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# Past, present and future habitat suitable for gaur (*Bos gaurus*) in Thailand

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**Abstract**

The gaur (*Bos gaurus*) distributes throughout mainland South and Southeast Asia. It is listed as an endangered species in Thailand, where its population has been decreasing and suitable habitat has been lost. This study explored the distribution of gaur in Thailand and assessed suitable gaur habitat in the past, present and future. Gaur occurrence data were obtained in 2010 and 2020 field surveys that recorded signs of gaur on wildlife trails and patrol routes in protected areas in Thailand. Maximum entropy was used to generate suitable habitat. The survey revealed gaur in 45 protected areas in 2010 and 59 protected areas in 2020. Although its range had expanded, suitable habitat had declined. The prediction of suitable areas for gaur showed that 10.0%, 7.7%, 8.0% and 8.2% of Thailand was suitable in the past, at present, and in the future based on models 1 and 2, respectively. By 2020, 31.8% of the suitable habitat in 2010 had been lost, while new suitable areas increased in extent by approximately 12.0%. Six potential forest zones for gaur conservation are the Western, Dong Phayayen-Khao Yai, Khlong Saeng-Khao Sok, Kaeng Krachan, Phu Khieo-Nam Nao and Eastern Forest Complexes. This study provided guidelines for gaur habitat management to maintain gaurs and their habitat in Thailand.

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## Introduction

The gaur (*Bos gaurus*) is a large wild ungulate that plays an important role as the main prey of large carnivores as well maintaining ecosystem quality by preventing vegetation overgrowth, especially of trees, grasses and herbs (Karanth and Sunquist, 1995; Roininen et al., 2007; Prasopsin et al., 2013; Sankar et al., 2013). The IUCN Red List notes the gaur as a vulnerable species, and its population is decreasing in scattered areas in 10 countries: Bhutan, Cambodia, China, India, Lao PDR, Peninsular Malaysia, Myanmar, Nepal, Thailand, and Vietnam (Duckworth et al., 2016). In Thailand, the gaur was upgraded to an endangered species from a vulnerable species in 2005 (Nabhitabhata and Chan-ard, 2005; Office of Natural Resources and Environment Policy and Planning, 2017). The gaur is a protected wild animal listed in the Wild Animal Reservation and Protection Act (2019). Gaurs are herbivorous and are more likely generalists than other wild Asian cattle, with two subspecies reported to inhabit forests of all elevations in Thailand: *Bos gaurus readei* occurs north of the Isthmus of Kra and *B. g. hubbacki* occurs south of it (Lekagul and McNeely, 1977). Gaurs are widespread in the 46 protected areas (PAs) in Thailand, with their abundance being highest in the Eastern Forest Complex, followed by the Dong Phayayen-Khao Yai, Khlong Sang-Khao Sok and Western Forest Complexes (Kanchanasaka et al., 2010). In 1995, the gaur population estimated from secondary sources was around 915 individuals, distributed in PAs in Thailand. The most important area for gaur conservation was Huai Kha Khaeng Wildlife Sanctuary (Srikosamatara and Suteethorn, 1995). With the expansion of agricultural areas, settlements and roads in Thailand, many wildlife habitats have become fragmented (Prayurasiddhi et al., 2013). The degradation, fragmentation and transformation of suitable habitat have resulted in small or extirpated gaur populations in many PAs. In addition, poaching and domesticated cattle are important threats to gaur, especially in northern and northeastern Thailand (Chaiyarat and Srikosamatara, 2009; Kanchanasaka et al., 2010).

Wildlife conservation depends on habitat maintenance (Reed, 2004), which requires habitat information to protect and improve habitat areas. However, recent data are lacking on the distribution and suitability of gaur habitat in Thailand. Such data are necessary to devise an action plan for gaur conservation. Understanding gaur habitat is very important for its maintenance and improvement. The objectives of this study were to assess the gaur distribution and identify past, present and future suitable gaur habitat in Thailand, and to provide guidelines for effective habitat management and conservation planning for gaur in Thailand.

## Materials and Methods

### *Study area*

The study was conducted in Thailand (5°37′–20°27′N and 97°22′–105°37′E, total area 513,115 km$^2$). In Thailand, 402 PAs covering 116,860 km$^2$ have been established to protect wildlife habitat, accounting for 22.8% of the country's area. These PAs comprise 60 wildlife sanctuaries (WSs; 37,377 km$^2$), 155 national parks (NPs; 70,651 km$^2$), 96 non-hunting areas (NHAs; 7,704 km$^2$) and 91 forest parks (1,128 km$^2$), which are grouped into 19 forest complexes (17 terrestrial and 2 marine), according to National Parks, Wildlife and Plant Conservation Department (2020). The 2010 surveys undertaken for the current study covered 151 PAs (91,882 km$^2$) consisting of 56 WSs (36,168 km$^2$) and 95 NPs (55,714 km$^2$). The 2020 surveys undertaken for the current study covered 211 PAs (105,173 km$^2$) consisting of 60 WSs (37,377 km$^2$), 133 NPs (63,616 km$^2$) and 18 NHAs (4,180 km$^2$). Many of the PAs had been designated recently, with the 2020 survey areas including all designated sites from 2010 onward.

### *Species occurrence data*

Gaur occurrence data were obtained from the Department of National Parks, Wildlife and Plant Conservation. The surveys conducted in 2010 and 2020 were standardized by creating 1 km$^2$ grid cells to analyze the study area, which covered all forest types and elevations. A past habitat suitability model was generated from 3,847 presence records. The presence data were recorded during a 'signs survey' and also included direct sightings in 2010 by the survey team, wildlife scientists in the Wildlife Research Division and park rangers trained to identify wildlife tracks and signs. Gaur signs in one 200 m line-survey section corresponded to one presence record. Gaur data were collected along wildlife trails and patrol routes in PAs. The survey in 2010 covered 14,673 grid cells (16.0% of the survey area). Present and future habitat suitability models were generated from 4,629 presence records. In 2020, the presence data were recorded from the signs survey and also included direct sightings by the Smart Patrol Monitoring Center. The survey team recorded the presence of gaur along wildlife trails, patrol routes and buffer zones in PAs across Thailand. Gaur signs in one 30 min survey period corresponded to one presence record. The survey in 2020 covered 72,428 grid cells (68.8% of the survey area). Distribution data were also extracted from camera trapping imagery.

*Environmental variables*

Habitat suitability was assessed based on 13 land cover (forest type and distances to the nearest intact forest landscape [IFL] and stream), topographic (elevation and slope), and bioclimatic (eight temperature, precipitation, diurnal range and isothermality parameters) variables (Table 1).

The Band Collection Statistics tool in ArcGIS were to select eight bioclimatic variables that had pairwise correlations less than 0.8 ($r < 0.8$) to predict habitat suitability (Trisurat et al., 2015; Ebrahimi et al., 2017): annual mean temperature (BIO1), mean diurnal range (BIO2), isothermality (BIO3), temperature seasonality (BIO4), maximum temperature of the warmest month (BIO5), annual precipitation (BIO12), precipitation seasonality (BIO15) and precipitation of warmest quarter (BIO18). The data for the period 1970–2000 were used to model the past and present. The future scenario used the same eight variables for 2050 based on the HadGEM2-ES model and the RCP45 scenario (Collins et al., 2011; Trisurat et al., 2012, 2015).

In 2000, forest covered 33.2% of Thailand, but this had declined to 31.7% by 2018 (Royal Forest Department, 2018). From satellite imagery, the forest was classified into 15 categories: moist evergreen, dry evergreen, hill evergreen, coniferous, peat swamp, mangrove, fresh-water swamp, beach, mixed deciduous, dry dipterocarp, bamboo, secondary forests, tropical grassland, vegetation on a rock platform and non-forest area. Each of these forest cover types as a proportion of the total area of Thailand in 2000 that provided suitable habitat in the past scenario was 2.8%, 4.5%, 2.9%, 0.1%, 0.1%, 0.4%, 0.1%, 0.01%, 17.3%, 3.7%, 0.3%, 0.6%, 0.3%, 0.1% and 66.8%, respectively. The present scenario used these forest types in 2018, which comprised 3.5%, 4.4%, 3.5%, 0.3%, 0.1%, 0.5%, 0.1%, 0.01%, 15.1%, 3.9%, 0.2%, 0.8%, 0.2%, 0.1% and 67.3%, respectively, of Thailand. For the future, two scenarios were generated. Future-model 1 predicted suitable habitat using the 2018 forest cover type data, while future-model 2 predicted the forest for 2050 from the 2018 forest cover type data. The 2050 forest excluded areas outside PAs. The percentage of forest cover in future-model 2 was 19.2% of Thailand, comprising 2.7%, 3.4%, 2.3%, 0.1%, 0.1%, 0.1%, 0.004%, 0.004%, 8.5%, 1.5%, 0.1%, 0.2%, 0.1%, 0.1% and 80.8%, respectively, of the 15 forest cover types.

