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Exploring habitat suitability for *Bubalus arnee* (Kerr, 1792) (Mammalia: Artiodactyla: Bovidae) and its interplay with domestic cattle within Koshi Tappu Wildlife Reserve

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Abstract

The wild water buffalo-WWB (*Bubalus arnee)* holds a significant ecological role within Koshi Tappu Wildlife Reserve, Nepal. Despite its importance, there has been a lack of comprehensive research addressing its distribution, habitat suitability, and interaction with domestic cattle. To address these gaps, this study was undertaken with the primary objectives of elucidating the population distribution of *B. arnee* within the reserve, mapping its habitat suitability, and evaluating the interplay between *B. arnee* and domestic cattle in the Koshi Tappu Wildlife Reserve. The study area was subdivided into cells to gather data on *B. arnee* presence using various indicators such as sightings, dung, and footprints. Interaction between *B. arnee* and domestic cattle was assessed based on their spatial overlap within and outside a 500-meter radius from observation points. Employing the MaxEnt algorithm, distribution data of *B. arnee* and climatic variables including maximum and minimum temperatures, mean temperature, and rainfall were analyzed, while land use and cover maps were acquired from the Department of Survey for further analysis. Results revealed a concentration of *B. arnee* in the southwest region of the Koshi Tappu Wildlife Reserve, with a total of 405 individuals recorded, comprising 26 calves, 6 sub-adults, and 373 adults. The distribution pattern displayed a prevalence of small-sized herds (1–15 individuals) followed by medium-sized (15–29 individuals) and large-sized (29+ individuals) herds. Notably, *B. arnee* presence was most prominent in grassland areas (approximately 49% of observations), while forested regions accounted for the lowest presence (approximately 10% of observations). Interestingly, domestic buffalo were observed near *B. arnee* only in a single cell in the southwest section of the study area, while in the eastern cells of the reserve, overlaps between domestic cows and *B. arnee* occurred within a 500-meter radius. Our study indicated a suitability index greater than or equal to 0.5876, encompassing only about 14% of the reserve's total area. The jackknife test highlighted the influential environmental variables in the model, with annual precipitation contributing around 60.8% and the maximum temperature of the warmest month contributing about 39.20% in determining the distribution of *B. arnee*. The results underscored the significance of annual precipitation, with a regularized training gain of 0.50, compared to 0.32 for the maximum temperature of the warmest month. In conclusion, this study sheds light on the distribution, habitat suitability, and interaction dynamics of *B. arnee* within the Koshi Tappu Wildlife Reserve, offering valuable insights for informed wildlife management and conservation strategies.

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Key words: Domestic cattle, Koshi Tappu Wildlife Reserve, Wild water buffalo (*Bubalus arnee*)

Introduction

Bubalus arnee, ancestor of the domestic water buffalo, has a history of domestication spanning thousands of years, resulting in various smaller breeds, weighing less than 500 kg, distributed worldwide (Choudhury, 2014). Domestication of the Asiatic wild buffalo is believed to have occurred least 4,500 years ago (Clutton-Brock, 1990). Presently, remnant populations of *B. arnee* persist in Nepal, Bhutan, Thailand, Cambodia, Myanmar, and several locations in India, predominantly in Assam, with extirpations noted in countries that include Bangladesh, Indonesia, Lao People's Democratic Republic, Malaysia, Sri Lanka, and Vietnam (IUCN, date). Classified as an 'Endangered' species on the Red List of Threatened Species by the International Union for Conservation of Nature (IUCN) and listed in Appendix III of the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES), it is also a protected species under Nepal's National Parks and Wildlife Conservation Act of 1973. The current global population of *B. arnee* is estimated to be 3300-3400 (Hedges, 1995; Heinen and Srikosamatara, 1996; Hedges et al., 2008).

In Nepal, records of *B. arnee* date back to the mid to late 1950s in the area that became Koshi Tappu Wildlife Reserve and the early 1960s in Chitwan National Park. Disease transmission from local livestock led to the presumed extirpation of the species in Chitwan National Park. The Koshi Tappu Wildlife Reserve was the last stronghold of *B. arnee* in Nepal until 15 individuals were introduced to old Padampur of Chitwan National Park in 2017. Since the establishment of the Koshi Tappu reserve regular censuses have been conducted, with the 2021 census reporting a population of 498 individuals (DNPWC, 2020). Despite population increases, the species remains threatened by inbreeding, genetic dilution from domestic buffalo, and diseases transmitted by domestic livestock (Heinen, 1993; Aryal et al., 2011; DNPWC, 2020). In 2011, a paper published as "Call to conserve the wild water buffalo (*Bubalus arnee*) in Nepal" suggested to translocate the *B.arnee* from the reserve due to the insufficient area of 0.80 km ^{2} per wild buffalo, during that time the population was only 219 individuals.

The majestic Koshi River molds both the physical features and ecosystem of the Koshi Tappu Wildlife Reserve, the wild buffalo's habitat is increasingly encroached upon by domestic cattle grazing in the reserve's buffer zones (Chaudhary, 2000). These interactions, along with insufficient habitat size of around 0.35 km^2 per wild buffalo, prompted this study to assess the distribution, suitable habitat, and interactions of *B. arnee* and domestic cattle within the reserve. Despite challenges, efforts towards the conservation of this endangered species continue in Nepal. The primary aim of this study is to evaluate the habitat suitability for *B. arnee* and its interactions with domestic cattle within the Koshi Tappu Wildlife Reserve. Additionally, the study seeks to achieve a comprehensive understanding about the population distribution of the *B. arnee* within the boundaries of the Koshi Tappu Wildlife Reserve and to create an accurate habitat suitability map specifically focused on the needs of the *B. arnee* population within this reserve.

Material and Methods

Study area

The study was carried out in Koshi Tappu Wildlife Reserve, Nepal, positioned within the geographic coordinates of 86°55'15"- 87°05'02" E longitude and 26°33'57"- 26°43'40''N latitude. The reserve, covering 65 square km (see Figure 1) was initially established in 1976. In 1978, the reserve was expanded to encompass 175 square km, including the Koshi River alluvial floodplain to the west of the river, and portions of Sunsari, Saptari, and Udayapur districts. Exhibiting a near-rectangular configuration, the reserve's dimensions measure 17.5 km from north to south and 10 km from east to west (KTWR, 2018). The reserve experiences a subtropical monsoon climate with distinct seasons - spring, summer, autumn, and winter. Spring (February-April) boasts pleasant warm temperatures and strong silt-laden winds, while summer (May) brings intense heat with minimal rainfall, resulting in maximum temperatures reaching 40 °C. The annual average rainfall stands at 2019 mm, and daily maximum temperatures fluctuate between 23.5 °C and 33.4 °C, with minimum temperatures ranging from 7.8 °C to 25.3 °C. Average monthly temperatures fall between 15.7 °C and 29.2 °C, accompanied by consistently high humidity levels ranging from 76% to 94%.

Within the reserve, a diverse assembly of 514 plant species, spanning 110 families, has been documented. Of these, 502 belong to 99 flowering plant families, and 12 belong to 11 Pteridophyte families (ferns and lycophytes), with the Gramineae family (grasses) exhibiting dominance. The reserve hosts patches of successional forests in primary and intermediate seral stages, primarily consisting of open and degraded woodlands dominated by one or more of three species: *Senegalia catechu*, *Bombax ceiba*, and *Dalbergia sissoo* (KTWR, 2018). The dominant land cover within the reserve is grassland, primarily influenced by frequent alterations in the course of the Koshi River. This grassland encompasses approximately 53.1% of the area, while riverbanks and water bodies constitute 37.5%, and forests cover 10% (KTWR, 2018). Utilizing ArcGIS 10.5, the land cover categories were identified as bush, forest, grass, pond, sand, scattered trees, swamp, and water bodies.

