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Research Article

Post-release Monitoring and Habitat Suitability of Siamese Eld's Deer (*Rucervus eldii siamensis*) in Thailand

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ABSTRACT

Post-release monitoring (PRM) is a critical component of wildlife reintroduction programs, providing essential information on population establishment, habitat use, and management effectiveness. The Siamese Eld's deer (*Rucervus eldii siamensis*), globally classified as Endangered, was extirpated from the wild in Thailand for approximately five decades. Reintroduction efforts have been implemented since 2018; however, post-release ecological assessments remain limited. This study aimed to evaluate population dynamics, environmental influences, and habitat suitability of reintroduced Siamese Eld's deer in Thailand. PRM was conducted at Phanom Dong Rak Wildlife Sanctuary (PDRWS) between November 2019 and July 2022 using an integrated approach, including camera trapping, population monitoring within permanent sampling plots, direct daytime and nighttime observations, and spatial records of deer occurrences. Habitat suitability was assessed using environmental and climatic variables. Population density ranged from 55 to 72 individuals per km², with the largest observed group size being 18 individuals. A total of 73 forage plant species were recorded, indicating high dietary resource availability within the release area. Key climatic variables influencing habitat suitability included annual temperature range, precipitation of the driest month, and total annual precipitation. Among environmental predictors, the digital elevation model (DEM) contributed most strongly to Siamese Eld's deer presence, followed by land surface temperature and the normalized difference vegetation index (NDVI). Habitat suitability modeling identified only 4.61 km² of suitable habitat within the total 119.05 km² study area. The results indicate that suitable habitat for long-term population establishment is limited, emphasizing the need for targeted habitat management. Recommended measures include the creation of mosaic grasslands, enhancement of herbaceous and shrub diversity, and maintenance of open foraging areas adjacent to forest cover. Continuous long-term PRM is essential to support adaptive management and improve the success of Siamese Eld's deer reintroduction programs in Thailand.

Key words: post-release monitoring; habitat suitability modeling; MaxEnt; Phanom Dong Rak Wildlife Sanctuary; Siamese Eld's deer (*Rucervus eldii siamensis*); soft release

INTRODUCTION

Eld's deer (*Rucervus eldii*) is globally classified as an Endangered species (Gray *et al*., 2015), and without immediate and effective conservation action, several remaining populations face a high risk of extinction (Wong *et al*., 2021). Captive breeding and reintroduction programs have therefore become key conservation tools for restoring endangered ungulates and rebuilding viable wild populations (Pan *et al*., 2014; Stewart *et al*., 2017; Valente *et al*., 2017; Heinrichs *et al*., 2018; Lott *et al*., 2020; Badia-Boher *et al*., 2021; Cheng *et al*., 2021; Khattak *et al*., 2022; Riga *et al*., 2022). The species comprises three recognized subspecies: the Manipur Eld's deer (R. e. eldii), restricted to Keibul Lamjao National Park, India (Singh & Khare, 2018); the Burmese Eld's deer (R. e. thamin), occurring in Myanmar and western Thailand (McShea *et al*., 2018; Ghazi *et al*., 2021); and the Siamese Eld's deer (R. e. siamensis), historically distributed across central, eastern, northern, and northeastern Thailand, as well as parts of Laos and Cambodia (Trisurat & Bhumpakphan, 2018). The Siamese subspecies has been extinct in the wild in Thailand since 1978 (Sukmasuang *et al*., 2022), primarily due to overhunting and habitat loss.

Thailand initiated Eld's deer recovery efforts in 1994 through the reintroduction of *R. e. thamin* into several protected areas, with more than 544 individuals released into at least 12 historical habitats by 2022 (Sukmasuang *et al*., 2022). In contrast, conservation actions for the Siamese Eld's deer began much later. The first reintroduction program for *R. e. siamensis* was launched in 2018 through collaboration among the Department of National Parks, Wildlife and Plant Conservation, the Zoological Park Organization under the Royal Patronage of Thailand, and Phanom Dong Rak Wildlife Sanctuary (PDRWS). Ten individuals were translocated from captive breeding facilities and released into the Thung Kabal Krabai area (TKBKB) of the sanctuary. Although Thailand has implemented multiple Eld's

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deer reintroduction programs since 1994, systematic post-release monitoring integrating population dynamics, habitat use, and habitat suitability remains limited, leaving critical uncertainties regarding how reintroduced Siamese Eld's deer adapt to local environmental conditions and whether current habitats can support long-term population persistence. Addressing these knowledge gaps is essential for evaluating reintroduction success, identifying ecological constraints, and guiding adaptive management for future restoration sites.

Accordingly, this study aimed to assess post-release population dynamics, age and sex structure, habitat use, forage composition, and habitat suitability of reintroduced Siamese Eld's deer at PNDRWS. Using an integrated monitoring framework combining camera trapping, direct field observations, and spatial habitat suitability modeling, we evaluated how environmental and climatic factors influence habitat use and early population establishment. We hypothesized that forest type, topography, and climatic conditions are key determinants of habitat suitability and population persistence. The results provide critical evidence on post-release adaptation processes and offer practical guidance for improving future reintroduction and translocation programs for endangered cervids in Thailand.

MATERIALS AND METHODS

Study site

TKBKB area of PDRWS, located along the Thai–Cambodia border in Sisaket Province, northeastern Thailand (Figure 1). The area was the site of reports of kouprey (*Bos sauveli*), the rarest wild cattle species, in 1976 (Bhumpakphan & Trisurat 2006). The area features a complex mountainous landscape with plains on elevated terrain, ranging from 180 to 671 m above sea level. Numerous mountains pass in the area serve as routes between Thailand and Cambodia. PDRWS has two primary seasons: a dry season (November–April) and a rainy season (May–October). Temperatures range from 10.5°C to 40.6°C, with an average temperature of ~32.8°C (DNP, 2024). The sanctuary is home to at least 34 mammal species, 85 bird species, 28 reptile species, and 21 amphibian species. It contains important wildlife, including the Dhole (*Cuon alpinus*), Clouded leopard (*Neofelis nebulosa*), Malayan sun bear (*Helarctos malayanus*), Asian elephant (*Elephas maximus*), Gaur (*Bos gaurus*) Banteng (*B. javanicus*), Pileated gibbon (*Hylobates pileatus*), and Asian black bear (*Ursus thibetanus*) (DNP, 2024).