**Table 1** Occurrence data and environmental variables for each scenario

| Occurrence data and variable | Scenario | | | | Source |
|---|---|---|---|---|---|
| | Past | Present | Future (Model 1) | Future (Model 2) | |
| Survey area | year 2010 (91,882 km²/151 PAs) | ------------------------year 2020--------------------- (105,173 km²/211 PAs) | | | National Parks, Wildlife and Plant Conservation Department, Thailand |
| Survey effort[a] | year 2010 (14,673 grid cells) | ------------------------year 2020--------------------- (72,428 grid cells) | | | |
| Gaur occurrence | year 2010 (3,847 records/1,301 grid cells) | ------------------------year 2020--------------------- (4,629 records/2,123 grid cells) | | | |
| Forest type[b] | year 2000 (165,598 km²) | year 2018 (157,899 km²) | year 2018 (157,899 km²) | year 2050[c] (94,836 km²) | Royal Forest Department, Thailand |
| Intact forest landscape | year 2000 (19,243 km²) | year 2016 (17,333 km²) | year 2016 (17,333 km²) | year 2050[d] (12,148 km²) | www.intactforest.org |
| Stream | year 2018 (created from topographic map at 1:50,000 scale) | | | | Royal Thai Survey Department, Thailand |
| Elevation | version 2.1 | | | | www.worldclim.org (version 2.1) |
| Slope | version 2.1 (created from elevation) | | | | |
| Bioclimatic variables[e] | ------------year 1970–2000------------ | | -------------year 2050----------- (HadGEM2-ES and RCP45) | | |

[a]Grid cell = 1 km²; [b]Forest area excluding islands; [c]Created from forest year 2018 by excluding forest area outside protected areas; [d]Created from intact forest area year 2016 by removing 1 km from edge of each patch; [e]Bioclimatic variables: annual mean temperature (BIO1), mean diurnal range (BIO2), isothermality (BIO3), temperature seasonality (BIO4), maximum temperature of the warmest month (BIO5), annual precipitation (BIO12), precipitation seasonality (BIO15) and precipitation of warmest quarter (BIO18)

IFL was defined as an unbroken forest expanse with a minimum area of 500 km$^2$, minimum patch width of 10 km, and minimum corridor or 'appendage' width of 2 km (Potapov et al., 2008). In Thailand, most IFL was in PAs and covered 19,243 km$^2$ in 2000 (17.9% of PAs, excluding islands and forest parks) and declined to 17,333 km$^2$ (16.1% of PAs) in 2016. The past model was generated from the IFL for 2000 and used the IFL for 2016 to generate the present model. Similarly, to predict future suitable habitat, future-model 1 used the IFL for 2016, while future-model 2 used the IFL predicted for 2050 that was created by reducing the area 1 km from each edge patch of the IFL in 2016 for the remaining 12,148 km$^2$ (11.3% of the PA). The reduction of each edge patch was determined from the buffer zone width (Potapov et al., 2008).

*Habitat suitability model*

Maximum entropy species distribution modeling (Maxent) ver. 3.3.3 was used to analyze habitat suitability (Phillips et al., 2006; Phillips and Dudik, 2008) in the past, present and future (Ebrahimi et al., 2017; Kim et al., 2020). Maxent was chosen because the dataset comprised presence-only data. In total, 75% of the occurrence data were randomly selected for use as training data and the remaining 25% was used as test data (Cianfrani et al., 2010; Trisurat et al., 2015). Maxent selected one presence record in each 1 km$^2$ grid cell and used 1,301 records to generate the past model and 2,123 records for the present and future ones (Fig. 1).

Each environmental layer was resampled to a 1 km$^2$ cell size covering 511,000 km$^2$ of the mainland. For the future models, habitat suitability was modeled under the 2050 climate change and land cover change scenario. The model with the lowest Akaike information criterion and the omission rate was determined using the kuenm package implemented in R Studio (Cobos et al., 2019) in conjunction with the R package (R Core Team, 2020). To identify suitable habitat, a cut-off probability for the presence value (0–1) was used based on the logistic threshold of the maximum training sensitivity plus specificity. To identity 'core' areas, equal training sensitivity and specificity were used (Trisurat et al., 2015; Planisong et al., 2018; Silva et al., 2020), as shown in Table 2. After identifying suitable habitat, patches were selected that exceeded the minimum gaur home range area (> 32 km$^2$) to analyze the change in suitable gaur areas (Conry, 1989; Arrendran, 2000; Sankar et al., 2013).

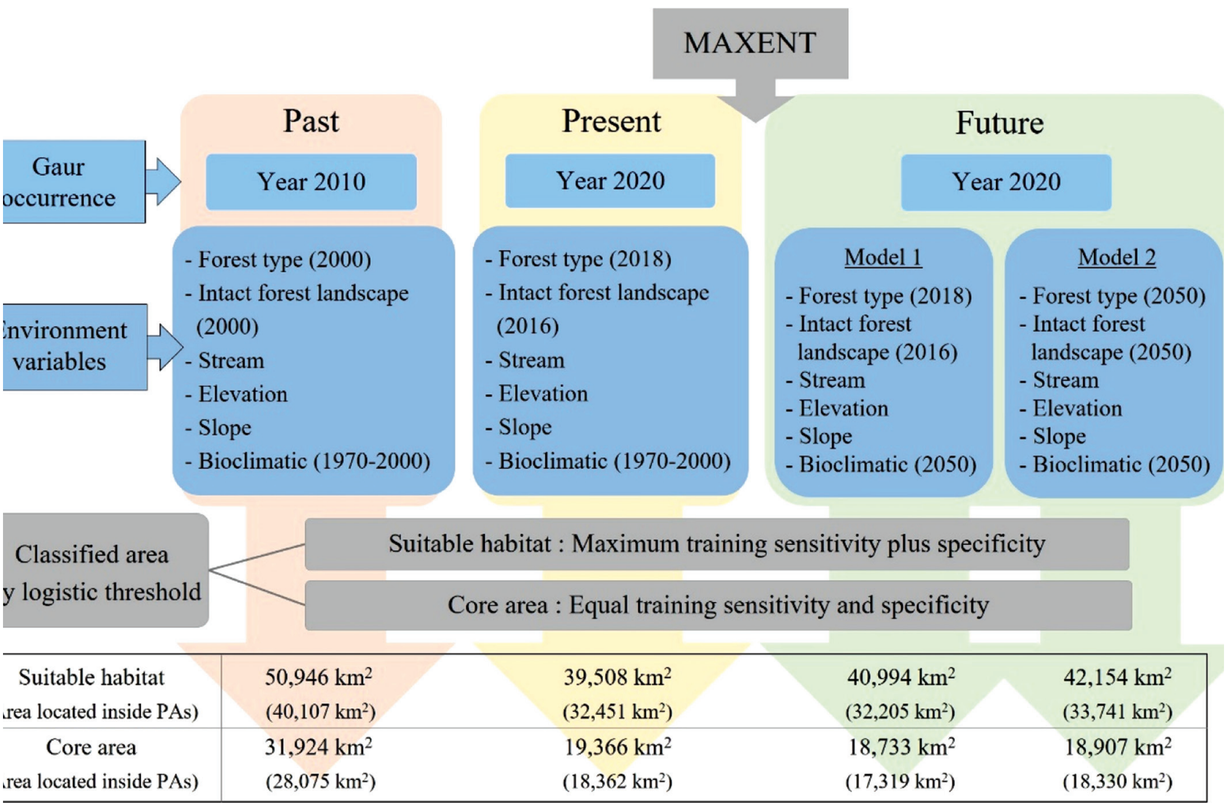


**Fig. 1** Variables used for species distribution modeling, where PA = protected area

**Table 2** Model selection using the kuenm R package and cut-off thresholds

| Period | RM | FC | Mean AUC ratio | Partial ROC | Omission rate 5% | AIC | Delta AIC | Weight AIC[c] | Number of parameters | Logistic threshold[c] | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | MTSPS | ETSAS |
| Past | 0.1 | lqp | 1.828 | 0.000 | 0.046 | 28285.145 | 0.000 | 0.999 | 68 | 0.196 | 0.367 |
| Present | 0.2 | lqh | 1.871 | 0.000 | 0.049 | 45135.845 | 0.000 | 0.999 | 207 | 0.197 | 0.427 |
| Future- | | | | | | | | | | | |
| model 1 | 0.1 | lqph | 1.866 | 0.000 | 0.047 | 45193.767 | 0.000 | 1.000 | 230 | 0.212 | 0.435 |
| model 2 | 0.1 | ph | 1.869 | 0.000 | 0.043 | 45226.721 | 0.000 | 0.999 | 237 | 0.195 | 0.424 |

RM = regularization multiplier; FC = feature classes (l = linear, q = quadratic, p = product, h = hinge); AUC = area under the curve; ROC = receiver operating characteristic; AIC = Akaike information criterion; AIC[c] = AIC cut-off value; Logistic threshold[c] = logistic threshold cut-off value; MTSPS = maximum training sensitivity plus specificity logistic threshold; ETSAS = equal training sensitivity and specificity logistic threshold

## Results

### *Distribution*

Gaurs occurred only in terrestrial forest complexes. In 2010, gaurs occurred in 45 PAs (13 forest complexes) covering 44,107.2 km$^2$. In 2020, gaurs were distributed in 59 PAs (11 forest complexes) covering 47,446.1 km$^2$. The gaur distribution was stable in 40 PAs (41,198.7 km$^2$), while they disappeared from 5 PAs (2,908.5 km$^2$) and newly occurred in 19 PAs (6,217.4 km$^2$), as shown in Table 3.

