock grazing, by showing that banteng habitat use and activity patterns began to recover after livestock removal and access regulation. Together with elephant-focused research from the same landscape (Phumsathan et al., 2024), these findings highlight the importance of managing buffer zones as active socio-ecological spaces, where conservation outcomes depend on both ecological recovery and community compliance.

The comparison between Year 1 and Year 2 suggests that early conservation responses in HTSHR were expressed mainly through changes in diel activity and habitat use rather than evidence of population recovery. The decline in overall banteng RAI from 14.8 ± 0.61 to 12.7 ± 0.63 should therefore be interpreted cautiously. Camera-trap

RAIs measure detection rates rather than directly estimating animal abundance or the intensity of human activity. Changes in these indices may reflect variation in abundance or human visitation, spatial distribution, movement behaviour, activity levels or detection probability. Consequently, the decline in banteng RAI alone does not establish a population decline. Similarly, the less strongly nocturnal pattern in Year 2 reflected a significant decline in nighttime RAI without a corresponding increase in daytime RAI. This pattern should not be interpreted as evidence that nocturnal activity was simply redistributed to daytime. Longer-term monitoring and independent demographic information would be needed to assess whether the observed changes were accompanied by population recovery.

Behavioural response to conservation management

The implementation of formal registration and daytime-only access in Year 2 was associated with a clear shift in banteng behaviour. In Year 1, unregulated human access occurred during both day and night, especially during the peak mushroom-harvesting season. This chronic and unpredictable disturbance likely created a landscape of fear, causing banteng to avoid periods of high human activity (Laundré et al., 2010). The Year 1 results showed a strongly nocturnal activity pattern, suggesting temporal avoidance of human presence. Similar behavioural plasticity has been reported for other threatened ungulates exposed to intense anthropogenic pressure (Pan et al., 2011).

The Year 2 management system altered this pattern. The management transition coincided with a shift in banteng activity from a strongly nocturnal pattern to a less strongly nocturnal pattern, driven by a decline in nighttime activity while daytime activity remained relatively stable. The changes in banteng diel activity coincided with several management interventions, including daytime-only access regulation, livestock removal, removal of livestock-related infrastructure and ranger patrols. Because these interventions occurred concurrently, their individual effects cannot be separated using the present study design. Reduced competition with livestock or changes in spatial use following livestock removal could also have contributed to the observed activity pattern. These findings are therefore interpreted as associations with the broader conservation-management transition rather than as evidence of the effect of daytime-only access alone.

The recovery of banteng activity was also linked to habitat conditions. During the dry season, receding water levels in the Huai Thap Salao Reservoir expose

drawdown zones that regenerate with nutrient-rich forage (Chookaew et al., 2026; Pongpattananurak, 2020). By returning to these open edges, which had previously been used by domestic cattle (Chookaew et al., 2026; Phumsathan et al., 2025), banteng appeared to regain access to important foraging patches following livestock removal (Figure S7). This pattern may reflect improved access to seasonal forage after livestock competition was reduced, although the present study cannot separate this effect from other concurrent management changes. This pattern was supported by our Year 2 models, in which forest basal area was a key environmental covariate. The negative association with basal area indicates that banteng increasingly used less densely forested environments, consistent with broader landscape models showing that large tiger prey species favour seasonally dry forests with low-slope, open-canopy terrain (Chankhao et al., 2022; Chookaew et al., 2026; Jornburom et al., 2020).

Collaborative governance: Beyond the limits of patrolling and local stewardship

Our findings also show that patrolling alone is unlikely to be sufficient in a buffer zone where forest entry is strongly linked to local livelihoods. This contrasts with Saisamorn et al. (2024), who reported that systematic patrolling contributed to large-herbivore recovery within the HKK core area and surrounding landscapes. In HTSHR, ranger patrol activity showed a negative association with banteng relative abundance. This association should be interpreted cautiously because patrol deployment may have been targeted towards areas with greater human disturbance or conservation concern, creating potential endogeneity or reverse causality. This result should therefore not be interpreted as evidence that patrols are unimportant. Patrols remain essential for law enforcement, visitor safety and the prevention of illegal activities. However, patrols need to be embedded within a broader governance system that includes agreed access rules, community participation and targeted regulation of high-impact activities.