Reintroduction of Siamese Eld's deer

Following the IUCN (2013) guidelines for reintroductions, Siamese Eld's deer were selected from the Bang La Mung Wildlife Breeding Station (BLMBS), Chonburi Province, based on genetic verification conducted by the Veterinary Medicine Genetic Laboratory, Kasetsart University (Sukmak *et al*., 2013; Pumpitakkul *et al*., 2023). Comprehensive quarantine and veterinary health examinations were carried out at each stage of the translocation process in accordance with the protocols of the Department of National Parks, Wildlife and Plant Conservation (DNP), the Zoological Park Organization under the Royal Patronage of Thailand (ZPO), and the Department of Livestock Development. A total of fifteen individuals were transferred from BLMBS to the Chulabhorn Wildlife Breeding Station (CLBBS) in Sisaket Province, where they were maintained in captivity for approximately one year to acclimate to semi-natural conditions. During this acclimation period, their diet was managed to simulate natural forage availability, and continuous monitoring of health status and behavioral adjustment was conducted to ensure readiness for release.

Ten adults Siamese Eld's deer, approximately 2 years old, comprising five males and five females, were selected based on health, external physiology, completeness, and wild behavior. These Siamese Eld's deer were moved to the TKBKB release site on July 20, 2018. Four 40 × 40 m pens were constructed to allow continuous movement between pens, enabling natural foraging and

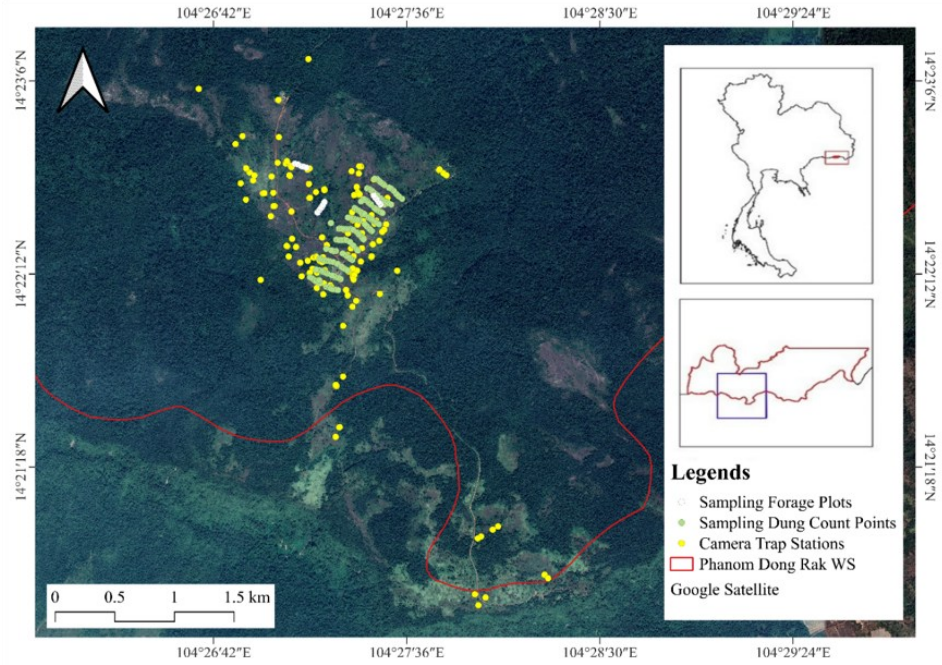

Figure 1. Location of the TKBKB area, PNDRWS, Sisaket Province, Thailand

supplemental food management if needed. All Siamese Eld's deer were quarantined in the pens for 3 months to ensure adaptation to the herd and release site. They were released into the wild on November 1, 2018, using a soft release method (de Milliano *et al*., 2016). During area preparation, food plants were evaluated, grass was burned in summer to promote forage growth, and local communities were informed to encourage their involvement in care and maintenance.

Population

The pellet-group count method (PGC) is commonly used to estimate the population density of ungulates (Camargo-Sanabria & Mandujano, 2011). This method assumes a positive linear relationship between the number of animals and the number of pellet groups (Lioy *et al*., 2014; Mandujano, 2014). Two years post-release, a monthly population study was initiated using the PGC method. In total, 132 circular plots with a 2-m radius were systematically established using a line-plot design (Supartono *et al*., 2021) with each perpendicular line extending 100 m (Figure 1).

Data collection involved identifying feces by size and counting fecal piles within each plot. Counts began 30 days after plot installation and were based on visual assessment of pellet characteristics. After counting, all pellet groups were removed to avoid double-counting in subsequent surveys. Population density per area was calculated using the number of piles and the defecation rate of 12 pellet groups/animal/day (Ngampongsai, 1977; Mandujano, 2014). The following formula, adapted from Sambar deer studies, was used to calculate population density (Bicho *et al*., 2023):

$$\text{Number of deer per unit area} = \frac{\text{Number of pellet group counted per unit area}}{\text{Number of days left in the plot x Defecation rate/individual/day}}$$

Age structure

To monitor population composition, five camera traps were deployed across the study area, spaced at least 500 m apart, and operated continuously for 30 days each month beginning in November 2019 (Figure 1). Photographic records were used to identify and classify individuals into four age and sex categories: adult, subadult, juvenile, and fawn, following the criteria of Prasanai *et al*. (2012). In addition to camera-trap monitoring, roadside and spotlight surveys were conducted along approximately 3–5 km transects between 18:00 and 21:00 h for three nights each month (Corlatti *et al*., 2016). During each survey, observers recorded the number of individuals per sighting, group composition, and classified each individual by age and sex. These combined methods provided complementary data on group structure and temporal variation in population demographics.