Fig. 2 shows 10 forest complexes with stable gaur distributions. Three forest complexes lost gaur, while in one complex a new range occurred. Due to habitat loss, gaurs disappeared from three large PAs in northern Thailand and two small PAs in the south. Conversely, gaurs occupied new ranges in several parts of Thailand: four PAs in the north, seven in the northeast, two in the east, five in the west and one in southern Thailand.

### *Habitat suitability*

Maxent was accurate (area under the curve > 0.9) for all habitat suitability models. Land cover variables made relatively large contributions, while bioclimatic variables made the greatest contribution, except in the past model (Table 4).

In the past scenario, 78.7% of the suitable area was within 107 PAs. An area of 50,946 km$^2$ (10% of Thailand) was suitable for gaurs and 31,924 km$^2$ (6.2% of Thailand) formed the core area (Table 5 and Fig. 3). Forest type, distance to intact forest and mean diurnal range were the most important environmental variables affecting gaur habitat suitability in the past (Table 4) when moist evergreen forest had the highest probability of guar presence (value 0.61).

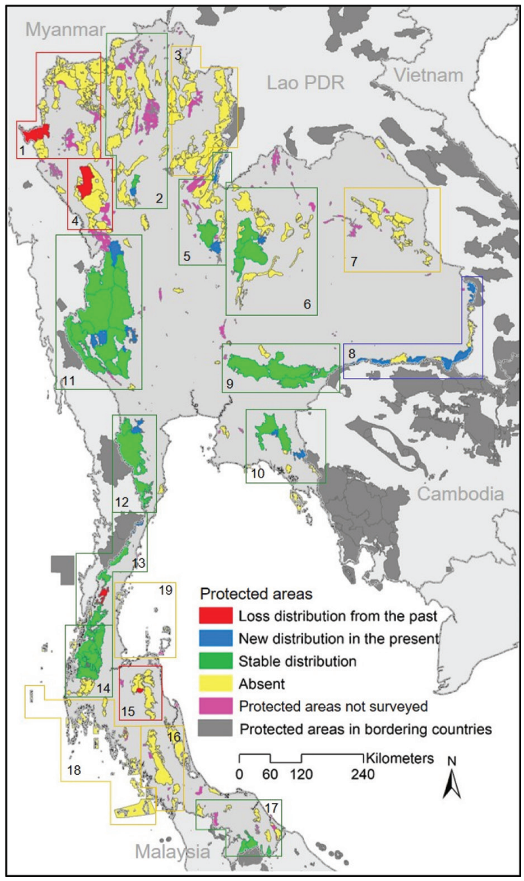


**Fig. 2** Gaur distribution in Thailand, where colored outlines of boxes indicate forest complex management units: 1) Lum Nam Pai-Salawin, 2) Srilanna-Khun Tan, 3) Doi Phu Kha-Mae Yom, 4) Mae Ping-Om Koi, 5) Phu Miang-Phu Thong, 6) Phu Khieo-Nam Nao, 7) Phu Phan, 8) Phanom Dongrak-Pha Tam, 9) Dong Phayayen-Khao Yai, 10) Eastern, 11) Western, 12) Kaeng Krachan, 13) Chumphon, 14) Khlong Saeng-Khao Sok, 15) Khao Luang, 16) Khao Ban That, 17) Hala-Bala, 18) Mo Kho Similan-Peepee-Andaman, 19) Mo Kho Ang Thong-Ao Thai, green boxes indicate stable distribution areas in the forest complex, blue boxes show new distribution areas in the forest complex, red boxes indicate a loss of distribution and yellow boxes are areas of no distribution in the forest complex

**Table 3** Distribution of gaurs in Thailand

| Protected area | Area ($km^2$) | Gaur presence | |
|---|---|---|---|
| | | 2010 | 2020 |
| Lum Nam Pai-Salawin Forest Complex (11,551 $km^2$) | | | |
| Mae Yuam Fang Khwa WS[a] | 292 | TS | NA |
| Salawin WS[a] | 955 | TS | NA |
| No. of survey grids[n] | | 1,410 | 8,147 |
| No. of presence grids | | 2 | 0 |
| Srilanna-Khun Tan Forest Complex (9,879 $km^2$) | | | |
| Si Satchanalai NP | 213 | TS | TS |
| Tham Chao Ram WS | 341 | NA | TS |
| No. of survey grids | | 686 | 5,619 |
| No. of presence grids | | 1 | 13 |
| Mae Ping-Om Koi Forest Complex (5,474 $km^2$) | | | |
| Omkoi WS | 1,224 | TS | NA |
| No. of survey grids | | 435 | 3,697 |
| No. of presence grids | | 1 | 0 |
| Phu Miang-Phu Thong Forest Complex (5,167 $km^2$) | | | |
| Khao Kho NP | 482 | NA | TS |
| Phu Soi Dao NP[b] | 340 | NA | TS |
| Thung Salaeng Luang NP | 1,262 | TS | TS |
| Wang Pong-Chon Daen NHA | 140 | NA | TS |
| *No. of survey grids* | | 573 | 3,686 |
| No. of presence grids | | 31 | 26 |
| Phu Khieo-Nam Nao Forest Complex (8,347 $km^2$) | | | |
| Nam Nao NP | 994 | TS | TS, CT |
| Pha Phueng WS | 189 | NA | TS |
| Phu Khieo WS | 1,560 | TS | TS, CT |
| Thabo-Huai Yai WS | 653 | TS | TS |
| Tat Mok NP | 290 | TS | TS |
| No. of survey grids | | 2,578 | 5,904 |
| No. of presence grids | | 300 | 199 |
| Phanom Dongrak-Pha Tam Forest Complex (3,146 $km^2$) | | | |
| Pha Taem NP[c] | 340 | NA | TS |
| Phu Chong-Na Yoi NP[d] | 686 | NA | TS |
| Yod Dom WS[d] | 225 | NA | TS |
| Phanom Dong Rak WS[e] | 316 | NA | TS |
| Huai Taptan-Huai Samran WS[f,k] | 501 | NA | CT |
| No. of survey grids | | 752 | 2,669 |
| *No. of presence grids* | | 0 | 9 |
| Dong Phayayen-Khao Yai Forest Complex (6,587 $km^2$) | | | |
| Dong Yai WS | 312 | TS | TS, CT |
| Khao Yai NP | 2,165 | TS | TS, CT |
| Khao Phaeng Ma NHA | 8 | NA | TS, CT |
| Pang Sida NP | 844 | TS | TS, CT |
| Thap Lan NP | 2,235 | TS | TS, CT |
| Western Forest Complex (19,816 $km^2$) | | | |
| Chaloem Rattanakosin NP | 59 | NA | CT |
| Erawan NP | 549 | TS | CT |
| Huai Kha Khaeng WS | 2,780 | TS | TS, CT |
| Khao Laem NP | 1,496 | TS | CT |
| Khlong Lan NP | 300 | TS | TS, CT |
| Khlong Wang Chao NP | 747 | NA | TS, CT |
| Khuean Srinagarindra NP | 1,532 | TS | CT |
| Lam Klong Ngu NP | 672 | NA | CT |
| Mae Wong NP | 894 | TS | TS |
| Phu Toei NP | 317 | NA | CT |
| Thong Pha Phum NP[i] | 1,235 | TS | CT |
| Thung Yai Nareasuan WS[a] | 3,647 | TS | TS, CT |
| Salak Phra WS | 858 | TS | CT |
| Sai Yok NP[a] | 500 | TS | CT |
| Umphang WS[a] | 2,590 | TS | TS |
| No. of survey grids | | 1,869 | 14,669 |
| No. of presence grids | | 349 | 678 |
| Kaeng Krachan Forest Complex (5,056 $km^2$) | | | |
| Chaloem Phra Kiat Thai Prachan NP | 328 | NA | TS |
| Kaeng Krachan NP[j] | 2,914 | TS | TS, CT |
| Kui Buri NP[a] | 969 | TS | TS |
| Mae Nam Phachi WS[a] | 489 | TS | TS |
| No. of survey grids | | 983 | 2,763 |
| No. of presence grids | | 126 | 96 |
| Chumphon Forest Complex (2,630 $km^2$) | | | |
| Namtok Huai Yang NP[k] | 161 | NA | TS, CT |
| Namtok Ngao NP | 668 | TS | TS |
| Utthayan Sadetnaikrom | 664 | TS | TS |
| Krommalaung Chumphon-North WS[l] | | | |
| Utthayan Sadetnaikrom | 315 | TS | TS |
| Krommalaung Chumphon-South WS[a] | | | |
| Thung Raya-Na Sak WS | 338 | TS | NA |
| No. of survey grids | | 340 | 1,866 |
| No. of presence grids | | 26 | 55 |
| Khlong Saeng-Khao Sok Forest Complex (5,563 $km^2$) | | | |
| Kaeng Krung NP | 541 | TS | TS |
| Khao Sok NP | 738 | TS | TS |
| Khlong Nakha WS | 530 | TS | TS |
| Khlong Saeng WS | 1,155 | TS | TS, CT |
| Khlong Yan WS | 488 | TS | TS |
| Khuan Mae Yai Mon WS | 464 | TS | TS |
| Si Phang-nga NP | 246 | TS | TS |

