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Spatio-temporal variations in activity budgets and reproductive success of the blue bull (*Boselaphus tragocamelus*) in the Cholistan Desert, Pakistan

Atif Amin, Irfan Ashraf, Tanveer Hussain, Junaid Naseer, Muhammad A. Yaqoob*, Muhammad Hashim & Anees Ahmad

ABSTRACT. Behavioral dynamics and reproductive biology of the blue bull (*Boselaphus tragocamelus*) across ecologically distinct habitats within the Cholistan Desert, Punjab, Pakistan, were investigated between the years 2023–2025. Three representative sites namely, Sheikh Mohamed Bin Zayed Al-Nahyan Conservation Breeding Centre, Abbasia Forest, and the agricultural landscapes surrounding Derawar Fort were selected. These observational sites were stratified to represent dry deciduous forest, irrigated farmland and desert shrubland habitats by surveying three (2 km) transects at each site during summer, monsoon and winter seasons. Behavioral ecology was assessed using focal animal sampling ($n = 8$, for each demographic group) daily from 07:00 hours to 18:00 hours. Daily activity budgets demonstrated that feeding was significantly influenced by both the demographic and diurnal factors, with males feeding longer across all seasons. Feeding followed a bimodal pattern in monsoon and summer, while winter activity was more evenly distributed. Locomotion and alertness exhibited demographic-specific variations but not significant seasonal shifts. Similarly, resting and miscellaneous behaviors (e.g., grooming, play) were also significantly affected by age group and time of the day. Male behaviors such as grunt calling, territorial marking, and sparring differed significantly in frequency ($p < 0.001$) but not across habitats ($p = 0.882$). Female reproductive metrics revealed no significant variation in gestation lengths (~244 days; $p = 0.720$), though calving intervals showed a marginal trend ($p = 0.055$). Birth and calf survival rates were highest in dry deciduous forests (100% and 46.15%, respectively) and lowest in irrigated croplands (92.86% birth rate, 38.46% survival), underscoring the role of habitat quality. Maternal behaviors such as grooming and suckling exhibited significant differences by behavior ($p = 0.025$) but not by habitat ($p = 0.980$), indicating stable maternal investment.

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KEY WORDS: nilgai, diurnal activity budget, juvenile survival, reproductive behavior, scent marking.

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Пространственно-временные изменения активности и репродуктивного успеха нильгау (*Boselaphus tragocamelus*) в пустыне Чолистан, Пакистан

А. Амин, И. Ашраф, Т. Хуссейн, Дж. Насир, М.А. Якуб*, М. Хашим, А. Ахмед

РЕЗЮМЕ. В период с 2023 по 2025 г. были исследованы поведение и репродуктивная биология нильгау (*Boselaphus tragocamelus*) в экологически различных местообитаниях в пустыне Холистан,

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Пенджаб, Пакистан. Были выбраны три участка, а именно: Заповедный селекционный центр шейха Мохаммеда Бен Заида Аль Нахайяна, лес Аббасия и сельскохозяйственные ландшафты, окружающие форт Деравар. Участки наблюдений, представляющие сухие лиственные леса, орошаемые сельскохозяйственные угодья и пустынные кустарниковые заросли, были обследованы на трёх трансектах длиной 2 км на каждом участке в течение летнего, муссонного и зимнего сезонов. Наблюдения за поведением проводились ежедневно с 07:00 до 18:00, оценивались выборки животных (n = 8, для каждой демографической группы). Суточные показатели активности свидетельствуют, что на кормление в значительной степени влияют как демографические, так и суточные факторы, причём самцы кормятся дольше в любое время года. Кормление происходило по бимодальной схеме в период муссонов и летом, в то время как зимняя активность была распределена более равномерно. Передвижение и бдительность демонстрировали демографические различия, но не значительные сезонные сдвиги. Аналогичным образом, возраст животных и время суток существенно влияли на отдых и другие виды поведения (например, уход за собой, игры). Поведение самцов, такое как хоркание, территориальная маркировка и стычки, значительно различалось по частоте ($p < 0.001$), но не зависело от биотопа ($p = 0.882$). Репродуктивные показатели самок не выявили существенных различий в продолжительности беременности (~ 244 дней; $p = 0.72$), хотя в интервалах между отёлами наблюдалась незначительная тенденция к их сокращению ($p = 0.055$). Рождаемость и выживаемость детёнышей были самыми высокими в сухих лиственных лесах (100% и 46.15% соответственно) и самыми низкими на орошаемых пахотных землях (92.86% рождаемости, 38.46% выживаемости), что подчёркивает важность качества среды обитания. Материнское поведение, такое как вылизывание и кормление детёнышей, значительно различалось в зависимости от вида поведения ($p = 0.025$), но не зависело от биотопа ($p = 0.980$), что указывает на стабильность материнского вклада в развитие потомства.