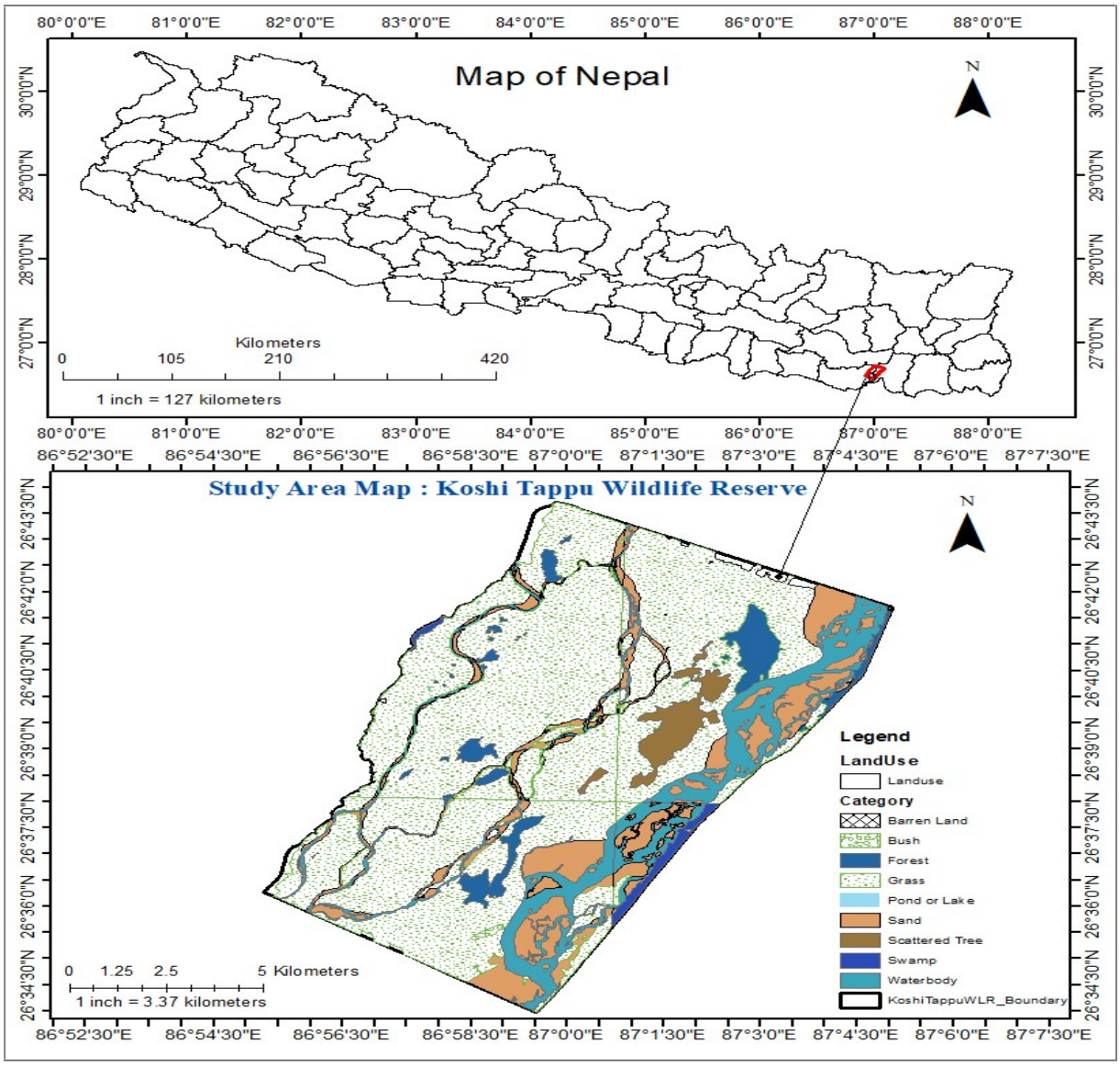

Figure 1: Study area map of the Koshi Tappu Wildlife Reserve, Nepal.

Research framework

Table 1: The research framework, outlining the objectives and the list of input variables and methods employed in the research process.

Objective	Data Collection	Data Analysis	Remarks
Distribution of *B. arnee*	• Occupancy survey in different grids • Presence data of *B. arnee* along with cattle is coordinated • Photographs and Visual observation • *B. arnee* (sex, age, calf)	ArcMap 10.5 to generate the distribution map	Gridded the total study area in 20 equal size cells that are approx. 6 km^2 The center point of the cell was used to conduct occupancy survey. (Annex 1: Grid format)
Habitat Suitability of *B. arnee*	• Different bioclimatic data is obtained from https://www.worldclim.org/data/bioclim.html. (Bio_6; Max temp of warmest month, Bio_6 Min temp of coldest month, Bio_1; annual mean temp and Bio_12 Annual rainfall)	• MaxEnt model is used to generate the suitable habitat area for the *B. arnee* population taking inputs as coordinate of presences data and bioclimatic data	None of the previous research has used MaxEnt model for habitat suitability of *B. arnee* at this study area
Interaction of *B. arnee* with the domestic cattle's and buffalos	• Observation and photograph during the occupancy survey	• descriptive analysis	*B. arnee* are one of the large size mammals and can be observed for the distance with help of binocular and captured with the camera

Primary data collection

Preliminary survey

A preliminary assessment was conducted prior to the fieldwork to gain insight into the current status of the *B. arnee* and to prepare logistically for the forthcoming study. This phase involved on-site visits, consultations with experts, discussions with the warden of Koshi Tappu Wildlife Reserve (KTWR), staff members, local residents, and a review of pertinent literature. The Koshi River dissects the study area and each year the river changes its course. The preliminary assessment was critical to logistical planning for a successful project. Relevant secondary data has been gathered from a range of sources, including reports, conservation area management plans, and published and unpublished materials originating from both individuals and the Department of National Park and Wildlife Conservation (DNPWC). Critical data facilitated the utilization of the MaxEnt model, including climatic information, specifically the maximum temperature of the warmest month, minimum temperature of the coldest month, annual mean temperature, and annual rainfall (https://www.worldclim.org/data/bioclim.html).

Key informant interview

Before entering the reserve, researchers held a formal meeting with stakeholders to gather information about the study and to obtain a research permit. Eight individuals including a ranger, the chairman of KTWR, the warden of KTWR, and other relevant agencies involved in conservation efforts, were consulted. These key informants provided much information about the current state and status of the *B. arnee*, as well as interactions with domestic livestock.

Occupancy survey

The occupancy survey gathered data about species present in the reserve. The data plays a crucial role in determining species distribution. Data collection involved the use of GPS devices, binoculars, and cameras. These tools facilitated the recording of indicators such as sightings, dung, tracks, footprints, and the precise coordinates of the species' current location. To guide the occupancy survey, the study area was gridded into 20 cells. Given that a *B. arnee* herd has an approximate home range of 3.9 square miles (Singh, 2015), each cell was designed to cover an area of nearly 6 km^2, resulting in a total of 70 km of occupancy surveys conducted across 20 grids. The center points of the cells were entered into the GPS for navigation purposes (Appendix 1). A total of 20 cells were covered during the field study. While cells along the Koshi River were accessed via boats, others were explored on foot. The survey was carried out June 2–9, 2022. A total of 405 *B. arnee* were directly sighted and recorded, of which 26 were calves, 6 sub-adults, and 373 adults. Coordinates denoting the presence of the species were documented across various cells using a GPS receiver. Locational coordinates of the domestic cattle as well as *B. arnee* herds were noted and uploaded to ArcMap 10.8 software to generate the distribution maps (Appendix 1). Employing an occupancy survey methodology, the aim of this part of the project was to document interactions between domestic cattle and *B. arnee*. Throughout the survey, the total count of domestic cattle and domestic water buffalo and their respective locations were recorded. *B. arnee* males, females, and calves; and domestic cows, and domestic buffalo were identified. Interactions were based on 500-meter radius around domestic cattle and *B. arnee* herds. Domestic livestock within 500 m of wild buffalo were recorded as interactions and vice versa. Domestic cattle and *B. arnee* compete for habitat and male domestic water buffalo and *B. arnee* also compete for mates. Thus, the underlying assumption is that if interactions occurred within a 500-m range, direct competition between *B. arnee* and domestic cattle was occurring.

Direct (sighting) and indirect (dung and footmark) evidence of *Bubalus arnee* presence

Most distribution data came from direct observations, with dung and footprints of *B. arnee* being more infrequent. Direct observations of *B. arnee* predominantly occurred near the Koshi River. Furthermore, direct observations accounted for the detection of approximately 75% of the *B. arnee* population within the Koshi Tappu Wildlife Reserve (Fig. 2).

Data processing and analysis tool

Habitat suitability modeling by MaxEnt

The MaxEnt software was utilized to predict the distribution of *B. arnee* herds in the reserve. MaxEnt, an extensively employed species distribution model (SDM), forecasts species distribution, primarily when presence data is available in the form of presence-only records (Pun et al., 2022). This model leverages distribution data and bio-climatic information to ascertain the probability of the target species' occurrence and suitable habitat. The MaxEnt model has also been applied to other mega-fauna species such as the European bison (*Bison bonasus*) (Kuemmerle et al., 2011). In Nepal, this model has been used for mammals like the Asiatic black bear (*Ursus thibetanus*) and Red panda (*Ailurus fulgens*) in Makalu National Park (Su et al., 2021). Similarly, few researchers from Nepal have used this MaxEnt model for determining habitat suitability of Rhino (*Rhinoceros unicornis*) (Pun et al., 2022), Sloth bear (*Melursus ursinus*) (Sharma et al., 2022) and Thar (*Capricornis sumatraensis*) (Joshi et al., 2022).