**Table 3** Continued

| Protected area | Area (km$^2$) | Gaur presence 2010 | Gaur presence 2020 |
|---|---|---|---|
| Ta Phraya NP[f] | 594 | TS | TS, CT |
| No. of survey grids | | 574 | 2,049 |
| No. of presence grids | | 193 | 427 |
| Eastern Forest Complex (3,695 km$^2$) | | | |
| Khao Ang Ruenai WS | 1,078 | TS | TS, CT |
| Khao Chamao-Khao Wong NP | 83 | TS | TS |
| Khao Sip Ha Chan NP | 117 | NA | TS |
| Khao Soi Dao WS | 744 | TS | TS |
| Khlong Khruea Wai Chaloem | 265 | NA | TS |
| Phra Kiat WS[h] | | | |
| No. of survey grids | | 373 | 1,861 |
| No. of presence grids | | 111 | 100 |
| No. of survey grids | | 772 | 3,879 |
| No. of presence grids | | 129 | 520 |
| Khao Luang Forest Complex (1,835 km$^2$) | | | |
| Kathun WS | 98 | TS | NA |
| No. of survey grids | | 366 | 1,155 |
| No. of presence grids | | 1 | 0 |
| Hala-Bala Forest Complex (2,474 km$^2$) | | | |
| Bang Lang NP[m] | 216 | TS | TS |
| Hala-Bala WS[m] | 626 | TS | TS |
| No. of survey grids | | 334 | 861 |
| No. of presence grids | | 31 | 2 |

WS = wildlife sanctuary, NP = national park; NHA = non-hunting area; TS = track and signs (footprint, dung, carcass, directed sighting), CT = camera trapping, NA = not apparent; [a]Borders forest of Myanmar (non-protected area); [b]Borders Protection Area of Lao PDR; [c]Borders Phu Xieng Thong National Protected Area of LaoPDR; [d]Borders Chhaeb WS of Cambodia; [e]Borders Preah Vihear Protected Landscape of Cambodia; [f]Borders Banteay Chhmar Protected Landscape of Cambodia; [g]Borders North West Biodiversity Corridor of Protected Area of Cambodia; [h]Borders Samlaut Multiple Use Area of Cambodia; [i]Borders Taninthayi Nature Reserve of Myanmar; [j]Borders Taninthayi NP of Myanmar; [k]Borders Lenya NP (extension proposed) of Myanmar; [l]Borders Lenya NP of Myanmar; [m]Borders Royal Belum State Park of Malaysia; [n]Survey grid cell = 1 km$^2$

**Table 4** Area under the curve (AUC) of receiver operating characteristic curve, relative percentage contributions (RC), and permutation importance (PI) normalized and presented as percentage values of environmental variables for modeling suitable gaur habitat

| Environmental variable | Past (AUC 0.923) | | Present (AUC 0.905) | | Future Model 1 (AUC 0.906) | | Future Model 2 (AUC 0.907) | |
|---|---|---|---|---|---|---|---|---|
| | RC | PI | RC | PI | RC | PI | RC | PI |
| Land cover variable | | | | | | | | |
| Forest type | 35.7 | 4.5 | 17.7 | 1.3 | 17.1 | 4.2 | 22.7 | 4.1 |
| Distance to intact forest landscape | 28.6 | 59.9 | 67.3 | 9.1 | 61.9 | 16.9 | 54.7 | 19.6 |
| Distance to stream | 0.2 | 0.5 | 0.1 | 0.1 | 0.2 | 0.5 | 0.1 | 0.3 |
| Topographic variable | | | | | | | | |
| Elevation | 1.5 | 2.7 | 1.5 | 2.7 | 2.6 | 11.5 | 2.7 | 11.5 |
| Slope | 0.8 | 0.5 | 0.2 | 0.2 | 0.2 | 0.5 | 0.1 | 0.3 |
| Bioclimatic variable | | | | | | | | |
| BIO1: Annual mean temperature | 2.1 | 1.1 | 1.9 | 21.8 | 0.8 | 3.9 | 1.1 | 2.6 |
| BIO2: Mean diurnal range | 17.3 | 1.8 | 0.7 | 0.8 | 2.4 | 9.0 | 3.5 | 9.3 |
| BIO3: Isothermality | 3.9 | 9.5 | 1.9 | 6.7 | 4.7 | 3.5 | 2.2 | 3.4 |
| BIO4: Temperature seasonality | 2.5 | 8.9 | 2.0 | 26.7 | 2.0 | 26.5 | 2.9 | 25.1 |
| BIO5: Max temperature of warmest month | 4.6 | 3.7 | 0.8 | 1.8 | 2.2 | 2.3 | 4.8 | 2.1 |
| BIO12: Annual precipitation | 1.0 | 1.5 | 0.5 | 1.4 | 0.6 | 2.7 | 0.4 | 2.3 |
| BIO15: Precipitation seasonality | 1.3 | 3.9 | 4.8 | 26.2 | 4.1 | 14.8 | 3.0 | 15.5 |
| BIO18: Precipitation of warmest quarter | 0.5 | 1.5 | 0.6 | 1.4 | 1.2 | 3.8 | 1.7 | 3.9 |

In the present scenario, 82.1% of the suitable habitat was located inside 80 PAs. An area of 39,508 km$^2$ (7.7% of Thailand) was suitable for gaurs and 19,366 km$^2$ (3.8% of Thailand) formed the core area (Table 5 and Fig. 3). In the 2020 scenario model, distance to intact forest, forest type and precipitation seasonality were the most important environmental variables affecting gaur habitat suitability (Table 4). The highest probability of presence was in bamboo forest (value 0.57), which is a subtype of mixed deciduous forest.

**Table 5** Suitable habitat (SH) and core area (CA) in the past, present and future

| Model | Area (km$^2$) | | % of Thailand[a] | | % of PAs[b] | | Area located inside PAs | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Area (km$^2$) | | % of Area | |
| | SH | CA | SH | CA | SH | CA | SH | CA | SH | CA |
| Past | 50,946 | 31,924 | 10.0 | 6.2 | 37.3 | 26.1 | 40,107 | 28,075 | 78.7 | 87.9 |
| Present | 39,508 | 19,366 | 7.7 | 3.8 | 30.2 | 17.1 | 32,451 | 18,362 | 82.1 | 94.8 |
| Future- | | | | | | | | | | |
| model 1 | 40,994 | 18,733 | 8.0 | 3.6 | 30.0 | 16.1 | 32,205 | 17,319 | 78.6 | 92.5 |
| model 2 | 42,154 | 18,907 | 8.2 | 3.7 | 31.4 | 17.0 | 33,741 | 18,330 | 80.0 | 96.9 |

PA = protected area

[a]Thailand area (511,000 km$^2$, excluding islands); [b]Total PA area (107,458 km$^2$, excluding islands and forest parks)