КЛЮЧЕВЫЕ СЛОВА: нильгау, суточная активность, выживаемость молодняка, репродуктивное поведение, запаховое мечение.

Introduction

The largest Asian antelope, blue bull, *Boselaphus tragocamelus* (Pallas, 1766), is commonly known as the nilgai. It belongs to the family Bovidae (Babbar *et al*., 2022) and predominantly indigenous to the Indian subcontinent. Researchers have observed that blue bull populations are distributed across the entire subcontinent including India, Nepal, and Pakistan (Khanal *et al*., 2018). However, within Pakistan, the species has primarily been sighted within the arid and semi-arid regions of Cholistan Desert (Koirala *et al*., 2020). Despite its adaptability to harsh environmental conditions, the ecological role, behavioral patterns, reproductive biology, and conservation challenges of the blue bull species indigenous to Pakistan remain poorly understood.

Generally, blue bull has been identified as an herbivore, favoring grasses, shrubs, and agricultural crops (Pandey *et al*., 2022). Blue bull has an integral part in keeping ecological integrity through effecting plant composition, seed dissemination, and predators-prey relationship (Quasin *et al*., 2014). It is particularly found in open plains, dry shrub-related ecosystems, and near aquatic areas of Cholistan Desert (Dhami *et al*., 2023). It can be seen demonstrating sedentary and migratory patterns, based on weather conditions and accessibility of food (Sathapathy *et al*., 2017). However, due to huge grazing, habitat destruction, and human disturbances, the species is under increasing survival pressure (Sathapathy *et al*., 2018).

The Cholistan Desert region is known to have a hot and dry climate with very low average annual rainfall (<200 mm). Scanty xerophytic vegetation (Fig. 1), sand dunes, dry scrub forests, and scattered irrigated plantations are common topographical features in this region. Subsequently, the fauna mainly comprises animals capable of surviving dry weather namely, chinkara (*Gazella bennettii*), desert hare (*Lepus nigricollis*), wild boar (*Sus scrofa*), desert fox (*Vulpes vulpes pusilla*), large number of reptilian species, and a variety of migratory birds. Similarly, indigenous vegetation mainly comprises *Prosopis cineraria*, *Capparis decidua*, *Salvadora oleoides*, *Acacia nilotica*, *Tamarix* spp., and some perennial grasses which are considered vital fodder for blue bull (Dhami *et al.*, 2023).

Blue bulls, or nilgai, are known to be active during the early mornings and late evenings (Quasin *et al.*, 2014). They also exhibit sexual dimorphism, with males living as solitary animals or being part of bachelor groups and the females and young ones living in large herds (Khanal *et al.*, 2018). They display complex social and vocal behaviors, important for mating, territory defense, and avoiding predators. Therefore, studying these behavioral aspects is important for analyzing their adaptation strategies, particularly in dry habitats (Aryal *et al.*, 2016). Blue bulls are polygamous (Vaghela & Dodia, 2022) whereby, dominant bulls claim their territories and engage in aggressive competition for access to the responsive females. Although the breeding season depends on the climatic factors, in Pakistan, it occurs between the months of October and March (Rani & Babbar, 2025). Gestation lasts 8–9 months, with the average number of calves being 1 or 2 (Rani & Babbar, 2024).