The application of Species Distribution Modeling (SDM) to predict the current range of *B. arnee* employs MaxEnt version 3.4.1 (Phillips et al., 2006). This model is a robust and widely adopted tool for projecting species distribution, even with limited presence-only data and minor location inaccuracies (Merow et al., 2013).

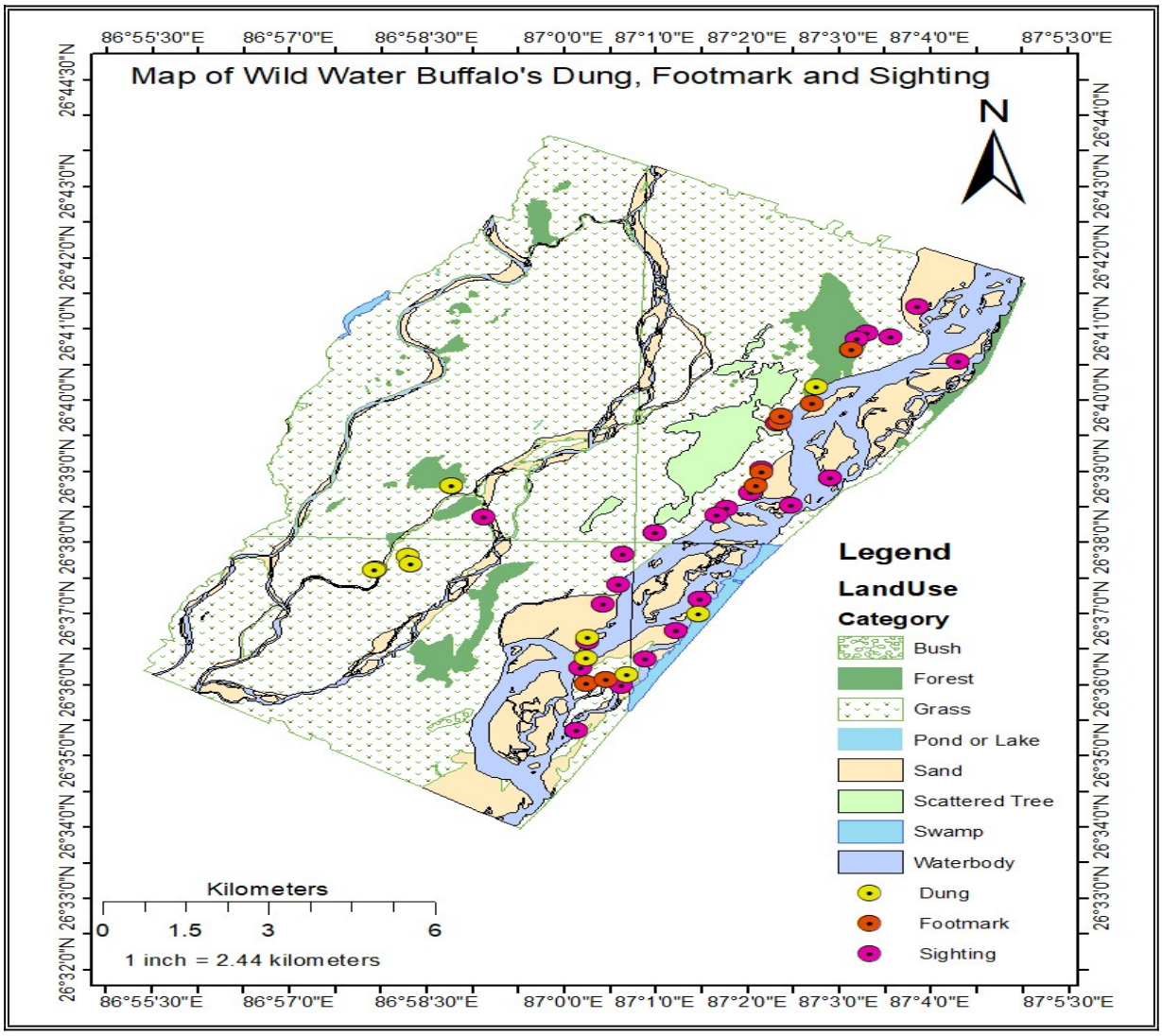

Figure 2: *Bubalus arnee* distribution map based on sighting, dung and footmark.

MaxEnt employs species locations and environmental predictors (such as temperature and precipitation) within a user-defined gridded landscape. Background locations are sampled from this landscape, which are then compared to the presence sites. The models forecast occurrence rates, defined as the expected number of individuals in each cell, assuming the entire population size is known. As population size is often unknown, only relative occurrence rates (ROR) are meaningful, indicating the relative probability that an individual originates from each cell. The ROR serves as MaxEnt's raw output, and its predictions represent indices of habitat suitability (Merow et al., 2013).

Output evaluation of MaxEnt

Two distinct methodologies were employed for model creation and validation, taking into account the number of presence data points available for modeling. We executed 10 replicates of the model employing default settings, 10,000 background points, and the auto feature for predicting species distribution. Predictions were assessed based on higher Area under the Receiver Operating Characteristic Curve (AUC-ROC) values and were subsequently confirmed through visual examination of the prediction results against known species occurrences. The predictive model's performance surpasses random prediction (where AUC value equals or approaches 0.5) when the AUC value approaches 1.0, indicating a high probability of suitability for AUC values > 0.70 and towards 1.0 (DeLeo, 1993). To transform the continuous predicted output probability into a binary response of presence and absence, the Maximum test sensitivity plus specificity threshold approach, deemed suitable for this purpose, was employed (Liu et al., 2005). The Jackknife procedure, incorporated in MaxEnt, was utilized to evaluate variable contributions (Phillips et al., 2006). This procedure involved comparing model performance gains using a single variable, excluding that variable, and excluding all variables to ascertain the significance of a specific variable's contribution (Harisena et al., 2021).

Results

Population trend of *Bubalus arnee* in Koshi Tappu Wildlife Reserve

After the establishment of the Koshi Tappu Wildlife Reserve in 1976, the initial population of *B. arnee* population consisted of 63 individuals. Subsequently, the population of *B. arnee* has exhibited a gradual increase, reaching 498 individuals by the year 2021. These data indicate a growth rate of 15.34%. Over nearly three decades, from its inception until 2004, the growth rate was a modest 5.4%. Remarkably, within a span of less than two decades, spanning 17 years, this growth rate escalated to double digits, reaching 12.5% (Fig. 3; Table 2). This growth can't be achieved without management effort from reserve. In Nepal, the Koshi Tappu Wildlife Reserve remains the sole habitat for this remaining population of *B. arnee*.

Population distribution of *Bubalus arnee* in Koshi Tappu Wildlife Reserve

The study findings reveal a predominant concentration of *B. arnee* along the eastern boundary of Koshi Tappu Wildlife Reserve (KTWR) adjacent to the Koshi River (Fig. 4). A similar distribution pattern of *B. arnee* was also observed in the reserve's southwest region. The distribution map vividly illustrates that *B. arnee* herds were primarily associated with water bodies during the summer season.

Bubalus arnee herd size

During the research period, *B. arnee* were primarily found in herds, while solitary adults were also occasionally observed. Groups mainly consisted of alpha males, females, calves, and subadults. A separate bachelor herd comprising 40-50 males was also noted. Herd size varied, ranging from small to medium and large. The largest observed herd, comprising 152 individuals, including males, females, calves, and sub-adults, was predominantly located on the eastern side of the reserve, near the river. The illustration provided below categorizes the herds based on the number of individuals they encompass. Analyzing the map below highlights that the prevalence of small herds is the highest, followed by medium-sized and large herds of *B. arnee* (Fig. 4).