Environmental variables

Environmental variables used for habitat suitability modeling were selected to minimize multicollinearity and maximize model accuracy. Variance inflation factors (VIFs) were calculated for 22 candidate variables using the "usdm" package in RStudio (Naimi *et al*., 2014; R Core Team, 2018). Variables with VIF > 5 were iteratively excluded from analysis (Chatterjee & Hadi, 2006; Dormann *et al*., 2013; Akinwande *et al*., 2015). However, the normalized difference vegetation index (NDVI) and elevation were retained due to their strong ecological relevance to *Rucervus eldii* habitat selection.

NDVI serves as an indicator of vegetation cover, where values < 0.1 represent barren areas, 0.2–0.5 correspond to shrubland or grassland, and 0.6–0.9 indicate dense or evergreen forest (USGS, 2018). Elevation distinguishes lowland, human-dominated areas from forested highlands and has been recognized as a key determinant of Siamese Eld's deer habitat suitability (Pepin *et al*., 2022). After applying VIF filtering, six and four environmental variables were retained at the 1 × 1 km and 30 × 30 m spatial scales, respectively (Tables 1 and 2). These final variables were used to develop species distribution and habitat suitability models for the reintroduced population.

Occurrence data

In total, 198 occurrence points of the Siamese Eld's deer were collected from camera traps and track data during 2018–2020. The study area was buffered 3.5 km from the outermost occurrence points, corresponding to the maximum straight-line daily movement range of the species (Pan *et al*., 2014). Occurrence points within the same grid cell were retained owing to the ecological relevance of repeated use within preferred areas.

Table 1. Environmental variables for each scenario

Environmental variables	Scenario	Source
Land cover variables		
Normalized difference vegetation index	2020–2022	Landsat 8 (Extracted from Google Earth Engine) (Rouse et al., 1974; Landsat Missions, 2013)
Topographic variables		
Elevation	Downloaded from Google Earth Engine	The National Aeronautics and Space Administration, Shuttle Radar Topography Mission (NASA SRTM) (Farr et al., 2007; Gorelick et al., 2017)
Slope	Downloaded from Google Earth Engine	NASA SRTM (Farr et al., 2007; Gorelick et al., 2017)
Climatic variables		
Bioclimatic variables (BIO1–7, BIO10–17)	1970–2000	WorldClim version 2.1 (https://www.worldclim.org) (Fick and Hijmans, 2017)
Land surface temperature	2020–2022	Landsat 8 (Extracted from Google Earth Engine) (Ermida et al., 2020)

Table 2. Environmental variables for each modeling scale

Environmental variables	1 × 1 km scale	30 × 30 m scale
Digital elevation model	Used	Used
Slope	Used	Used
Land surface temperature	-	Used
Normalized difference vegetation index	Used	Used
BIO7	Used	-
BIO12	Used	-
BIO14	Used	-

Habitat suitability model

Habitat suitability modeling was conducted using the Maximum Entropy (MaxEnt) algorithm (version 3.4.4) (Phillips *et al*., 2017), which is widely applied for presence-only species distribution modeling. Models were run with 10 bootstrap replicates, a maximum of 500 iterations, and 10,000 background points, with 25% of the occurrence records randomly withheld for model testing. Background points were randomly generated across the accessible study area (M) to represent available environmental conditions, following recommended best practices (Merow *et al*., 2013). To reduce model complexity and minimize overfitting, only linear, quadratic, and product feature classes were included. Model outputs were produced using the cloglog transformation, as this output format provides values that are more interpretable as relative probabilities of species presence and is recommended for ecological inference (Phillips *et al*., 2017). Habitat suitability was subsequently classified into four categories: unsuitable (0.0–0.2), poorly suited (0.2–0.4), moderately suited (0.4–0.6), and well suited (0.6–1.0). Model performance was evaluated using standard accuracy metrics, including the area under the receiver operating characteristic curve (AUC), true skill statistic (TSS), and omission rates, which are reported in the Results section. The relative importance of environmental variables was assessed using percent contribution, permutation importance, and Jackknife tests, and species–environment relationships were further examined using response curves generated by MaxEnt.

RESULTS

Field observations

During the 2018–2022 study period, at least four fawns were observed in the Siamese Eld's deer population. An additional fawn was identified earlier, in November 2018, before the commencement of the project. Subsequent fawns were recorded in June, October, December 2020, and June 2022. No Siamese Eld's deer carcasses were found throughout the study.

In the first year following release, 63.64% of Siamese Eld's deer were observed alone, predominantly adult males foraging in grasslands near and east of the release site. The largest group recorded during this period consisted of four individuals: two adult males, one adult female, and one juvenile feeding together near the release site in March, while the smallest group, observed in April, comprised two adult males foraging in the same vicinity. In the second year, solitary individuals accounted for 38.89% of all observations, again mainly adult males foraging along the Thailand–Cambodia border in newly formed grasslands created by controlled burns approximately 4 km from the release site. In December, a female was observed giving birth and remaining with her fawn concealed near the release area. Group sightings became more frequent during the second year, with 61.11% of individuals recorded in herds, indicating increasing social cohesion as the population stabilized.

By the third year, herd formation became more pronounced. The largest group observed comprised 18 individuals, including a female with a newborn and 16 additional deer, feeding in grasslands east of the release site in September. During this period, 55.56% of deer were observed alone and 44.44% in groups. However, the dense grass covers prevalent during the rainy season likely reduced detectability, suggesting that actual group sizes and frequencies may have been underestimated as some individuals moved into open areas near the ranger base.

Population monitoring

In 2020, Siamese Eld's deer were primarily distributed in open habitats around the release site, including grasslands near the officers' residences, the former forest plantation site, and adjacent mixed deciduous forest. The average Siamese Eld's deer density within the managed grassland area was 0.62 individuals/ha, although this does not represent the broader PDRWS.