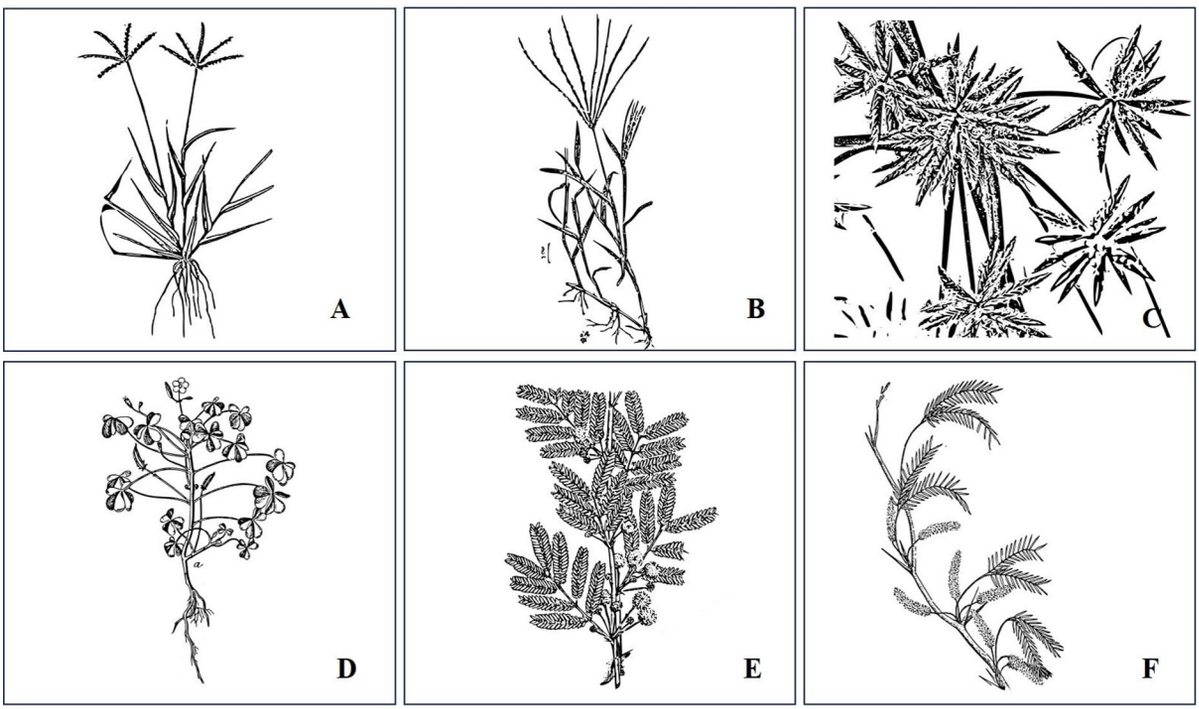


Fig. 1. Some common species of flora browsed by indigenous ruminants of Cholistan Desert: (A) *Cynodon dactylon*, (B) *Digitaria sanguinalis*, (C) *Cyperus rotundus*, (D) *Oxalis corniculata*, (E) *Acacia nilotica*, (F) *Prosopsis juliflora*.

Since, a sound social and reproductive inquiry is essential to developing conservancy strategies for native blue bull populations of Cholistan region, the present research was carried out to observe the effects of habitat, seasons and demographics on behavioral as well as reproductive budgeting.

Material and methods

Ethical compliance

The Islamia University of Bahawalpur's Institute of Forest Sciences, Faculty of Agriculture and Environment, officially approved the research methods used in this work. All field procedures, animal observation techniques, and data collection methods were conducted in strict compliance with the guidelines mandated by Pakistan's Prevention of Cruelty to Animals Act (1890) and the Punjab Wildlife Protection, Preservation, Conservation and Management Act (1974).