The improved conditions observed in Year 2 were closely linked to formal regulation, community agreement and locally meaningful conservation incentives. The removal of livestock and related infrastructure reduced a major source of disturbance in open foraging habitats. At the same time, the designation of HTSHR as a key area for community-based wildlife tourism helped create a practical reason for local communities to support banteng recovery. This incentive structure helped shift the buffer landscape from a contested resource-use area towards a shared conservation asset.

Table 2. Model selection results comparing candidate GLMMs for banteng occurrence in pre-intensification management phase (Year 1) and post-intensification management phase (Year 2). Models are ranked by AIC.

Phase/model candidate	Formula	df(K)	AIC	ΔAIC_{null}
Year 1				
Null model	~ 1 + (1 Station)	4	6878.7	0.0
Environmental model	~ tree_rf + BA_rf + canopy_rf + slope + DIS_water + (1 Station)	9	6885.8	7.1
Ranger patrol model	~ RAI_ranger + (1 Station)	5	6878.9	0.2
Accessibility threat model	~ village_DIS + patrol_DIS + (1 Station)	6	6873.6	-5.1
Research activities model	~ RAI_researcher + (1 Station)	5	6853.6	-25.1
NTFP activities Disturbance model	~ RAI_villager + (1 Station)	5	6768.9	-109.8
Seasonal model	~ month_char + (1 Station)	15	6455.4	-423.3
Top-ranked model	~ RAI_villager + RAI_researcher + RAI_villager: RAI_researcher : RAI_Ranger + RAI_Villager : RAI_researcher + village_DIS + month_char + (1 Station)	20	6412.9	-465.8
Year 2				
Null model	~ 1 + (1 Station)	4	4478.7	0.00
Environmental model	~ tree_rf + BA_rf + canopy_rf + slope + DIS_water + (1 Station)	10	4484.5	5.8
Accessibility threat model	~ village_DIS + patrol_DIS + (1 Station)	6	4481.0	2.3
Research activities model	~ RAI_researcher + (1 Station)	5	4479.7	1.0
Ranger patrol model	~ RAI_ranger + (1 Station)	5	4478.0	-0.7
NTFP activities Disturbance model	~ RAI_villager + (1 Station)	5	4451.4	-27.3
Seasonal model	~ month_char + (1 Station)	15	4362.7	-116.0
Top-ranked model	~ RAI_villager + RAI_ranger + BA_rf + month_char + (1 Station)	18	4350.7	-128.0

Note: NTFP = non-timber forest product; df = degrees of freedom; AIC = Akaike's Information Criterion; RAI = relative abundance index. canopy_rf = percentage canopy cover; BA_rf = tree basal area (m²/ha); tree_rf = tree density (tree/ha); DIS_water = distance to the nearest water source (m); village_DIS = distance to the nearest village (m); patrol_DIS = distance to patrol roads (m); RAI_villager = NTFP collector activity; RAI_ranger = ranger patrol activity; RAI_researcher = researcher activity.

This ecological and social transition suggests a broader change in local attitudes towards wildlife and protected area management (Newmark et al., 1994; Phumsathan, 2026). By linking banteng recovery with future livelihood opportunities, HTSHR has begun to strengthen local support for access rules, reduce high-risk forest use and encourage participation in long-term stewardship. This does not imply that all resource-use pressures have been resolved. Rather, it shows that legal designation is more likely to be effective when combined with negotiated rules, community participation and incentives that make conservation meaningful to local people.