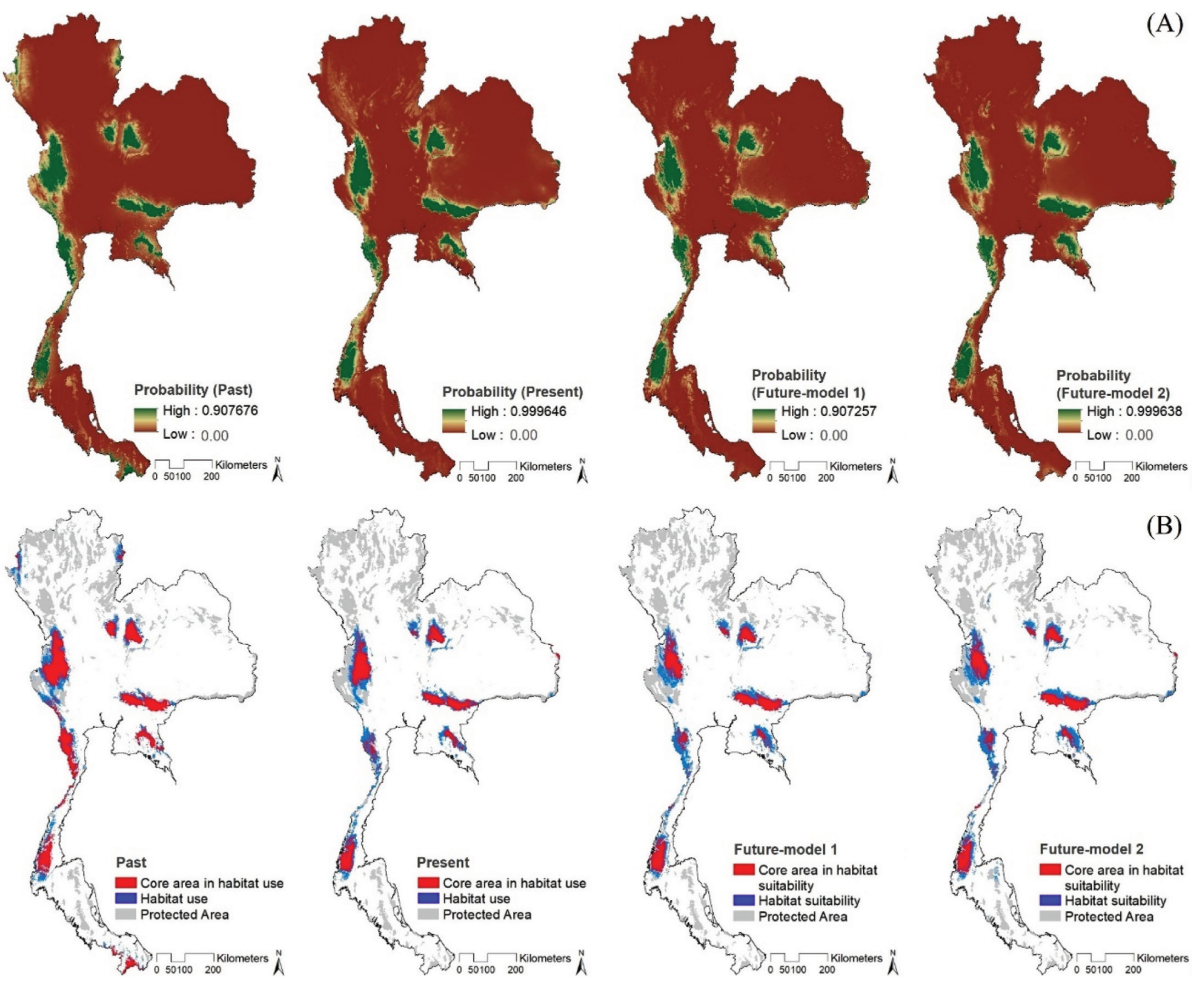


**Fig. 3** Habitat suitability (A) for gaurs in the past, present and future; (B) habitat classified as suitable habitat and core areas in different periods

In future-model 1, 78.6% of the suitable habitat was located inside 87 PAs. An area of 40,994 km$^2$ (8% of Thailand) would be suitable for gaurs and 18,733 km$^2$ (3.6% of Thailand) will form the core area. Similarly, in future-model 2, the suitable habitat and core areas comprised 42,154 km$^2$ (8.2% of Thailand) and 18,907 km$^2$ (3.7% of Thailand), respectively, with around 80% of the suitable habitat located inside 101 PAs (Table 5 and Fig. 3). In both future models, the distance to intact forest and forest type will be the most important environment variables affecting gaur habitat suitability (Table 4). Secondary forest had the highest probability of guar presence (value 0.59) in both models.

The most important environmental variable in the past was forest type, whereas the distance to intact forest was the most important in the present and future analyses. Different forest types had high values in each of the three periods (forest in the past, bamboo forest in the present and secondary forest in the future). In all periods, the probability of presence was higher close to intact forest.

*Changing habitat suitability and source sites*

The habitat prediction showed that the suitable habitat will change from the past to the future (Fig. 4). At present, 16,201 km$^2$ of suitable area (31.8% of the past suitable area) has been lost, while the predicted new suitable area is 4,748 km$^2$ (12% of the present suitable area). In the future, 5,326 km$^2$ and 5,425 km$^2$ (13.5% and 13.7% of the present suitable area) will be lost in models 1 and 2, respectively. These models predicted future gains of suitable areas of 6,813 km$^2$ (16.6% of the future-model 1 suitable area) and 8,072 km$^2$ (19.1% of the future-model 2 suitable area) in models l and 2, respectively. The main change in suitable area from the past to the present was the loss of 2,991 km$^2$ of suitable area in the far north (Lum Nam Pai-Salawin and Doi Phu Kha-Mae Yom Forest Complexes) and far south (Hala-Bala Forest Complex). Most of the lost suitable habitat was in fragmented areas, at the edges of patches or outside PAs. New suitable forest complex areas were located in the northeast (Phanom Dong Rak-Pha Tam Forest Complex), which is separated from the other suitable patches (Fig. 4A). Examining the future trends, future-models 1 (Fig. 4B) and 2 (Fig. 4C) both predict similar changes in suitable areas. Most of the lost and new suitable areas will be fragmented and located at the edges of suitable patches.

Although suitable habitat accounted for over 30% of the PAs in all periods, some patches were fragmented and small. After selecting suitable patches, the habitat area remaining in each model was 47,702 km$^2$, 38,273 km$^2$, 38,337 km$^2$ and 40,067 km$^2$ in the past, present, and future-models 1 and 2, respectively, or losses of 6.4%, 3.1%, 6.5% and 5.0%, respectively, of the

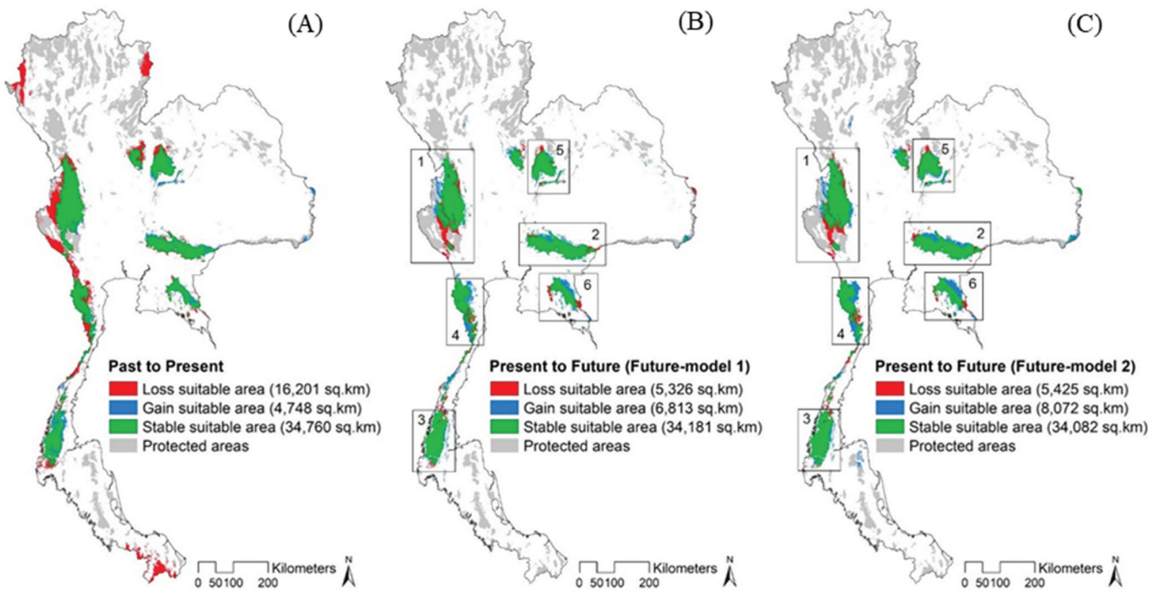


**Fig. 4** Changes in suitable gaur habitat in three periods: (A) between past and present based on change from 2010 under land cover variable changes; (B) between present and future-model 1, based on change from 2020 under climate change 2050 scenario; (C) between present and future-model 2, based on change from 2020 under combined land cover change and climate change 2050 scenario, where boxes indicate suitable habitat with greatest potential for gaur conservation in six forest complexes: 1) Western, 2) Dong Phayayen-Khao Yai, 3) Khlong Saeng-Khao Sok, 4) Kaeng Krachan, 5) Phu Khieo-Nam Nao and 6) Eastern Forest Complexes

suitable habitat. Specifically, the suitable patches located inside PAs covered 38,943 km$^2$ in the past, 31,863 km$^2$ in the present, 31,196 km$^2$ in future-model 1 and 32,175 km$^2$ in future-model 2 (Table 6). Most of the suitable patches were in large PAs or PAs bordered by more than two other PAs. From a size perspective, the areas with the most potential as forest complex for gaur conservation and habitat were located in the Western, Dong Phayayen-Khao Yai, Khlong Sang-Khao Sok, Kaeng Krachan, Phu Khieo-Nam Nao and Eastern Forest Complexes. The Western Forest Complex was the largest area in all three periods.