Ecology of the study areas within Cholistan Desert

The Cholistan Desert, an extension of the Thar Desert in southern Punjab, Pakistan, spans approximately 26,300 km² and is characterized by an arid to semi-arid climate, shifting sand dunes, scattered vegetation, and seasonal water bodies known as Tobas. Sheikh Mohamed Bin Zayed Al-Nahyan Conservation Breeding Centre (CBC), situated at the interface of the desert and Indus floodplains, features a mixture of sandy terrain, desert scrubland, artificial water bodies, and dry tropical thorn forests, with extreme continental climate fluctuations, reaching up to 50°C in summer and dropping as low as 2–5°C in winter. Abbasia Forest, a man-made plantation within an arid desert landscape, consists of low undulating dunes with sandy soils and scattered patches of *Acacia nilotica*, *Dalbergia sissoo*, and *Prosopis juliflora,* benefiting from canal-fed irrigation despite the region's low annual rainfall (<200 mm). The third site, located near Derawar Fort in Yazman, represents a semi-desert transitional zone with agricultural fields, shifting dunes, and croplands dominated by wheat, cotton, and fodder crops, benefiting from the Sutlej River irrigation system. The use of these three study locations could be rationalized by the presence of distinctly different ecological conditions at these sites. Sheikh Mohamed Bin Zayed Al-Nahyan Conservation Breeding Centre (CBC) is a protected wildlife habitat, Abbasia Forest is a semi-natural forest while the third site, located near Derawar Fort in Yazman could be classified as a human-modified agricultural zone.

Study area and habitat stratification

The study was conducted in three distinct locations within the Cholistan Desert over a two-year period (2023–2025). These included the Sheikh Mohamed Bin Zayed Al-Nahyan Conservation Breeding Centre

(CBC) near Lal Suhanra National Park, Bahawalpur (29.29° N, 72.04° E) representing protected semi-arid scrubland and dry deciduous forest. Silvicultural plantation, characterized by mixed vegetation and canal-fed irrigation at Abbasia Forest (Bahawalpur-Rahim Yar Khan border region) (29.01° N, 71.04° E) were sampled as well (Fig. 2). Moreover, agro-ecosystem adjacent to Derawar Fort, representing semi-arid irrigated croplands were also monitored (Yazman) (28.75° N, 71.27° E). All these sampling sites were stratified based on the predominant habitat type of that particular area, namely dry deciduous forest, irrigated croplands or desert scrubs. Observations were carried out year-round, with specific seasonal stratification to capture temporal variations between summer (June), monsoon (September), and winter (December). Furthermore, observations were intensified during peak breeding (September–December) and calving seasons (May–June).

Assessment of diurnal activity pattern

Diurnal activity budgets were quantified using continuous focal animal sampling conducted daily. Each focal observation lasted one hour and was repeated at weekly intervals throughout each season during morning (07:00–10:00), midday (10:00–14:00), afternoon (14:00–17:00), and evening (17:00–18:00) hours. A total of 24 animals were observed within each habitat (adult male, $n = 8$; adult female, $n = 8$; juvenile, $n = 8$)