Implications for World Heritage buffer-zone management

From a protected area management perspective, the HTSHR case shows that buffer-zone designation can function as more than a legal boundary adjustment. When combined with practical access regulation, community agreements and locally relevant incentives, buffer-zone management can support the recovery of habitat use by threatened wildlife while maintaining socially acceptable forms of resource access. This is particularly important in Southeast Asian conservation landscapes, where protected areas often overlap with long-standing livelihood practices.

The findings suggest that management should prioritise temporal predictability in human activities. In HTSHR, the registration system and daytime-only access helped reduce nocturnal disturbance and created more predictable conditions for banteng. Future management should therefore maintain clear access rules, agreed entry times and regular monitoring during peak NTFP collection periods. Patrols should support these access arrangements by monitoring compliance, preventing illegal activities and reducing high-risk use, rather than functioning as the only conservation intervention.

A phased management approach is also needed to align banteng recovery with local socio-economic aspirations. In the short term, NTFP collection should be managed through spatial zoning and quotas. High-value wildlife areas, particularly reservoir-edge foraging habitats, should be prioritised for habitat recovery and carefully regulated wildlife tourism. NTFP collection should be directed towards areas where banteng occurrence is lower and disturbance risk is less severe. Quotas for both resource users and visitors should be reviewed using camera-trap data, registration records, patrol observations and community compliance monitoring.

In the longer term, community-based wildlife tourism should be developed as a complementary livelihood pathway that gradually reduces dependence on high-impact forest use. According to the 2025 annual report of the Wildlife Tourism Community Enterprise of Rabam Subdistrict, tourism-related activities generated THB 2.46 million in revenue in 2025 (Wildlife Tourism Community Enterprise of Rabam Subdistrict, 2025). Although this does not yet demonstrate a full transition away from forest resource dependence, it shows that wildlife recovery has begun to create tangible local benefits that can strengthen access compliance, reduce high-risk forest use and support long-term stewardship.

Tourism development must also be carefully regulated. Visitor numbers, vehicle movements, viewing distances, viewing duration and access times should be managed through clear operating procedures and adaptive monitoring. Carrying capacity should be assessed not only in terms of visitor experience, but also in relation to banteng behaviour, habitat use and disturbance thresholds. Wildlife tourism should remain predictable, low-impact and non-lethal, without causing displacement, over-habituation or dependence on human presence.

Overall, HTSHR offers a practical model for reconciling endangered wildlife recovery, local livelihoods and the protection of the OUV of the Thung Yai–Huai Kha Khaeng World Heritage property. Effective buffer-zone management should combine clear rules, targeted

patrolling, community participation, transparent benefit-sharing, local guide training and continued ecological monitoring. This approach can help transform the buffer zone from a contested resource-use landscape into a shared conservation asset that supports both wildlife recovery and local stewardship.

CONCLUSIONS

This study evaluated buffer-zone management interventions in the HTSHR and showed that the transition from unregulated access to a registration system was associated with positive behavioural and spatial responses by endangered banteng. By restricting forest access to daylight hours and reducing nocturnal disturbance, the management system created more predictable conditions for wildlife. Banteng shifted from a strongly nocturnal activity pattern under high human disturbance to a more cathemeral pattern, suggesting reduced temporal avoidance and greater use of open-canopy foraging habitats along the reservoir edge. The findings also highlight the limitations of relying on enforcement alone in landscapes where conservation objectives overlap with livelihood-based forest use. Active patrolling remains important for law enforcement, safety and the prevention of illegal activities, but may be insufficient to reduce livelihood-driven forest entry and may contribute to disturbance if not carefully targeted. In HTSHR, improved conditions for banteng were more closely linked to regulated access, livestock removal, community adherence to agreed rules and locally meaningful incentives from community-based wildlife tourism. Overall, this study demonstrates that temporally predictable human access, when embedded within collaborative governance, can support wildlife habitat recovery in a World Heritage buffer landscape. The HTSHR case provides a practical model for balancing sustainable resource use, local livelihoods and threatened species conservation while contributing to the protection of the Outstanding Universal Value of the Thung Yai–Huai Kha Khaeng World Heritage property.