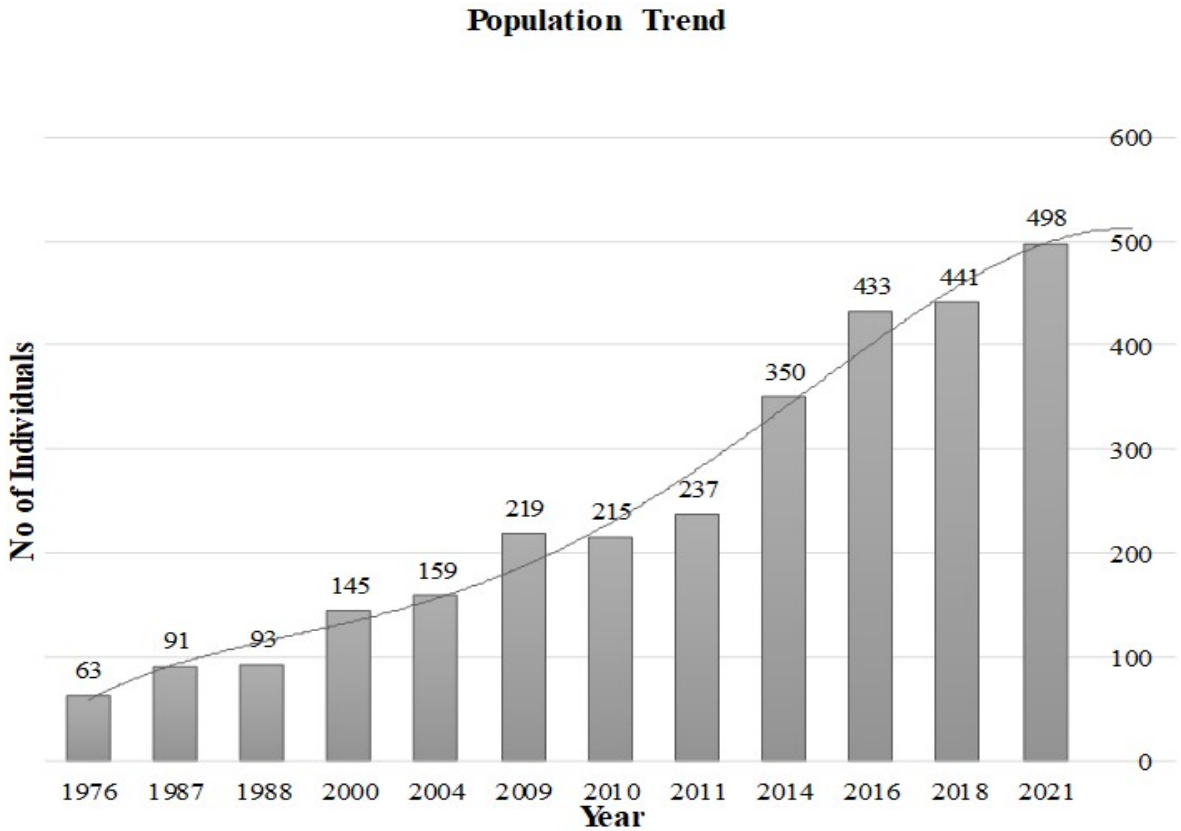

Figure 3: Population trend of *Bubalus arnee* in Koshi Tappu Wildlife Reserve, Nepal.

Table 2: Population trend of *Bubalus arnee* in Nepal.

Period	Number of years	Cumulation	Population growth rate
1976–2004	28	96	5.4%
2004–2021	17	339	12.5%

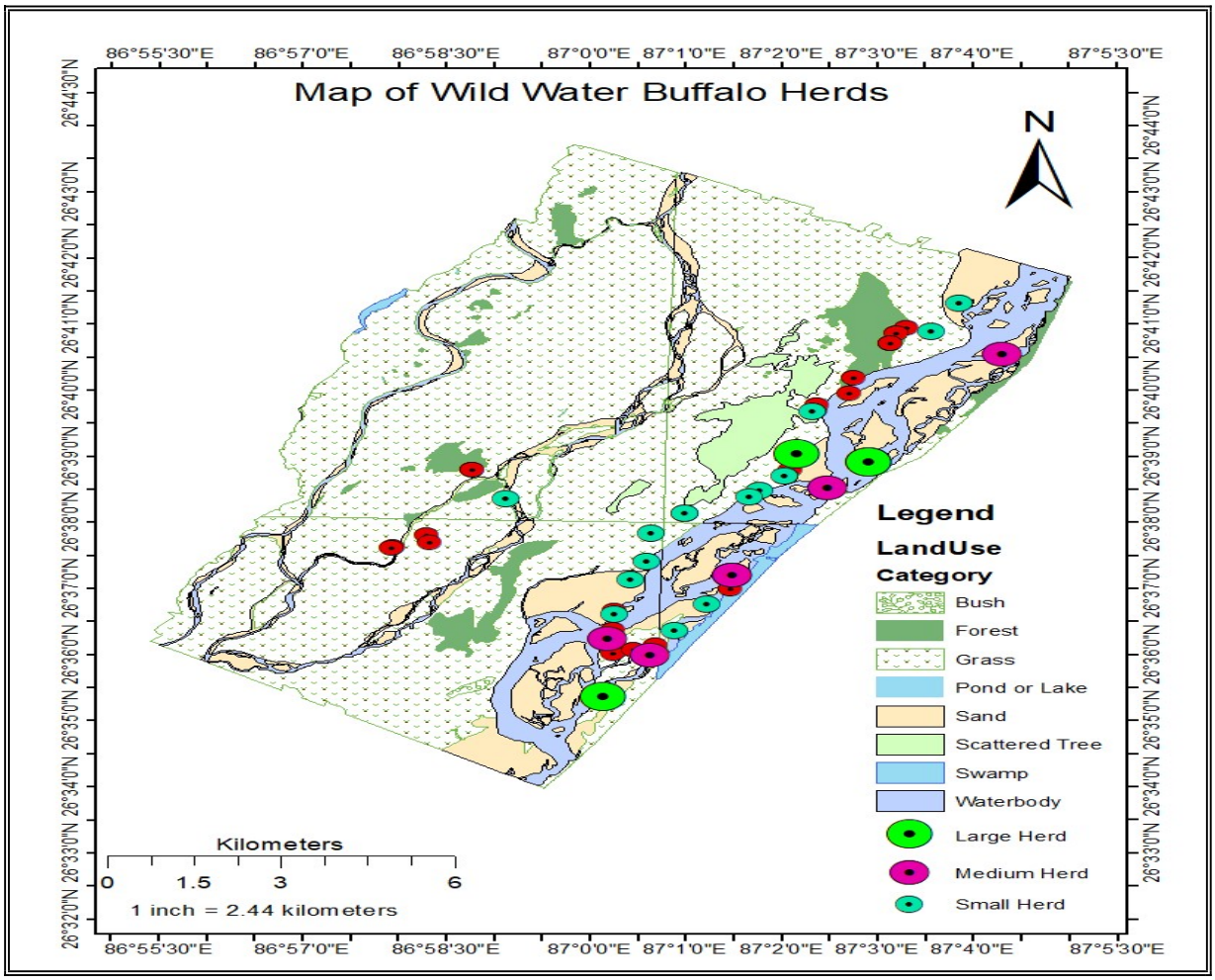

Figure 4: Map of *Bubalus arnee* herds in the study area, Nepal.

Bubalus arnee presence in different habitats

Herds of *B. arnee* were most frequently recorded in grassland, water bodies, sand, and forest. The field survey yielded the highest concentration of *B. arnee* observations in grassland habitat (49%), while the lowest number of observations were registered in forested regions (10%) (Fig. 5). Similarly, the number of observations recorded in sand and waterbody region was found to be 23% and 18% respectively. As already mentioned, the grassland encompasses approximately 53.1% of the area, while riverbanks and water bodies constitute 37.5%, and forests cover 10% (KTWR, 2018).

Occurrences of *Bubalus arnee* and livestock within the preserve

Bubalus arnee and domestic cattle and buffalo were observed coexisting in the same area (Fig. 6). Throughout the study, domestic buffalo herds were only identified in a single cell (Cell 24O), accompanied by their owners or shepherds, that coincided with the presence of *B. arnee* in the same cell (Fig. 7). However, the domestic buffalo and *B. arnee* did not show a spatial overlap within a 500-meter radius. In a number of cells (such as 42O, 35O, 27O, 19O, 45O, 41O, 34O, 26O, 18O, 11O, and 4O), herds of domestic cows were observed utilizing the same grazing areas as *B. arnee* (Annex 2). Interestingly, these two groups, domestic cow and *B. arnee*, grazed within 500 meters of each other. Only domestic cows were present in several cells (23O and 47O), while one cell had *B. arnee* only (12O). This interaction has definitely caused the competition for grazing space inside the study area.

Bubalus arnee and livestock numbers in respective grids

The study documented 405 *B. arnee* and 1966 domestic cattle. The ratio between the current *B. arnee* population and domestic cattle is approximately 1:4 (Fig. 8; Table 3). No *B. arnee* signs were noted in three cells (23O, 47O, and 41O), while four cells (42O, 12O, 41O, and 11O) showed no presence of domestic cattle (Appendix 2). The highest count of *B. arnee*, observed within a single cell (26O) was 152 individuals (38% of the entire population). The highest count of domestic cattle in a single cell was 700 individuals in cell 47O. Examination of the chart and map reveals a distinct pattern: the cells with the highest (n= 47O) and second highest (n= 23O) counts of domestic cattle lacked any recorded presence of *B. arnee*. The larger domestic cattle population may have displaced *B. arnee* from those specific cells or areas.