The highest monthly density was recorded in December at 229 individuals/km^2, followed by February (95 individuals/km^2) and January (94 individuals/km^2), indicating that released Siamese Eld's deer primarily continue to use areas near the release site and the ranger's station. However, some individuals ranged farther along the Cambodian border, likely following new grass growth. Seasonal analysis showed higher average densities during the dry season (92 individuals/km^2) compared with the rainy season (37 individuals/km^2, suggesting greater use of accessible, open grasslands under dry conditions. Yearly average population densities were 62 individuals/km^2 in 2020, 55 individuals/km^2 in 2021, and 72 individuals/km^2 in 2022 (Table 3). Over the years, Siamese Eld's deer were more frequently observed in the study area during the dry season.

Age structure and herd size

Camera trap surveys conducted between 2020 and 2022 accumulated a total effort of 5,385 trap nights, yielding

Table 3. Number of pellet groups and estimated density and ±SD of Siamese Eld's deer in Tung Kabal Krabai, Phanom Dong Rek Wildlife Sanctuary, during 2020 – 2022

	2020		2021		2022	
Month/year	No. of pellet groups	Density (individual/km^2)	No. of pellet groups	Density (individual/km^2)	No. of pellet groups	Density (individual/ km^2)
November	NS	NS	20	33	7	12
December	137	229	43	72	116	194
January	56	94	71	119	93	156
February	57	95	72	120	17	28
March	13	22	43	72	91	152
April	12	20	73	122	17	28
Dry season (mean±SD)	55.00±50.84	92.00±84.00	53.66±21.77	90.00±36.00	56.83±48.23	95±80
95% CL		92 ±74		90 ±29		95 ±64
May	53	89	NS	NS	34	57
June	49	82	28	47	13	22
July	14	23	9	15	1	2
August	5	8	8	13	NS	NS
September	1	2	1	2	NS	NS
October	11	18	30	50	NS	NS
Rainy season (mean±SD)	22.16±22.82	37±38	15.20±12.98	25.00±21.00	16.00±16.70	27±27
95% CL		37 ±30		25 ±19		27±69
Average		62		55		72

215 images representing 201 independent events of the reintroduced Siamese Eld's deer population. A total of 151 adult males, 54 adult females, two subadult males, one juvenile, and seven individuals of undetermined age were identified (Table 4). The ratio of adult males: adult females: sub-adults: juveniles was approximately 70: 25: 0.9: 0.5, indicating a markedly male-biased population structure. The estimated recruitment rate within the released Siamese Eld's deer population was 0.48 %, reflecting limited juvenile representation during the survey period. Most detections (86.84 %) involved solitary individuals, while only 13.16 % showed group foraging behavior. The largest group recorded consisted of four individuals: two adult males, one adult female, and one subadult. Most group formations comprised two adult males foraging together, a pattern observed consistently in both the dry and wet seasons. Additionally, one adult male was recorded foraging with an adult female during January and February, coinciding with the species' mating season, suggesting possible courtship behavior.

Age Structure and Herd Size

Camera-trap monitoring over 5,385 trap nights yielded 215 photographs representing 201 independent events of Siamese Eld's deer. A total of 215 individuals were identified, comprising 151 adult males, 54 adult females, 2 subadult males, 1 juvenile, and 7 individuals of undetermined age. The resulting ratio of adult males to adult females to subadults to juveniles was 70:25:0.93:0.47 (Table 4), indicating a strongly male-biased population structure. The estimated recruitment rate within the released population was 0.48%, reflecting limited juvenile representation during the monitoring period.

Behavioral observations derived from camera-trap data showed that 86.84% of the recorded individuals were solitary, while only 13.16% appeared in groups. The largest group observed consisted of four individuals two adult males, one adult female, and one subadult recorded foraging together near the release area. Most small groupings involved pairs of adult males, a pattern detected during both dry and rainy seasons. Additionally, an adult male was observed foraging with an adult female during January and February, coinciding with the species' breeding season. These findings suggest that the reintroduced Siamese Eld's deer exhibited natural social behavior, with solitary foraging predominating outside the breeding season and small mixed groups forming during periods of reproductive activity.

Factors Affecting Siamese Eld's Deer Occurrence

Habitat suitability models demonstrated strong predictive performance, with a mean area under the curve (AUC) value of 0.98 at both spatial scales (1 × 1 km and 30 × 30 m), indicating excellent model accuracy. At the broader 1 × 1 km scale, the principal environmental predictors influencing Siamese Eld's deer occurrence were the digital elevation model (DEM), normalized difference vegetation index (NDVI), and three bioclimatic variables: BIO7 (temperature annual range), BIO12 (annual precipitation), and BIO14 (precipitation of the driest month). Among these, elevation contributed the most to model performance (45.3%), with the mean elevation of predicted suitable areas at approximately 543.93 m above sea level, suggesting a preference for mid-elevation habitats. NDVI ranked second in importance (31.1%), with an average value of 0.71, reflecting the species' association with moderately to densely vegetated areas.

At the finer 30 × 30 m resolution, the DEM remained the most influential predictor (34.4%),

followed closely by land surface temperature (34.0%) and NDVI (30.8%), whereas slope made a minor contribution (0.9%) (Table 5). Highlight the combined importance of topographic stability, vegetation productivity, and suitable thermal conditions in determining the occurrence of Siamese Eld's deer across the reintroduction landscape.

Habitat suitability

Habitat suitability analysis within the 119.05 km² study area identified approximately 4.61 km² of suitable habitat for Siamese Eld's deer at the 30 × 30 m spatial scale.At the coarser 1 × 1 km resolution, the estimated suitable area was 4.85 km². The two spatial scales produced highly comparable results, indicating consistency in model performance across resolutions (Table 6; Figures 2–3). These showed that suitable habitats are spatially limited but concentrated around key grassland forest mosaics near the release site, providing important baseline information for future habitat management and expansion planning.