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RESUMEN

La gestión de las interacciones entre las personas y la fauna silvestre en las zonas de amortiguación es esencial para la conservación de la megafauna en aquellos lugares donde los objetivos de conservación se solapan con los medios de vida locales. Evaluamos las intervenciones de gestión en el paisaje de Huai Kha Khaeng, en Tailandia, declarado Patrimonio de la Humanidad, tras la retirada del ganado, comparando las respuestas del banteng (*Bos javanicus*), especie en peligro de extinción, en condiciones de acceso no regulado (Año 1) y de acceso solo durante el día mediante registro (Año 2). Mediante el uso de cámaras de vigilancia en 99 ubicaciones, evaluamos la abundancia relativa del banteng, su actividad diurna y nocturna y el uso del hábitat en relación con la actividad humana. La actividad del banteng pasó de ser principalmente nocturna en el Año 1 a ser menos nocturna en el Año 2, con una distribución más amplia que incluía zonas con menor cobertura del dosel arbóreo y mejor forraje cerca del borde del embalse. La actividad del banteng alcanzó su punto álgido durante la estación seca, cuando los aldeanos eran menos propensos a salir a recolectar setas. La actividad del banteng se asoció negativamente con la actividad humana y era más probable que se produjera a mayor distancia de la aldea. A pesar de las patrullas diurnas de los guardabosques, los aldeanos eran menos activos a cierta distancia de las rutas de patrulla y continuaban con sus actividades nocturnas durante la recolección de setas. Estos hallazgos indican que el acceso regulado, el acuerdo comunitario y los incentivos significativos pueden favorecer la recuperación del comportamiento y el uso del hábitat por parte de la fauna silvestre amenazada. La gobernanza colaborativa, respaldada por el turismo de fauna silvestre de base comunitaria, ofrece una vía para equilibrar la conservación, los medios de vida y la gestión a largo plazo en los paisajes de zona de amortiguación del Patrimonio Mundial.

RÉSUMÉ

La gestion des interactions entre l'homme et la faune sauvage dans les zones tampons est essentielle pour la conservation de la mégafaune lorsque les objectifs de conservation entrent en conflit avec les moyens de subsistance locaux. Nous avons évalué les mesures de gestion mises en œuvre dans le site du patrimoine mondial de Huai Kha Khaeng, en Thaïlande, après le retrait du bétail, en comparant les réactions du banteng (*Bos javanicus*), espèce menacée, dans un contexte d'accès non réglementé (année 1) et d'accès autorisé uniquement pendant la journée et soumis à enregistrement (année 2). À l'aide de caméras de surveillance installées à 99 emplacements, nous avons évalué l'abondance relative des bantengs, leur activité diurne et nocturne ainsi que leur utilisation de l'habitat en fonction de l'activité humaine. L'activité des bantengs, principalement nocturne au cours de la première année, est devenue moins nocturne au cours de la deuxième année, avec une distribution plus étendue incluant des zones présentant un couvert forestier moins dense et un meilleur fourrage près des berges du réservoir. L'activité des bantengs a atteint son pic pendant la saison sèche, lorsque les villageois étaient moins enclins à partir à la cueillette de champignons. L'activité des bantengs était négativement corrélée à l'activité humaine et plus fréquente à mesure que l'on s'éloignait du village. Malgré les patrouilles diurnes des gardes forestiers, les villageois étaient moins actifs à distance des itinéraires de patrouille et poursuivaient leurs activités nocturnes pendant la cueillette des champignons. Ces résultats indiquent qu'un accès réglementé, un accord communautaire et des incitations significatives peuvent favoriser le rétablissement des comportements et l'utilisation de l'habitat par la faune menacée. Une gouvernance collaborative, soutenue par un tourisme faunique communautaire, offre une voie permettant de concilier conservation, moyens de subsistance et gestion durable dans les zones tampons des sites du patrimoine mondial.