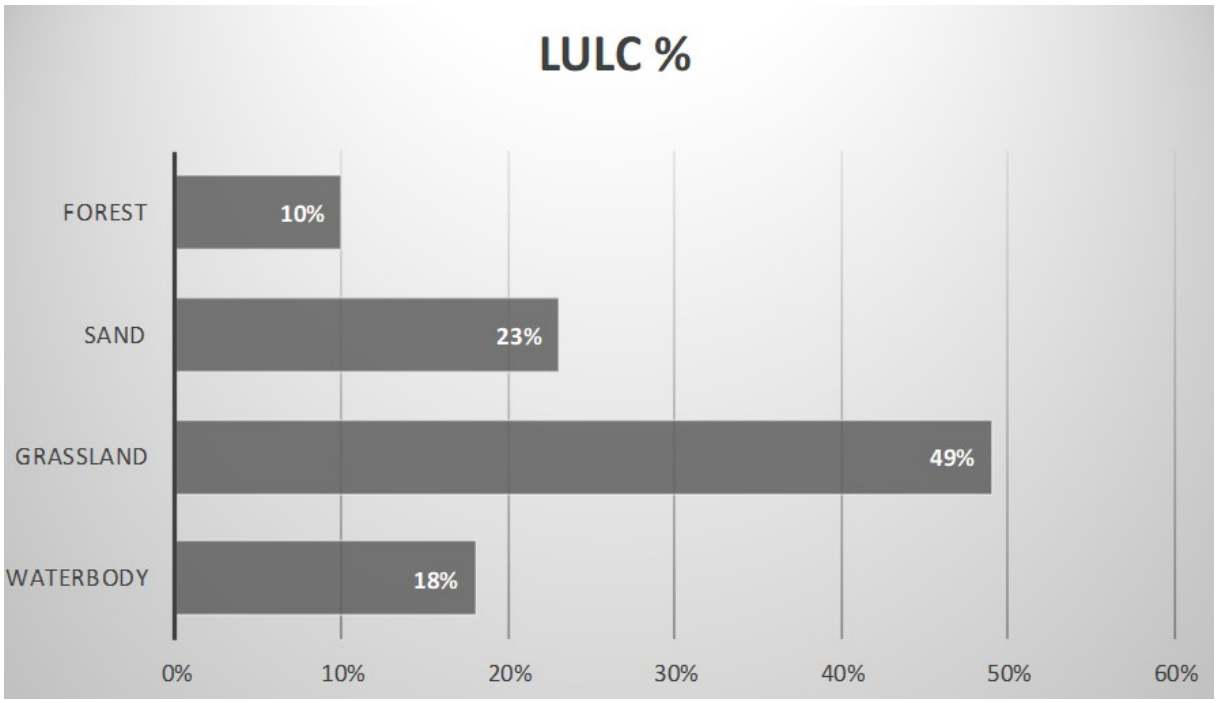

Figure 5: Presence data of *Bubalus arnee* on different land use type of Koshi Tappu Wildlife Reserve (KTWR).

Figure 6: Presence of domestic cow in *Bubalus arnee* herd, Nepal.

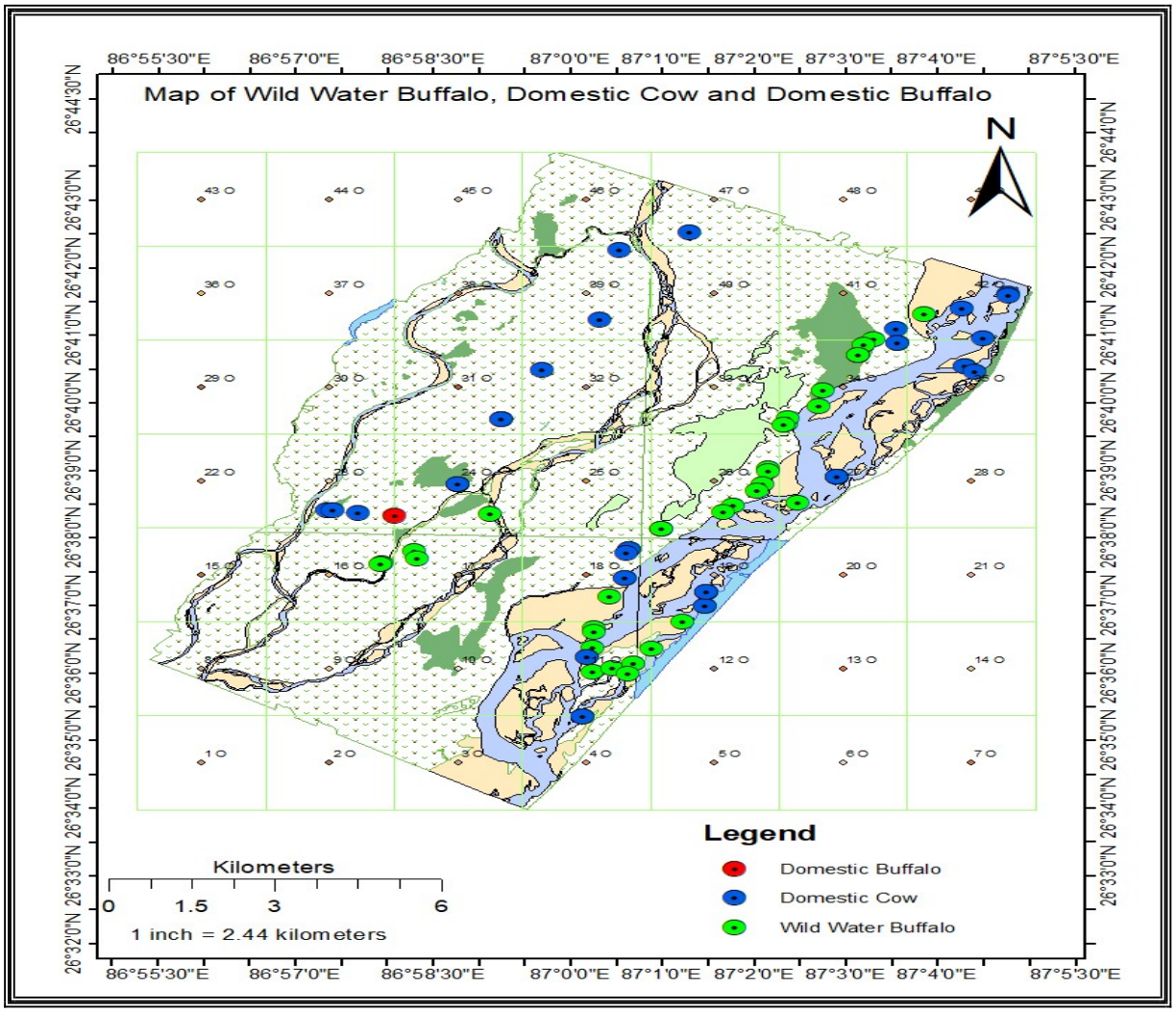

Figure 7: Distribution of *Bubalus arnee* (WWB) and domestic cattle in cells.