Table 4. Age and sex structure of the reintroduced Siamese Eld's deer population based on camera trap data collected in 2020–2022

Population structure	Adults		Subadults		Juveniles	Fawns	Unknown	Total
	Males	Females	Males	Females				
2020	85	28	2	-	1	-	6	122
2021	52	15	-	-	-	-	-	67
2022	14	11	-	-	-	-	1	26
	151	54	2	-	1	-	7	215
%	70.23	25.12	0.93	-	0.47	-	3.26	100
%	95.35		0.93		0.47		3.26	100

Table 5. Relative contributions (RCs) and mean values of environmental variables influencing Siamese Eld's deer occurrence in models at two spatial resolutions

Environmental variables	1 × 1 km scale		30 × 30 m scale	
	RC (%)	Sample average (±SD)	RC (%)	Sample average (±SD)
Land cover variables				
Normalized difference vegetation index	31.1	0.71 ± 0	30.8	0.59 ± 0.01
Topographic variables				
Digital elevation model	45.3	545.93 ± 1.47	34.4	561.33 ± 0.99
Slope	5.4	6.73 ± 0.07	0.9	4.39 ± 0.16
Climatic variables				
Land surface temperature	-	-	34	30.35 ± 0.13
BIO7	6.3	16.96 ± 0	-	-
BIO12	5.8	1,509.32 ± 0.38	-	-
BIO14	6.1	1.06 ± 0.01	-	-

Table 6. Predicted suitable habitat area for Siamese Eld's deer by suitability class and spatial resolution

Habitat suitability		1 × 1 km scale	30 × 30 m scale
Unsuitable (0.0–0.2)	Area (km^2)	111.8	114.43
	% (of study area)	95.84	96.13
Poorly suited (0.2–0.4)	Area (km^2)	1.94	1.76
	% (of study area)	1.66	1.48
Moderately suited (0.4–0.6)	Area (km^2)	0.97	1.27
	% (of study area)	0.83	1.07
Well-suited (0.6–1.0)	Area (km^2)	1.94	1.58
	% (of study area)	1.66	1.33
Summary area (km^2)		116.65	119.05

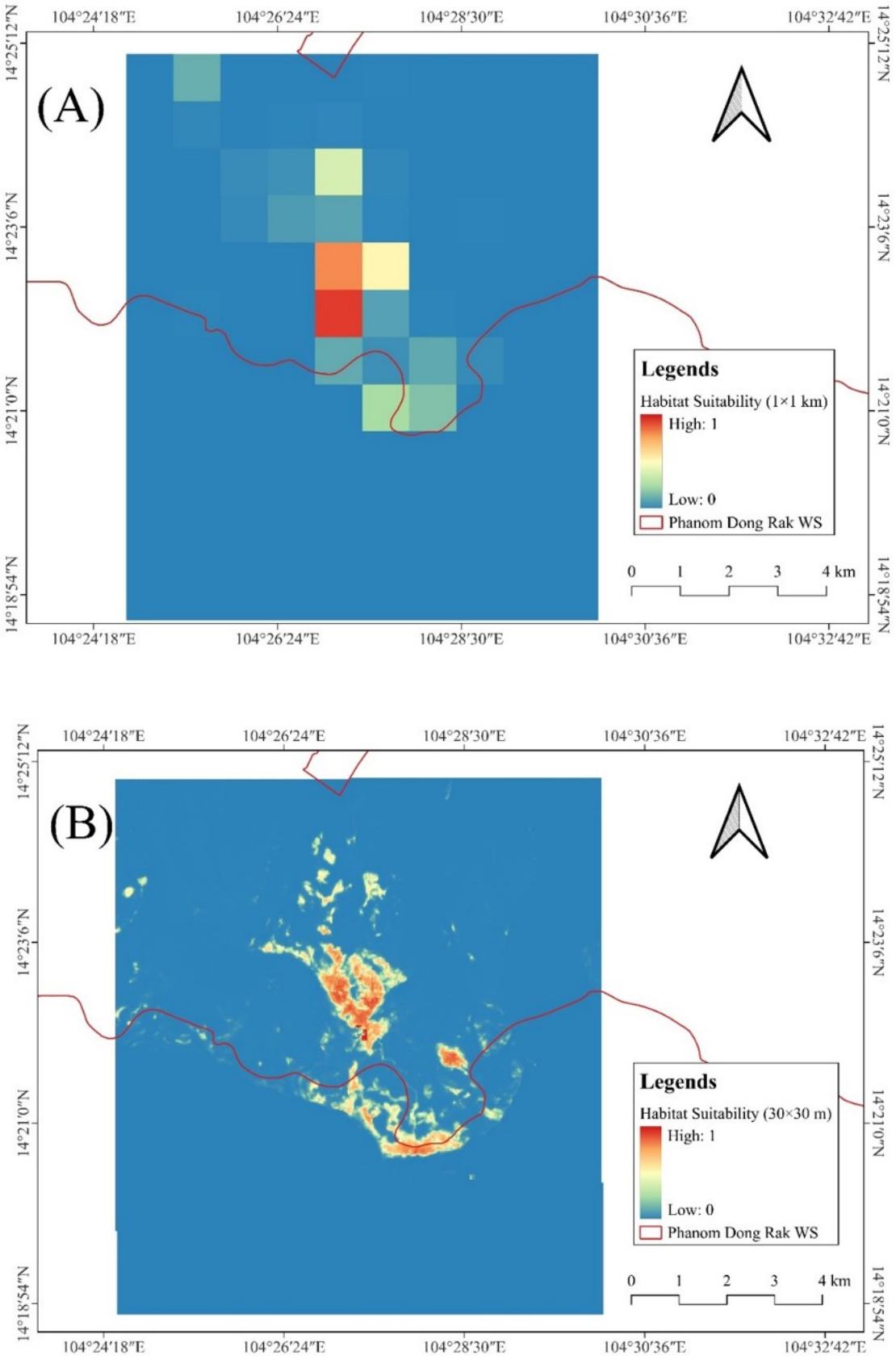

Figure 2. Habitat suitability maps for Siamese Eld's deer at two spatial resolutions: (a) 1 × 1 km and (b) 30 × 30 m