## Discussion

### *Distribution*

Gaurs disappeared from two terrestrial forest complexes (FCs; Doi Phu Kha-Mae Yom FC and Phu Pan FC) in the past and were still not detected in the surveys carried out in the current study (Table 3 and Fig. 2). Fragmented habitat and major human activities in these areas likely resulted in gaur extirpation (Pisdamkham et al., 2010; Kanchanasaka et al., 2010; Trisurat et al., 2015). At present, gaurs are disappearing from northern (Lum Nam Pai-Salawin and Mae Ping-Om Kai FC) and southern (Khao Luang FC) Thailand. The 19 new PAs with gaurs in 2020 mostly bordered the 2010 range. This might have been due to the greater survey effort in 2020. Other possible reasons for the additional areas include the increased protection and patrolling of PAs and the decreased demand for gaur horn (National Parks, Wildlife and Plant Conservation Department, personal communication). Similarly, Duangchantrasiri et al. (2016) reported that intensive patrolling after 2006 in the Western FC reduced poaching, which increased tiger survival and recruitment. Kanchanasaka et al. (2010) also discovered that gaur abundance was increasing in large PAs connected to large patch habitats. In addition, small groups of gaurs inhabit areas outside PAs in both completely separated areas and agricultural areas bordering PAs.

New distribution areas separated from other parts of the gaur range in 2010 include the Phu Miang-Phu Thong FC (Phu Soi Dao NP) and Eastern FC (Khlong Khruea Wai Chaloem Phra Kiat WS). The gaur found at present might have been due to the increased survey effort in these areas. For the Phanom Dong Rak-Pha Tam FC, a new area for gaurs in 2020, the surveys in 2010 and 2020 covered 23.9% and 84.8% of this forest complex, respectively. Thus, the survey in 2010 might not have covered all areas where gaurs occur. Additionally, strong habitat protection in some PAs has resulted in more

**Table 6** Suitable habitat (each patch > 32 km$^2$) located within forest complexes

| Forest Complex | Suitable area in each period (km$^2$) | | | | Stable suitable area (km$^2$) | |
|---|---|---|---|---|---|---|
| | Past | Present | Future-model 1 | Future-model 2 | Stable1 | Stable2 |
| Lum Nam Pai-Salawin | 1,097.8 | – | – | – | – | – |
| Srilanna-Khun Tan | – | – | – | 51.3 | – | – |
| Doi Phu Kha-Mae Yom | 936.7 | – | – | – | – | – |
| Phu Miang-Phu Thong | 1,592.8 | 1,250.4 | 1,280.0 | 1,275.9 | 1,098.8 | 1,079.3 |
| Phu Khieo-Nam Nao | 3,475.9 | 3,520.0 | 3,369.9 | 3,446.9 | 2,826.4 | 2,818.6 |
| Phanom Dongrak-Pha Tam | – | 118.6 | 207.6 | 388.6 | – | – |
| Dong Phayayen-Khao Yai | 5,391.8 | 5,489.0 | 5,577.5 | 5,753.9 | 5,154.9 | 5,178.8 |
| Eastern | 2,210.5 | 2,182.3 | 1,871.4 | 2,103.6 | 1,634.8 | 1,780.1 |
| Western | 13,603.7 | 10,424.5 | 9,434.1 | 9,513.9 | 8,505.5 | 8,600.7 |
| Kaeng Krachan | 4,524.1 | 3,665.6 | 4,332.8 | 4,465.9 | 3,504.3 | 3,535.3 |
| Chumphon | 1,247.8 | 1,118.9 | 1,085.9 | 960.5 | 565.1 | 604.1 |
| Khlong Saeng-Khao Sok | 3,905.1 | 4,094.1 | 4,036.8 | 4,146.8 | 3,530.5 | 3,586.8 |
| Khao Luang | – | – | – | 67.9 | – | – |
| Hala-Bala | 957.2 | – | – | – | – | – |
| Total Area | 38,943.5 | 31,863.5 | 31,195.9 | 32,175.3 | 26,820.4 | 27,183.6 |
| (% of Protected areas) | (36.2%) | (29.6%) | (29.3%) | (29.9%) | (25.0%) | (25.3%) |

Stable1 = stable suitable area from past to future-model 1; Stable2 = stable suitable area from past to future-model 2 gaurs occurring near the borders of the PA. This explains why gaurs now exist in Phanom Dong Rak-Pha Tam FC. However, this FC has experienced a high degree of disturbance by human settlements and forest conversion to agriculture (Trisurat and Bhumpakphan, 2018).

Lastly, small gaur populations were found in the Srilanna-Khun Tan FC and Hala-Bala FC. In the latter, small groups of gaurs were noted in Bang Lang NP and Hala-Bala WS. However, this habitat is at high risk of population extirpation because these forests are experiencing changes in habitat, high habitat loss and forest degradation due to agricultural development (Schwabe et al., 2015).

*Habitat suitability*

The habitat suitability model for the different scenarios showed that the land cover variables of forest type and distance to intact forest were the most important determinants of gaur presence in all periods. In the past model, forest type was the most important variable determining gaur presence, while the distance to IFL was the most important in the present model and future-models 1 and 2. The forest type with the highest probability of gaurs was moist evergreen forest in the past, bamboo forest (a subtype of mixed deciduous forest) in the present and secondary forests in the future. These forest types could provide various natural forage species for herbivores. Of the topographic variables, elevations with the highest probability of presence were 700–800 m above mean sea level (msl) in the past and 900–1,000 m above msl in the present. This shift was likely a consequence of the destruction of suitable lowland habitat. Similarly, Prayurasiddhi (1998) reported that gaurs in the Huai Kha Khaeng WS, Western FC preferred mixed deciduous forest habitat with elevations of 200–600 m above msl in the wet season, while they used evergreen forest > 400 m above msl in the dry season. In addition, Bhumpakphan (1997) reported that mixed deciduous and dry evergreen forests at elevations of 180–1,500 m above msl were the most suitable habitat type in Huai Kha Khaeng WS. In Khlong Saeng WS, Khlong Saeng-Khao Sok FC, the most suitable habitats were moist evergreen and moist mixed deciduous forest at elevations of 65–650 m above msl. In Kui Buri NP (Kang Krachan FC), gaur populations were high in lowland areas with human-modified secondary forest habitats dominated by grass patches (Tanasarnpaiboon, 2016). Furthermore, in central Pahang Malaysia, gaurs heavily used elevations below 61 m above msl, where the most important habitats were secondary forests, agricultural areas and lowland riverine areas (Conry, 1989). In the Xe Pian National Protected Area in Lao PDR, gaurs were reported to be common in mixed deciduous forest, dry dipterocarp forest and semi-evergreen forests (Steinmetz, 2004). In Asia overall, deciduous forest is more suitable habitat for gaurs and herbivores, such as banteng (*Bos javanicus*), sambar (*Cervus unicolor*) and barking deer (*Muntjac* spp.), than evergreen forests (McShea et al., 2011).

The main predictors of gaur distribution were forest type, distance to IFL and bioclimatic variables (mean diurnal range, precipitation seasonality, isothermality and maximum temperature of the warmest month). In contrast, Trisurat et al. (2015) found that the variables most strongly associated with gaurs in northern Thailand were temperature variables (mean, maximum and minimum temperatures), precipitation in the coldest season and distance to roads. In the Western FC, suitable gaur habitat has shallow slopes and is closer to ranger stations and streams and farther from villages. Gaurs avoid disturbed areas and are more likely to be present near streams (Trisurat et al., 2010). Deforestation had a greater effect on the loss of suitable habitat than climate change (Trisurat et al., 2015). Similarly, the most suitable gaur habitat in the Chandoli Tiger Reserve, India was determined based on land use and land cover (grassland), forest cover density (40–70%) and the proximity of patches (Imam and Kushwaha, 2013). Thus overall, forest area seems to be important for gaur habitat selection.