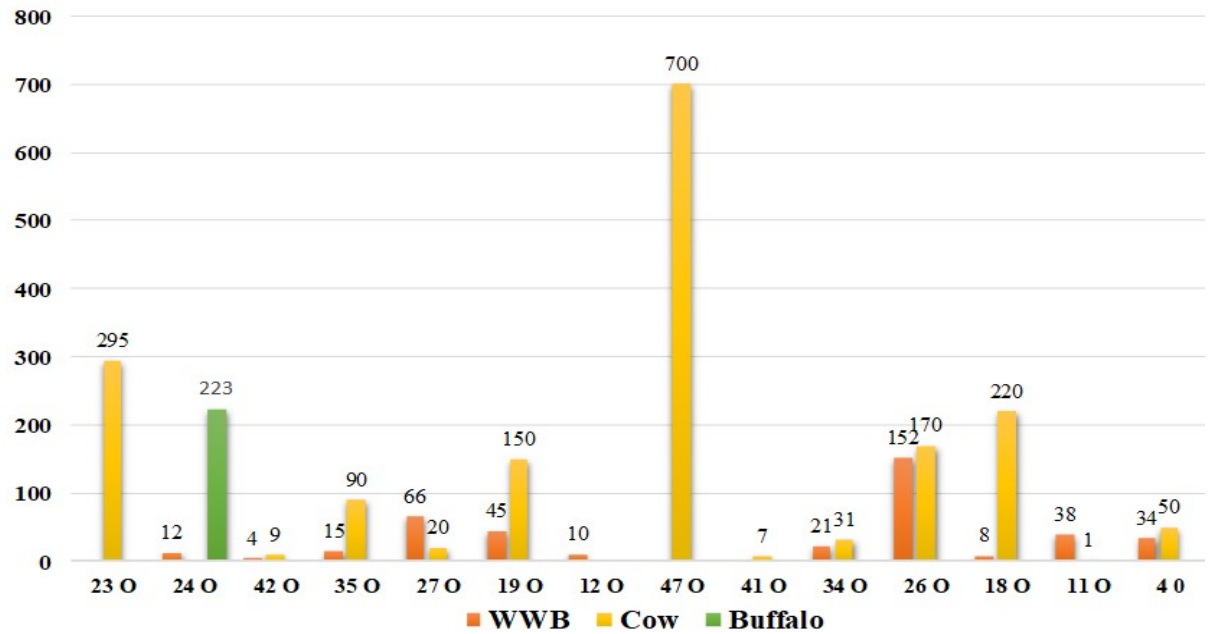

Figure 8: Sightings of *Bubalus arnee* (WWB) and domestic cattle by grid.

Table 3: Percentage of *Bubalus arnee* and domestic cattle in grid.

Grid	No. of *Bubalus arnee*	*Bubalus arnee* (%)	No. of cattle	Cattle (%)
23 O	0	0	295	15
24 O	12	3	223	11
42 O	4	1	9	0
35 O	15	4	90	5
27 O	66	16	20	1
19 O	45	11	150	8
12 O	10	2	0	0
47 O	0	0	700	36
41 O	0	0	7	0
34 O	21	5	31	2
26 O	152	38	170	9
18 O	8	2	220	11
11 O	38	9	1	0
4 O	34	8	50	3
Total	**405**		**1966**	

Habitat suitability of *Bubalus arnee*

The MaxEnt model predicts the likelihood of a species' presence, spanning from 0 to 1, with values approaching 1 indicating a higher probability of species occurrence. The reserve habitat was divided into four suitability classifications: unsuitable (0–0.2), low suitability (0.2–0.4), moderate suitability (0.4–0.6), and high suitability (0.6–1) (Xu et al., 2019). The model was applied to the area of Koshi Tappu Wildlife Reserve, incorporating the respective coordinates and variables. The resulting habitat suitability score obtained exceeds or equals 0.5876, placing it within the category of moderate suitability. This encompasses merely around 14% of the total area of the Koshi Tappu Wildlife Reserve (Fig. 9; Table 4).

The precision of the model's simulation outcomes is linked to the Area Under Curve (AUC) value. AUC values exceeding 0.9 are deemed excellent, those ranging from 0.8 to 0.9 are considered good, values between 0.7 and 0.8 are categorized as fair, and predictions with an AUC below 0.7 are considered poor. The model calculates the suitability of *B. arnee* for each pixel (~1 km^2) within a range of 0 to 1, where 0 signifies unsuitability and 1 indicates perfect suitability. The obtained AUC value is 0.783, reflecting a fair level of accuracy (Fig. 10; Table 5).

The outcomes of the Jackknife test illustrated the individual impacts of each key environmental factor on the model (depicted in Fig. 11). Out of the four selected covariates influencing distribution, two played a significant role in determining the pattern. Annual precipitation contributed 60.8%, while the maximum temperature during the warmest month contributed 39.20%. Annual precipitation held the highest regularized training gain of 0.50. Among the environmental variables, when considered independently, annual precipitation displayed the most valuable information. Similarly, the maximum temperature during the warmest month demonstrated a regularized training gain of 0.32, whereas the remaining two variables, the minimum temperature during the coldest month and the annual mean temperature showed no significant contribution.

Discussion

The Koshi Tappu Wildlife Reserve houses the remaining population of *B. arnee* in Nepal (Bhattarai et al., 2023). Grasslands and floodplains dominate the Koshi Tappu wildlife area. More than half of the *B. arnee* distribution was recorded in grasslands, followed by water bodies. The majority of *B. arnee* presence data were collected along the Koshi River, with additional data obtained from the reserve's southwestern region. While most *B. arnee* individuals were observed in small herds, solitary individuals were also occasionally spotted. Besides *B. arnee*, the grasslands of the Koshi Tappu Wildlife Reserve supported a substantial herd of domestic buffalo and cows. Within the *B. arnee* habitat, 223 domestic buffalo and 1743 domestic cows were recorded. The prevalence of domestic cattle was highest on the reserve's northwest side, where evidence of *B. arnee* presence was minimal. The abundance of domestic cattle might have contributed to the displacement of *B. arnee* from this area. Currently, each *B. arnee* individual occupies an approximate area of 0.35 sq. km, which remains inadequate for a mega-species with a home range of 10 sq. km. Furthermore, *B. arnee* habitat is encroached upon by domestic cattle. The ratio of *B. arnee* to domestic cattle within the Koshi Tappu Wildlife Reserve stands at around 1:4.

The MaxEnt model yielded habitat suitability results exceeding 0.5876, indicating that merely about 14% of the reserve's area is suitable for *B. arnee*. The jackknife test outcomes provided insights into the contributions of key environmental variables to the model, with annual precipitation and maximum temperature of the warmest month accounting for 60.8% and 39.2% of the model's influence, respectively. Notably, the model's predictions align with the distribution data acquired from the field, particularly in the vicinity of the Koshi River and its floodplain. During the 2009 *B. arnee* census in the Koshi Tappu Wildlife Reserve, nearly 80% of the population was concentrated on the reserve's eastern side, close to the Koshi River.

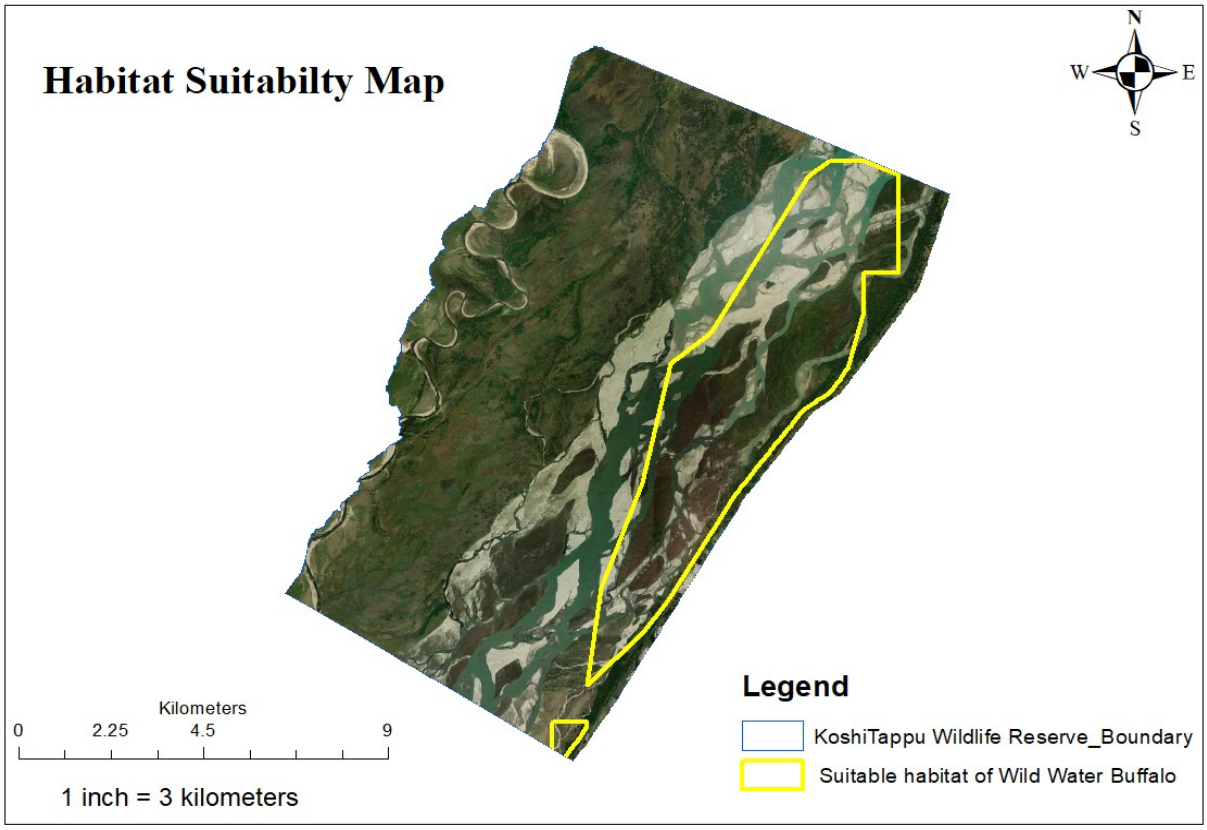

Figure 9: A map with a graduation of colors in relation to the level of suitability.