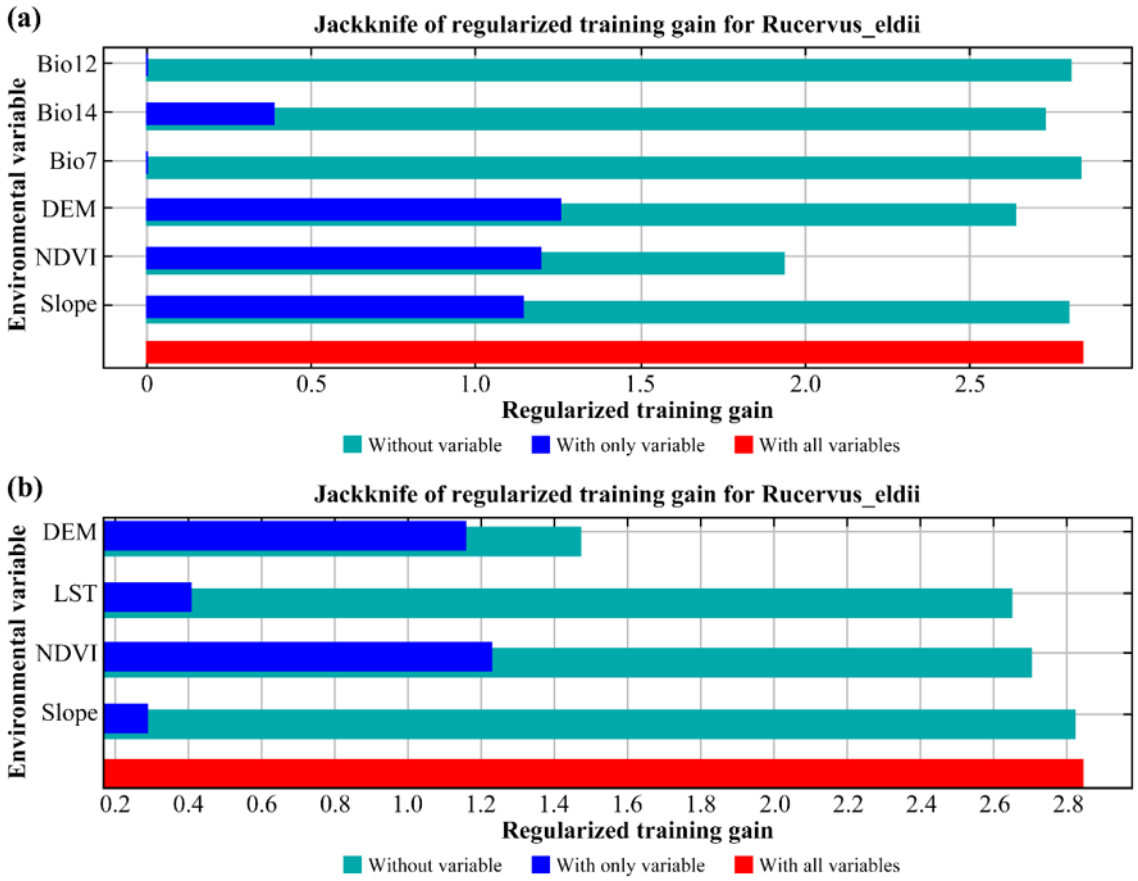

Figure 3. Jackknife test results showing the relative importance of environmental variables for habitat suitability at two scales: (a) 1 × 1 km and (b) 30 × 30 m

Habitat use patterns

Seasonal analysis of habitat use revealed clear preferences by Siamese Eld's deer across the study period. During the dry season, mixed deciduous forest (MDF) was the most frequently utilized habitat type, accounting for 47.18% of all observations, followed closely by grasslands (42.25%). Less commonly used habitats included dry dipterocarp forest (DDF; 6.34%), dry evergreen forest (DEF; 3.52%), and rocky plains (0.70%).

In the rainy season, the pattern shifted slightly, with grasslands becoming the most frequently used habitat (46.58%), followed by MDF (43.84%), while DDF, DEF, and rocky plains continued to be used infrequently. These results indicate that the Siamese Eld's deer relies primarily on the mosaic of grasslands and mixed deciduous forest throughout the year, with minor seasonal variation in habitat preference. Such patterns underscore the importance of maintaining open grassland forest interfaces to support foraging and shelter requirements during both wet and dry seasons.

In the first year following their release, Siamese Eld's deer predominantly occupied grassland areas near the officers' residences, likely attracted by the readily available food and water sources in the TKBKB area. As time progressed, individuals gradually expanded their range into more remote zones, particularly those adjacent to dense forest patches. During the early part of the second year, the deer continued to forage extensively across the study area, suggesting active exploration in search of suitable food, water, and shelter from daytime heat. Notably, pregnant females were observed returning to the vicinity of the release site, especially near the officers' residences, indicating the area's importance as a secure and resource-rich habitat for reproduction and fawn rearing.

In December 2020, a female Siamese Eld's deer was observed with a fawn concealed in tall grass, suggesting that females tend to return to the release area during late pregnancy and remain there for parturition. In contrast, males continued to forage both within and beyond the study zone. By the third year, pellet group surveys indicated increased use of dry dipterocarp forest (DDF) habitats during the dry season, with several individuals also recorded south of the original release site. During the rainy season, foraging areas became more evenly distributed across the landscape as grass growth expanded, covering approximately 70% of the study area with dense vegetation. A total of 73 forage plant species were identified, including tree seedlings (39 species), herbs (15), grass (7), shrubs (6), and climbers (6). This high diversity of available forage corresponds with the species' observed preference for open grassland habitats that provide abundant food resources.