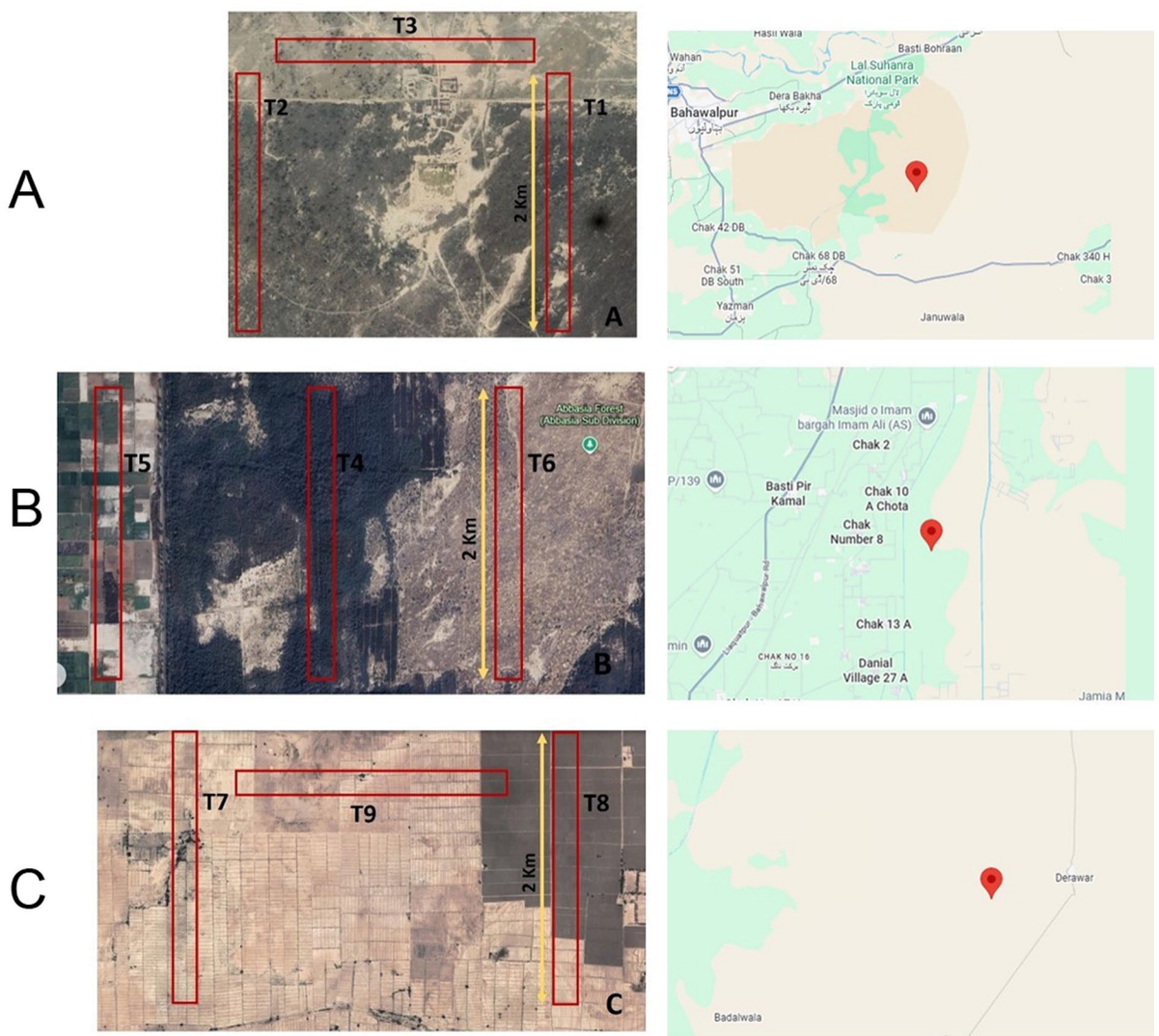


Fig. 2. Satellite images of: (A) Sheikh Mohamed Bin Zayed Al-Nahyan Conservation Breeding Centre (CBC) (29.29° N, 72.04° E); (B) Abbasia Forest (29.01° N, 71.04° E); (C) Derawar Fort (Yazman) (28.75° N, 71.27° E). Three transects, each 2 km long and representative of the predominant habitats (i.e. dry deciduous forest, irrigated farmland, and desert shrubland), have been marked with red borders. Images courtesy of Google Earth ®, as of 05-06-2025.