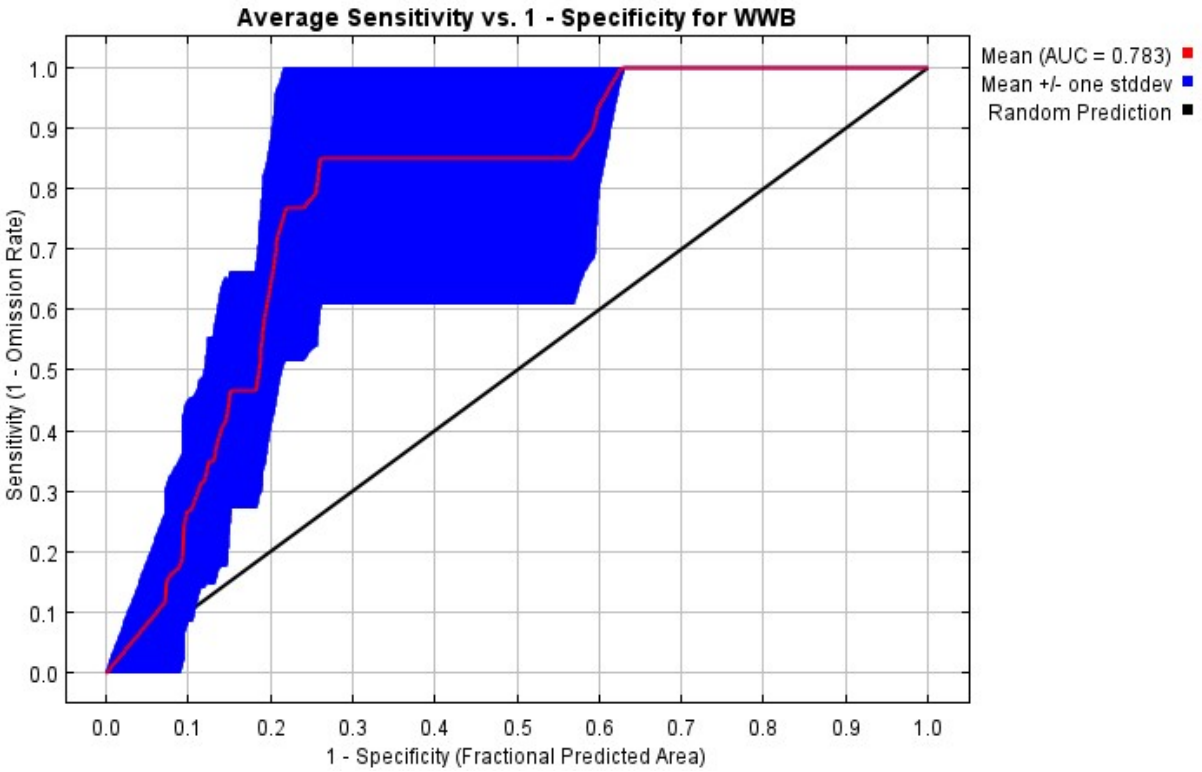

Figure 10: Area under the ROC curve of MaxEnt prediction.

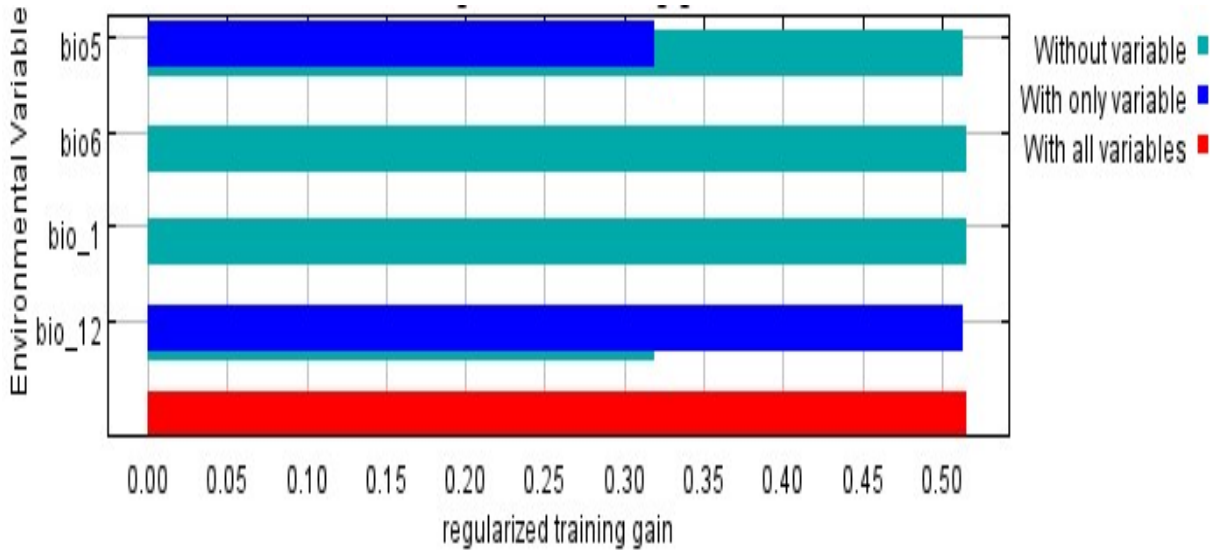

Figure 11: Importance of environment variables to *B. arnee* (WWB) by Jackknife analysis.

Table 4: Habitat suitability area indicating probability of species occurrence.

Habitat Type	Area (sq. km)	Percentage (%)	Remark
Suitable	24.49	13.99	>0.5876
Unsuitable	150.5	85.5	0-5876

Table 5: Variable contribution to the MaxEnt model.

Variable	Variable characteristics	Percentage contribution
Bio-12	Annual precipitation	60.8
Bio-5	Max Temperature of warmest month	39.2
Bio-1	Annual mean temperature	Null
Bio-6	Min temperate of coldest month	Null

This census also documented over 4,000 domestic cattle. Similarly, survey data from 2018/19 showed a higher prevalence of *B. arnee* on the reserve's eastern side and adjacent to the Koshi River (Arna management plan, 2020-2024). Considering the findings from the present study and historical data, the past distribution patterns of *B. arnee* closely correspond to the present situation. In the past, *B. arnee* were present in the Chitwan valley until 1960, their extirpation likely due to diseases transmitted by domestic cattle and buffalo (Seidensticker, 1976). The *B. arnee* population within the Koshi Tappu Wildlife Reserve faces similar significant risks of disease transmission and hybridization from domestic cattle, attributable to unauthorized grazing and habitat overlap. Within the reserve, instances of diseases such as Foot and Mouth Disease (FMD) and Rinderpest have been observed in some buffaloes. In 2017, a total of 15 *B. arnee* (12 from KTWR and 3 from the Central Zoo) were relocated to a 30-hectare enclosure in the old Padampur area of Chitwan National Park. Unfortunately, severe flooding in the same year led to the deaths of five *B. arnee*, raising concerns regarding the relocation program's viability (DNPWC, 2020). Similarly, a study assessing the habitat suitability of *B. arnee* in the Babai floodplain of Bardiya National Park found the suitability to be only moderate for the species.

Preservation of the grasslands and water within that region will be critical to success of wild buffalo reintroduction (Thapa et al., 2020). For this investigation, the MaxEnt was employed to assess the habitat suitability of KTWR, revealing that only approximately 15% of the area is deemed suitable. Consequently, in the current context, it would be prudent to exclude domestic cattle from the grassland area of the reserve and focus on managing the natural habitat for wild buffalo. This approach would create more space for the *B. arnee* population within the reserve and simultaneously mitigate the risks associated with disease transmission and hybridization. In India, the *B. arnee* population is concentrated in Assam in the northeastern region and in Chhattisgarh and Maharashtra in central India. The country's current *B. arnee* count stands at around 4,000, with mere 50 individuals located in central India. Notably, the Udanti-Sitanadi and Indravati tiger reserves serve as critical habitats in Chhattisgarh, while some animals have been observed moving within the Maharashtra area adjacent to the Indravati Tiger Reserve. In Chhattisgarh, the Udanti Wildlife Sanctuary plays a vital role, encompassing a total area of 237.27 square kilometers. A 2007 survey conducted by the Chhattisgarh Forest Department revealed the presence of five adult males, an adult female, and a

male calf. Interestingly, within the sanctuary, an estimated 5,000 people reside alongside over 4,000 livestock, while eight villages situated on the sanctuary's periphery house an additional 3,000 livestock (Mishra and Gaur, 2019). Conversely, the *B. arnee* is no longer extant in Bangladesh and the Lao PRD, with habitat loss identified as a significant threat to the species (Choudhary, 2022).