DISCUSSION

During the first year following release, most Siamese Eld's deer were observed alone, particularly adult males foraging in open grassland habitats near the release site. This pattern aligns with the species' natural behavior, in which adult males tend to be solitary or form small groups outside the breeding season. Occasional mixed

groups, such as the four individuals (two adult males, one adult female, and one juvenile) recorded in March, likely reflected temporary associations around preferred feeding sites or seasonal food availability. Similar grouping patterns have been reported in natural populations, where typical group sizes range from two to eight individuals (Thu *et al*., 2019), and smaller groups often occur in habitats with patchy resource distribution (Khotpathoom & Vu, 2020). The predominance of solitary males, therefore, indicates that reintroduced individuals have begun to express natural social organization and spatial segregation characteristic of wild populations, an encouraging sign of behavioral adaptation to the release environment. The behavioral adaptations observed were consistent with the patterns of habitat use and population density recorded during the study period. Most sightings occurred within grassland and adjacent dry dipterocarp forest near the release area, suggesting that these habitats provide optimal combinations of forage and cover. The relatively high local density observed implies that individuals have established stable home ranges, benefiting from abundant palatable grasses, shrubs, and early successional vegetation. Comparable associations between Eld's deer density and open or ecotonal habitats have been reported in Shwesettaw Wildlife Sanctuary, Myanmar (Thu *et al*., 2019), and Xonnabouly, Lao PDR (Khotpathoom & Vu, 2020). These findings collectively suggest that the release site and its surrounding grassland–forest mosaic currently offer favorable ecological conditions for population establishment, if habitat connectivity is maintained and human disturbance remains minimal as the population expands.

Reproductive evidence, including at least four newborns and the absence of observed carcasses, further supports the establishment of a viable founding population. Estimated population densities remained consistently high throughout the monitoring period, exceeding those reported in natural populations. For instance, densities of Thamin Eld's deer in Myanmar ranged from 1.90–3.94 individuals/km² (Thu *et al*., 2019), while those in Lao PDR averaged 0.58 individuals/km² (Khotpathoom & Vu, 2020). The comparatively higher density observed in the present study likely reflects favorable habitat conditions and effective post-release management that facilitated early survival and reproduction. Based on the current density estimates, the 119.05 km² study area contained approximately 4.61 km² (3.87%) of suitable habitat. Extrapolation to the full 316 km² sanctuary suggests the potential carrying capacity of roughly 100 individuals under optimal conditions. However, long-term persistence will depend on maintaining high-quality habitats, abundant and diverse forage, and continued protection from anthropogenic disturbance.

This study deployed only five camera traps across the study area, which may limit the representativeness of estimates of age and sex structure and group size. The restricted spatial coverage could bias detections toward areas near the release site; therefore, demographic estimates should be interpreted with caution. Increasing camera-trap density and spatial coverage in future monitoring would improve the reliability of population assessments following reintroduction.

The strongly male-biased sex ratio and low recruitment observed in this study raise concerns about the long-term viability of the reintroduced Siamese Eld's deer population. These patterns may result from sampling and detection bias associated with limited camera-trap coverage, as well as sex-biased post-release mortality, particularly among females during reproductive periods. The skewed sex ratio may also reflect management decisions during the initial release, including the small founder population and its sex composition, while delayed reproduction or reduced juvenile survival under suboptimal habitat conditions may further limit recruitment. Together, these findings underscore the need for enhanced demographic monitoring and management actions focused on improving female survival and reproductive success.

The diversity of forage resources recorded in this study, comprising 73 plant species, indicates a high degree of dietary flexibility in reintroduced Siamese Eld's deer, which is a key indicator of ecological adaptability and population resilience following release (Yangling & Shanyuan, 2006). The ability to utilize a wide range of forage types including tree seedlings, shrubs, herbs, grasses, and climbers suggests that SEDs can adjust their foraging strategies to heterogeneous and dynamically changing habitats, a trait critical for long-term persistence in restored landscapes. Forage composition also provides important insights into habitat quality and successional status. The predominance of tree seedlings reflects ongoing forest regeneration and moderate disturbance levels within the reintroduction area, while the relatively lower availability of herbaceous and grass species suggests limited early-successional vegetation. Such structural characteristics indicate a transitional habitat that offers cover and browse resources but may not consistently supply high-quality forage throughout the year. Seasonal variation in forage availability is likely to further influence dietary patterns. Herbs and grasses are expected to be particularly important during the wet season, when productivity and nutritional quality are highest, whereas woody browse (tree seedlings and shrubs) likely becomes a critical food source during the dry season, when herbaceous cover declines. However, the predominance of tree seedlings and reduced herbaceous diversity may constrain nutritional intake during prolonged dry periods, potentially affecting body condition and reproductive performance. These findings have direct implications for reintroduction site management. Maintaining early-successional vegetation through periodic grassland management such as controlled burning, selective clearing, or rotational mowing would promote the regeneration of herbs and shrubs and enhance forage availability across seasons. Sustaining a mosaic of grasslands and regenerating forest patches is therefore essential to support dietary requirements, improve habitat quality, and strengthen the resilience of reintroduced Siamese Eld's deer populations.

Despite positive population and behavioral indicators, the reintroduced population exhibited a pronounced male-biased sex ratio and limited recruitment. Such demographic imbalance can constrain effective population size, reduce mating opportunities, and slow population growth, particularly in small, reintroduced populations (IUCN/SSC, 2013). Low recruitment may reflect delayed female breeding responses, stress related to translocation, or predation on fawns during early establishment (Maor-Cohen, 2021). Continued demographic monitoring focusing on female survival, fawn production, and juvenile recruitment is therefore critical to evaluate reproductive success and ensure long-term viability.

Habitat suitability modeling supported these ecological observations. The MaxEnt models performed well (mean AUC = 0.98), indicating that the environmental variables effectively captured the species' habitat preferences, though the exceptionally high AUC values suggest possible overfitting. Elevation emerged as the most influential predictor, with deer favoring mid-elevation zones (~540 m a.s.l.) characterized by mixed grassland and dry deciduous forest mosaics. NDVI also contributed strongly, underscoring the importance of vegetation productivity and green cover in shaping habitat quality. At finer spatial scales, land surface temperature (LST) was a key determinant, reflecting the species' sensitivity to thermal stress and its preference for habitats that provide shade and microclimatic buffering. Additional variables such as slope, annual precipitation (BIO12), and precipitation of the driest month (BIO14) further highlighted the importance of moderate topography and consistent moisture availability for foraging and thermoregulation. These results are consistent with previous findings that identify structural and climatic stability as critical components of suitable deer habitat (Torres *et al*., 2014; Neupane *et al*., 2022; Trisurat & Bhumpakphan, 2018). Together, they emphasize that successful population establishment depends not only on habitat structure and vegetation diversity but also on the maintenance of favorable microclimatic and hydrological conditions. As climate variability increases, mid-elevation zones with high vegetation productivity may serve as important refugia. Consequently, long-term conservation strategies should prioritize the protection of grassland–forest interfaces, maintenance of water sources, and enhancement of landscape connectivity to facilitate seasonal movement and population expansion.