*Changes in habitat suitability and source site*

Although the forest areas in Thailand have been designated PAs, the area of suitable gaur habitat located within these PAs decreased by 7,080 $km^2$ over 10 years (2010–2020), resulting in 18.2% of the suitable area in 2010 being lost by 2020. The loss of suitable gaur habitat has various causes. Based on habitat suitability, the most important environmental variables for habitat selection were forest type and IFL. Currently, forest area is in decline, especially the important evergreen and mixed deciduous forest habitat, due to the reduction in IFL (Potapov et al., 2008; Heino et al., 2015; Royal Forest Department, 2018). In addition, gaurs are now more likely to occur at higher elevations than in the past, probably because suitable lower habitat has been increasingly disturbed. Threats to wildlife habitat include human activities, habitat loss and habitat degradation, which have reduced the gaur population and suitable habitat. Many PAs border villages, resulting in the PA habitat being disturbed by humans. Furthermore, the edges of PAs have been transformed into agricultural areas and plantations, which are important causes of habitat loss.

*Management recommendations*

The current study found that suitable patch areas remained in six forest complexes and that most suitable gaur habitat was connected to large patches. The management of these forest complexes is important for protecting and maintaining gaur habitat sustainability in Thailand. Areas including the Western, Kaeng Krachan, Chumphon and Khlong Saeng-Khao Sok Forest Complexes should be prioritized for intensive management (Fig. 5A). In the largest suitable patch area, the Western FC, previously suitable habitat bordering present habitat should be improved to protect the gaur population there. The PAs in the Western FC (Huai Kha Khaeng WS and Thung Yai Nareasuan WS) are strongly protected and patrolled World Heritage sites that provide habitat for gaur. However, wildlife in other PAs surrounding the World Heritage sites is highly threatened. The threat levels should be reduced to support gaur populations that have expanded from the source site. In particular, suitable areas that connect western and southern areas should be protected to provide stable areas within PAs to reduce the loss of suitable habitat. Strengthening the management of wildlife corridors for gaur and other endangered species in PAs and forest complexes is important for gaur conservation. Effective management of gaur and its habitat will result in this landscape becoming a stronghold for gaur in Thailand and Southeast Asia. A new suitable habitat area is the Phanom Dong Rak-Pha Tam FC (Fig. 5B). This forest complex should be strengthened to protect the few remaining gaur populations and to maintain a small sustainable area of suitable habitat. Gaurs are abundant in the Dong Phayayen-Khao Yai FC, which is connected to this area, and most of this forest complex is suitable for gaurs. The population status and carrying capacity of this area should be studied to assess its habitat potential. Some gaur populations inhabit the area between the edges of PAs and the surrounding agricultural areas, such as the gaur population in the Khao Phang Ma Non-hunting Area and in Khao Yai National Park (Pharejaem et al., 2016; Laichanthuek et al., 2017). Similarly, habitat suitability studies show that some suitable areas are located outside PAs in agricultural areas and small forest patches. These areas should be included in gaur habitat management planning. Lastly, the Hala-Bala FC in the southernmost region (Fig. 5C) contains few gaur groups because of the loss of suitable habitat. Gaur extirpation in this area is a concern, so the remaining gaur population needs to be protected in conjunction with habitat improvement. Management plans for suitable areas outside the PAs should be developed to protect gaur populations. Currently, an outbreak of lumpy skin disease is affecting both domestic and wild cattle in Thailand (Arjkumpa et al., 2021). Active surveillance and remedial action should be implemented in suitable gaur habitat in intact forest as soon as possible.

In summary, the current study highlighted some key points and made recommendations for gaur conservation and future monitoring research, including in corridors of suitable patch areas. It emphasized the need to maintain and restore suitable habitat and core areas. The findings should provide baseline information for authorities responsible for preparing a conservation action plan for gaurs and their habitat in Thailand.

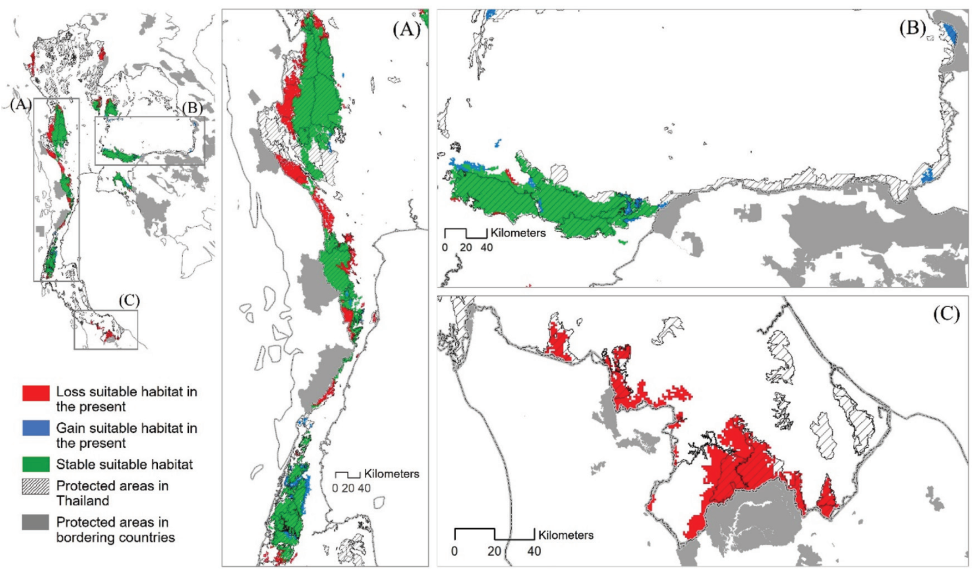


**Fig. 5** Suitable habitat (each patch > 32 km²) in the past and at present (2010–2020): (A) Western, Kaeng Krachan, Chumphon and Khlong Saeng-Khao Sok Forest Complexes; (B) Phanom Dongrak-Pha Tam and Dong Phayayen-Khao Yai Forest Complexes; (C) Hala-Bala Forest Complex

## Conflict of Interests

The authors declare that there are no conflicts of interests.

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## References

Arjkumpa, O., Suwannaboon, M., Boonrawd, M., et al. 2021. First emergence of lumpy skin disease in cattle in Thailand, 2021. Transbound. Emerg. Dis. 2021. 14246. doi.org/10.1111/tbed.14246

Arrendran, G. 2000. A study on vegetation ecology in Pench Tiger Reserve, Madhya Pradesh with reference to gaur (*Bos gaurus*) using Remote Sensing and GIS techniques, Ph.D. thesis, Saurashtra University. Gujarat, India.

Bhumpakphan, N. 1997. Ecological characteristics and habitat utilization of gaur (*Bos gaurus* H. Smith, 1827) in different climatic sites. Ph.D. thesis, Kasetsart University. Bangkok, Thailand.

Chaiyarat, R., Srikosamatara, S. 2009. Populations of domesticated cattle and buffalo in the Western Forest Complex of Thailand and their possible impacts on the wildlife community. J. Environ. Manage. 90: 1448–1453. doi.org/10.1016/j.jenvman.2008.09.004

Cianfrani, C., Le Lay, G., Hirzel, A.H., Loy, A. 2010. Do habitat suitability models reliably predict the recovery areas of threatened species? J. Appl. Ecol. 47: 421–430. doi.org/10.1111/j.1365-2664.2010.01781.x

Cobos, M.E., Peterson, A.T., Barve, N., Osorio-Olvera, L. 2019. Kuenm: An R package for detailed development of ecological niche models using Maxent. PeerJ 7: e6281. doi.org/10.7717/peerj.6281

Collins, W.J., Bellouin, N., Doutriaux-Boucher, M., et al. 2011. Development and evaluation of an Earth-System model–HadGEM2. Geosci. Model Dev. 4: 1051–1075. doi.org/10.5194/gmd-4-1051-2011

Conry, P.J. 1989. Gaur *Bos gaurus* and development in Malaysia. Biol. Conserv. 49: 47–65. doi.org/10.1016/0006-3207(89)90112-2

Duangchantrasiri, S., Umponjan, M., Simcharoen, S., et al. 2016. Dynamics of a low density tiger population in Southeast Asia in the context of improved law enforcement. Conserv. Biol. 30: 639–648. doi.org/10.1111/cobi.12655

Duckworth, J.W., Sankar, K., Williams, A.C., Samba Kumar, N., Timmins, R.J. 2016. *Bos gaurus*. The IUCN Red List of Threatened Species: *Bos gaurus*. doi:10.2305/IUCN.UK.2016-2.RLTS.T2891A46363646.en.