Conclusion

Effective habitat management remains integral to the conservation of Nepal's last remaining *B. arnee* population. A critical imperative is the undertaking of comprehensive research to accurately delineate the distribution patterns of the *B. arnee* in Nepal and in India. Effectively addressing the challenge of habitat overlap of wild and domestic water buffalo and cattle becomes pivotal in the formulation of impactful habitat management strategies. The utilization of the MaxEnt modeling technique proves to be an invaluable asset in the assessment of habitat suitability for the *B. arnee*. Releasing the grassland habitats from domestic cattle and buffalo is recommended to conserve the wild buffalo for long term.

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Data availability

The data used to support the findings of this study are available from the corresponding author upon reasonable request.

Author contributions

A.S. and R.J. conceptualize and designed the research. A.S., R.J., and S.G. performed the survey. A.S., R.J., and S.G. analyzed and interpreted the data. A.S., R.J., S.G., S.B., and K.P. wrote the draft and reviewed the manuscript draft. A.S. wrote the final article and R.J. plays corresponding role to the journal.

Conflicts of Interest

The authors declare that there are no conflicting issues related to this research article.

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Appendix

Appendix 1: GPS coordinates collected in field.

S. No.	X	Y	S. No.	X	Y
1	86.94882	26.64219	39	87.05348	26.68113
2	86.94932	26.64229	40	87.05246	26.67859
3	86.95147	26.64211	41	87.0524	26.67848
4	86.95321	26.64055	42	87.04693	26.67262
5	86.95585	26.64022	43	87.04607	26.66994
6	86.95704	26.64017	44	87.04524	26.66587
7	86.96158	26.63955	45	87.03938	26.66168
8	86.96803	26.63883	46	87.03963	26.66297
9	86.96805	26.63883	47	87.03875	26.66138
10	86.98541	26.6394	48	87.03602	26.65061
11	87.07965	26.69364	49	87.03596	26.64993
12	87.07961	26.69312	50	87.03491	26.64664
13	87.07522	26.68256	51	87.03408	26.64496
14	87.0737	26.67446	52	87.02969	26.64135
15	87.0719	26.67587	53	87.02788	26.63969
16	87.06179	26.65867	54	87.01662	26.63562
17	87.04843	26.64845	55	87.01672	26.63572
18	87.02466	26.61672	56	87.01074	26.63065
19	87.0247	26.62016	57	87.01018	26.62962
20	87.01466	26.72293	58	87.00992	26.62348
21	87.02171	26.7088	59	87.00729	26.61904
22	87.00902	26.7044	60	87.0045	26.61107
23	87.00547	26.68732	61	87.0043	26.61013
24	86.99505	26.67482	62	87.00425	26.60635
25	86.98758	26.66265	63	87.00313	26.60411
26	86.98758	26.66264	64	87.00409	26.60038
27	86.97954	26.64662	65	87.00782	26.60123
28	86.97954	26.64661	66	87.01147	26.60235
29	86.97177	26.63012	67	86.99863	26.57874
30	86.97226	26.62833	68	86.99866	26.57878
31	86.96576	26.62708	69	86.99734	26.57993
32	86.96563	26.62699	70	87.00223	26.58926
33	87.08032	26.69521	71	87.01052	26.59997
34	87.07123	26.68989	72	87.01498	26.60603
35	87.0644	26.68867	73	87.02036	26.61268
36	87.05922	26.68499	74	87.02473	26.62018
37	87.05953	26.68142	75	87.04139	26.64201
38	87.05515	26.6824	76	87.04842	26.64842

Appendix 2: *Bubalus arnee* and domestic cattle data in different grids.

Grid	Way points	Total no. of *B. arnee*	Total no. of domestic cow	Total no. of domestic buffalo	Domestic cattle and *B. arnee* interaction		Sign					
					Less 500-meter radius	More than 500-meter radius	S	D	T	C	B	O
23 O	Way point 01,02,03,04,05,06,07 86.948816 26.642193 86.949324 26.642293 86.951471 26.642111 86.953209 26.640545 86.955847 26.640223 86.957041 26.640174 86.961577 26.639551	×	295	×	-	-	√	√	×	√	×	√
24 O	Way Point: 09,10,27,28 86.968052 26.638834 86.985409 26.639404 86.979536 26.646618 86.979536 26.646612	12 *B. arnee* (9 adult, 3 calf)	×	223	-	√	√	√	×	×	√	×
42 O	Way point: 011,012,013,033, 034,035 87.079646 26.693642 87.079611 26.693122 87.07522 26.682564 87.080315 26.695207 87.071227 26.689893 87.064396 26.688667	4 *B. arnee* adult	9	×	-	√	√	×	×	√	×	√
35 O	Way Points 014,015 87.073698 26.674458 87.071899 26.675865	15 *B. arnee* (13 adult, 3 calf)	90	×	√		√	×	×	√	×	×
27 O	Way Points 017,075,076 87.048434 26.648447 87.041393 26.642007 87.048416 26.648422	66 *B. arnee* (4 calf, 62 adult)	20	×	√		√	×	×	√	×	×
28 O	No sighting 016	×	×	×	×	×	×	×	×	×	×	×
19 O	Way Points 18,19,73,74, 054,055 87.024656 26.616715 87.024696 26.620155 87.020355 26.612682 87.024731 26.620181 87.016619 26.635619 87.016718 26.635718	45 *B. arnee* (4 calf, 3 sub-adult, 38 adult)	150	×	√		√	×	×	√	×	×
12 O	Way Points 072 87.014977 26.606026	10 *B. arnee* (4 calf, 3 sub-adult)	×	×			√	×	×	×	×	×
47 O	Way Points021 87.021713 26.708802	×	700-800					×	×	√	×	×
39 O	No Sighting 022,023	×	×	×	×	×	×	×	×	×	×	×
32 O	No sighting 024	×	×	×	×	×	×	×	×	×	×	×
31 O	No sighting 025.026	×	×	×	×	×	×	×	×	×	×	×
17 O	Way Points 029, 030 86.971765 26.630115 86.97226 26.62833	×	×	×	×	×	×	√	×	×	×	×
16 O	Way Points 031,032 86.965761 26.627081 86.965631 26.626991	×	×	×	×	×	×	√	×	×	×	×
41 O	Way Points 036, 038 87.059223 26.684991 87.055149 26.6824		7					√	√	√	×	×

Appendix 2: (Continued).

Grid	Way points	Total no. of *B. arnee*	Total no. of domestic cow	Total no. of domestic buffalo	Domestic cattle and *B. arnee* interaction		Sign					
					Less 500-meter radius	More than 500-meter radius	S	D	T	C	B	O
34 O	037,39,40,41,42,43,44, 45,46,47 87.059529 26.681421 87.053483 26.681131 87.052462 26.678585 87.052398 26.678477 87.046931 26.672622 87.046065 26.669937 87.045242 26.665871 87.039377 26.661676 87.039632 26.662966 87.038745 26.661375	21 *B. arnee* (20 adult, 1 calf)	31		√		√	√	√	√	×	×
26 O	Way Points 48,49,50,51,52,53 87.036024 26.650608 87.035964 26.649925 87.034908 26.646637 87.034081 26.644956 87.029689 26.641351 87.02788 26.63969	152 *B. arnee*	170		√		√	√	√	√	×	×
18 O	Way Paints 56,57,58,59 87.010744 26.630649 87.010178 26.629617 87.009916 26.623475 87.007285 26.619037	8 *B. arnee*	220		√	`	√	√	√	√	×	×
11 O	Way Points 60,61,62,63,64,65,66,7 1 87.004501 26.61107 87.004299 26.61013 87.004249 26.606353 87.00313 26.604105 87.004087 26.600378 87.007816 26.601229 87.011465 26.602354 86.998633 26.578738	38 *B. arnee* (36 adult, 2 calf)	1		√		√	√	√	√	×	×
4 O	Way Points 068,067,069 86.998658 26.578775 86.998633 26.578738 86.997339 26.579928	34 *B. arnee* (5 calf, 29 adult)	50		√		√	√	√	√	×	×