To improve the robustness of future modeling efforts, spatial cross-validation, variable reduction, and regularization adjustments should be applied to mitigate overfitting and enhance model generalization under changing environmental scenarios (Merow *et al*., 2013; Phillips *et al*., 2017). Given that occurrence data were derived from clustered release-area observations, apparent high AUC values may partly reflect sampling bias limitations that should be addressed in subsequent studies.

In addition to environmental and demographic factors, anthropogenic threats such as habitat encroachment and illegal hunting, poaching remain serious constraints to the recovery of endangered wildlife in the region. Effective conservation planning for future releases must therefore integrate habitat protection with community engagement and enforcement measures. Establishing buffer zones and local conservation networks around the sanctuary could help reduce human–deer conflicts and foster community stewardship.

Overall, the reintroduction of Siamese Eld's deer at this site demonstrates encouraging early success in terms of post-release adaptation, habitat use, and initial reproduction. However, sustaining long-term population growth will require a holistic management approach that integrates habitat management, demographic balance, genetic reinforcement, and adaptive monitoring. Supplementation with genetically compatible females or unrelated individuals may be necessary to correct observed sex-ratio imbalances and maintain genetic diversity, in line with IUCN/SSC reintroduction guidelines (IUCN/SSC, 2013). Continued camera-trap and GPS-collar monitoring will be essential to document movement patterns, home-range expansion, and reproductive outcomes, thereby enabling timely management responses to emerging ecological or anthropogenic pressures. Integrating population monitoring with long-term ecosystem and climate-change assessments will provide a comprehensive framework for securing a self-sustaining Siamese Eld's deer population and contribute to Thailand's broader efforts to restore endangered cervid species within their historical range. Although this study provides encouraging evidence of post-release establishment such as the continued presence of Siamese Eld's deer around the release site, the absence of detected mortality, and confirmed evidence of breeding the demographic results also highlight several challenges that may affect long-term population persistence. In particular, the strongly male-biased sex ratio and low recruitment suggest potential constraints on population growth, especially given the small founding population and the limited proportion of suitable habitat identified within the study area. These patterns may reflect a combination of sampling limitations, post-release demographic processes, and ecological constraints, including suboptimal habitat conditions for females and juveniles. Therefore, while the current findings indicate short-term persistence and initial success of the reintroduction program, they also underscore the importance of cautious interpretation and proactive management. Long-term population viability will depend on sustained monitoring, targeted habitat management to improve forage availability and female survival, and, if necessary, adaptive interventions such as population supplementation or habitat expansion to mitigate demographic risks. Taken together, the findings of this study provide important guidance for the long-term management and conservation of reintroduced Siamese Eld's deer populations. Management actions should extend beyond site-level habitat maintenance to include the design of functional buffer zones around core habitats, enhancement of landscape connectivity between grassland–forest mosaics, and the mitigation of predation and anthropogenic risks during early population establishment. Ensuring long-term population viability will further require attention to demographic stability, maintenance of genetic diversity through adequate founder numbers or future supplementation, and proactive surveillance of disease risks as population density increases. Although the present study is constrained by a relatively short temporal scope, limited sample size, and restricted spatial coverage of camera traps, the consistency of behavioral, habitat-use, and reproductive evidence nonetheless provides a robust early indication of successful establishment. Future monitoring incorporating broader spatial and temporal scales will be essential to refine estimates of carrying capacity, demographic trends, and dispersal dynamics. In a broader conservation context, these results align with IUCN reintroduction and translocation guidelines by demonstrating that reintroductions grounded in habitat suitability, adaptive management, and post-release monitoring can contribute meaningfully to species recovery. As such, this study offers a scalable, evidence-based framework to support coordinated national and regional efforts aimed at restoring viable Eld's deer populations across their historical range and strengthening the resilience of tropical ecosystems in Southeast Asia.

CONCLUSIONS

In summary, the reintroduced Siamese Eld's deer population has become established in areas surrounding the release sites, as evidenced by stable population densities (55–72 individuals/km²), observations of natural recruitment and consistent patterns of habitat use. These findings indicate that the species is capable of persisting in managed tropical landscapes when appropriate habitat structure and forage resources are maintained. Habitat suitability analyses further highlight the importance of topography, vegetation productivity, and temperature in shaping habitat use patterns, underscoring the need for explicit spatial planning in reintroduction programs and emphasizing the broader conservation potential of ungulate reintroductions in supporting species recovery and ecosystem restoration. Nevertheless, the observed population densities may partly reflect spatial aggregation of individuals around release areas and key resources rather than a uniform distribution across the broader landscape. Such clustering may limit the spatial representativeness of density estimates and reduce the ability of habitat suitability analyses to fully capture patterns of habitat use at larger spatial scales, representing an important limitation of this study. To ensure long-term population viability, management should prioritize the maintenance of mosaic grassland–forest habitats, enhancement of herbaceous and shrub forage resources, protection of highly suitable core areas, and the implementation of long-term post-release monitoring to support adaptive management. As populations expand, increased movements beyond protected areas—and potentially across international borders are likely to emerge as additional conservation challenges requiring coordinated planning. Looking forward, this study provides a practical framework for replicating and scaling up Siamese Eld's deer reintroduction in suitable protected areas in Thailand and across the species' historical range. The long-term success of such efforts will depend on integrating site-level habitat management with sustained monitoring, improved spatial coverage in future studies, and strengthened regional and transboundary conservation cooperation, thereby contributing to broader strategies for restoring viable populations of threatened large herbivores and enhancing ecosystem resilience.

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