Ebrahimi, A., Farashi, A., Rashki, A. 2017. Habitat suitability of Persian leopard (*Panthera pardus saxicolor*) in Iran in future. Environ. Earth Sci. 76: 697. doi.org/10.1007/s12665-017-7040-8

Heino, M., Kummu, M., Makkonen, M., Mulligan, M., Verburg, P.H., Jalava, M., Räsänen, T.A. 2015. Forest loss in protected areas and intact forest landscapes: A global analysis. PloS One 10: e0138918. doi.org/10.1371/journal.pone.0138918

Imam, E., Kushwaha, S.P.S. 2013. Habitat suitability modelling for Gaur (*Bos gaurus*) using multiple logistic regression, remote sensing and GIS. J. Appl. Anim. Res. 41: 189–199. doi.org/10.1080/09712119.2012.739089

Kanchanasaka, B., Tunhikorn, S., Winitpornsawan, S., Prayoon, U., Faengbubpha, K. 2010. Status of Large Mammals in Thailand. Wildlife Research Division, Department of National Parks, Wildlife and Plant Conservation, Thailand. [in Thai].

Karanth, K.U., Sunquist, M.E. 1995. Prey selection by tiger, leopard and dhole in tropical forests. J. Anim. Ecol. 64: 439–450. doi.org/10.2307/5647

Kim, D.I., Park, I.K., Bae, S.Y., et al. 2020. Prediction of present and future distribution of the Schlegel's Japanese gecko (*Gekko japonicus*) using MaxEnt modeling. J. Ecol. Environ. 44: 5. doi.org/10.1186/s41610-020-0147-y

Laichanthuek, P., Sukmasuang, R., Duengkae, P. 2017. Population and habitat use of gaur (*Bos gaurus*) around Kha Phaeng Ma Non-hunting Area, Nakhon Ratchasima Province. Journal of Wildlife in Thailand 24: 83–95. [in Thai].

Lekagul, B., McNeely, J.A. 1977. Mammals of Thailand. Kurusaphra Press. Bangkok, Thailand.

McShea, W.J., Davies, S.J., Bhumpakphan, N. 2011. The Ecology and Conservation of Seasonally Dry Forests in Asia. Smithsonian Institution Scholarly Press. Washington, DC, USA.

Nabhitabhata, J., Chan-ard, T. 2005. Thailand Red Data: Mammal, Reptiles and Amphibians. Office of Natural Resources and Environment Policy and Planning. Thailand. https://www.pangolinsg.org/wpcontent/uploads/sites/4/2018/06/Nabhitabhata_Chan_ard_2005_Thailand-Red-Data-Book_Mammals-et-al..pdf, 7 September 2021.

Office of Natural Resources and Environment Policy and Planning. 2017. Thailand Red Data: Vertebrates. Ministry of Natural Resource and Environment, Thailand. http://58.82.155.201/chmthaiNew/doc/Publication/publication2/red_data_EN/AW_RedData-VertebratesEN.pdf, 7 September 2021.

Pharejaem, T., Pattanavibool, A., Phongkhieo, N.T. 2016. Management of human and gaur conflict along forest edge of Khao Phang Ma Non-hunting Area. Journal of Wildlife in Thailand 23: 33–44. [in Thai].

Phillips, S.J., Anderson, R.P., Schapire, R.E. 2006. Maximum entropy modeling of species geographic distributions. Ecol. Modell. 190: 231–259. doi.org/10.1016/j.ecolmodel.2005.03.026

Phillips, S.J., Dudík, M. 2008. Modeling of species distributions with Maxent: New extensions and a comprehensive evaluation. Ecography 31: 161–175. doi.org/10.1111/j.0906-7590.2008.5203.x

Pisdamkham, C., Prayurasiddhi, T., Kanchanasaka, B., et al. 2010. Thailand Tiger Action Plan 2010–2022. Department of National Parks, Wildlife and Plant Conservation, Thailand. https://www.dnp.go.th/TigerCenter/Thailand_tiger_action_plan_2010-2022.pdf, 7 September 2021.

Planisong, K., Trisurat, Y., Bhumpakphan, N., Sookchaloem, D., Podchong, S. 2018. Co-habitat model of gaur and elephant at Phu Khieo Wildlife Sanctuary, Chaiyaphum Province. Thai Journal of Science and Technology 8: 116–126. [in Thai].

Potapov, P., Yaroshenko, A., Turubanova, S., et al. 2008. Mapping the world's intact forest landscapes by remote sensing. Ecol. Soc. 13: 51.

Prasopsin, S., Bhumpakphan, N., Chaiyarat, R. 2013. Diversity of food plants and food preference of Indochinese gaur (*Bos gaurus laosiensis*) at Khlong Pla Kang buffer zone of Khao Yai National Park, Nakhon Ratchasima province. Thai Journal of Forestry 32: 1–13. [in Thai].

Prayurasiddhi, T. 1998. The ecological separation of gaur (*Bos gaurus*) and banteng (*Bos javanicus*) in Huai Kha Khaeng Wildlife Sanctuary, Thailand. Ph.D. thesis, University of Minnesota. Minneapolis and Saint Paul, MN, USA.

Prayurasiddhi, T., Pichaisiri, A., Chaiwatana, S. 2013. Wildlife Conservation in Thailand. Department of National Parks, Wildlife and Plant Conservation, Thailand. [in Thai].

R Core Team. 2020. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/, 29 August 2021.

Reed, D.H. 2004. Extinction risk in fragmented habitats. Anim. Conserv. 7: 181–191. doi.org/10.1017/S1367943004001313

Roininen, H., Veteli, T.O., Piiroinen, T. 2007. The role of herbivores in the ecosystem and management of Miombo woodlands. In: Proceedings of the First MITMIOMBO Project Workshop. Morogoro, Tanzania, pp.107–114.

Royal Forest Department. 2018. Forest Cover Assessment in Thailand. Forest Land Management Office, Royal Forest Department, Thailand. [in Thai].

Sankar, K., Pabla, H.S., Patil, C.K., et al. 2013. Home range, habitat use and food habits of re-introduced gaur (*Bos gaurus gaurus*) in Bandhavgarh Tiger Reserve, central India. Trop. Conserv. Sci. 6: 50–69. doi.org/10.1177/194008291300600108

Schwabe, K.A., Carson, R.T., DeShazo, J.R., Potts, M.D., Reese, A.N., Vincent, J.R. 2015. Creation of Malaysia's Royal Belum State Park: A case study of conservation in a developing country. J. Environ. Dev. 24: 54–81. doi.org/10.1177/1070496514551173

Silva, S., Wu, T., Thieme, A., et al. 2020. The past, present and future of elephant landscapes in Asia. bioRxiv preprint. doi.org/10.1101/2020.04.28.066548.

Srikosamatara, S., Suteethorn, V. 1995. Populations of Gaur and Banteng and their management in Thailand. Nat. His. Bull. Siam Soc. 43: 55–83.

Steinmetz, R. 2004. Gaur (*Bos gaurus*) and banteng (*B. javanicus*) in the lowland forest mosaic of Xe Pian Protected Area, Lao PDR: Abundance, habitat use, and conservation. Mammalia 68: 141–157. doi.org/10.1515/mamm.2004.015

Tanasarnpaiboon, S. 2016. Gaur (*Bos gaurus*) Abundance, Distribution, and Habitat Use Patterns in Kuiburi National Park, Southwestern Thailand. Ph.D. thesis, University of Nebraska-Lincoln. Nebraska, USA.

Trisurat, Y., Bhumpakphan, N. 2018. Effects of land use and climate change on Siamese Eld's Deer (*Rucervus eldii siamensis*) distribution in the transboundary conservation area in Thailand, Cambodia, and Lao PDR. Front. Environ. Sci. 6: 35. doi.org/10.3389/fenvs.2018.00035

Trisurat, Y., Bhumpakphan, N., Reed, D.H., Kanchanasaka, B. 2012. Using species distribution modeling to set management priorities for mammals in northern Thailand. J. Nat. Conserv. 20: 264–273. doi.org/10.1016/j.jnc.2012.05.002

Trisurat, Y., Kanchanasaka, B., Kreft, H. 2015. Assessing potential effects of land use and climate change on mammal distributions in northern Thailand. Wildl. Res. 41: 522–536. doi.org/10.1071/WR14171

Trisurat, Y., Pattanavibool, A., Gale, G.A., Reed, D.H. 2010. Improving the viability of large-mammal populations by using habitat and landscape models to focus conservation planning. Wildl. Res. 37: 401–412. doi.org/10.1071/WR09110

Wild Animal Reservation and Protection Act. 2019. Royal Thai Government Gazette. 136: 104–144. http://www.ratchakitcha.soc.go.th/DATA/PDF/2562/A/071/T_0104.PDF, 8 September 2021.