that could be reliably identified for focal observations during each season. Though it was quite difficult to identify the same animal in the wild, Individuals were recognized using permanent natural markings including horn morphology, body size, facial markings, scars, coat coloration, and repeated association within stable social groups. Owing to fragmentation of these habitats, they have been separated by several man-made structures, namely roads, canals and human settlements thereby limiting migration across these aforementioned study areas. To minimize observer influence, data were collected from concealed vantage points. Observations were conducted between three different types of ecological settings namely, dry deciduous forest, irrigated croplands and desert scrubs. Three 2-kilometer-long transects were surveyed within each site (habitat). Behaviors were categorized into feeding, locomotion, resting, alertness, and miscellaneous activities (including social interactions), and activity budgets were calculated as the proportion of total observation time allocated to each category. Supplementary to direct focal animal observations, 12 motion-sensitive camera traps were deployed along movement corridors and water points 500 meters apart at heights of 50–80 cm.

The camera traps worked in passive infrared (PIR) motion-trigger mode, so they only turned on when animal movement was seen. They just helped to confirm reproductive events and record behavior outside of planned observations. Furthermore, this method lowered memory use and battery drain, therefore allowing continuous deployment over the study duration. Every trigger captured three straight photos with a 30 seconds delay between event activation. Regular field visits included camera checks to replace batteries and memory cards when needed. Moreover, camera-trap records were not included in the statistical analysis and were not combined with the main observational dataset.

Reproductive biology and behavior

Field observations were conducted longitudinally to assess reproductive dynamics. The reproductive investigation was undertaken amongst semi-captive blue bull populations. A combination of line transect sampling, point count surveys, and camera trapping were utilized to estimate nilgai population density. Distance sampling estimated an average population density of 15.75 blue bulls km² within the study areas. During the course of conducting line transect and focal observation, individuals were identified visually into adult males, adult females, and juveniles through external physical attributes. The adult males were identified by their large body size, grey-blue coat, conical horns, and dewlap. While adult females were identified to be smaller, poled, adorned with tawny-brown coat, and in certain cases, recognizable due to presence of nursing udders. Furthermore, the identification of juveniles was carried out on the basis of smaller body size, pale coloration of fur, undeveloped horns, and their association with adult females.

Only females that could be repeatedly recognized throughout the study period were included in gestation and calving interval analyses. Among the pregnant females encountered, 33 individuals that could be reliably identified throughout the study were included in reproductive analyses. These females were repeatedly observed throughout gestation and calving, and all analyses of gestation length, calving interval, maternal behavior, and juvenile survival were restricted to this subset. Focal animals were observed for rutting behavior at the three most common habitat types in Cholistan region (dry deciduous forest, irrigated cropland and desert shrubland). During observation of diurnal activity budget hourly frequency of territorial marking, sparring bouts (head butting, aggressive posturing) and grunt calls (mating calls) were recorded for an hour during each of the three divisions of the daylight active period (7:00–18:00) i.e., morning, afternoon, dusk. Observations were repeated at weekly intervals for about a month. Concurrently, pregnancy determination of adult females was based on their physical changes (abdominal distension, enlarged udders, visible teats, reduced tail movement and frequent licking of abdomen), overall body condition, and behavioral indicators (reduced locomotion, increased feeding, isolation, cautious behavior and avoidance of aggressive social interactions). Moreover, the number and presence of newborns in herds were also recorded to determine birth rates. Calving periods and interbirth intervals were also documented for the previously identified females. Close-range observations using binoculars and spotting scopes were employed for determining the male to female sex ratio amongst newborns.

Juvenile survival and maternal care

Certain juvenile individuals were identified based upon one or more of their unique physical features (scabs, distinct features, ear notches) and their survival rates were monitored over time. The fate of calves (survived, predated, or abandoned) was recorded. Causes of mortality, including predation, malnutrition, and anthropogenic factors, were inferred from field evidence and carcass examinations, supported by camera trap records obtained near calving areas, water points, and frequently used movement corridors. Simultaneously, instances of maternal care (suckling, grooming) were recorded by employing Focal sampling methodology. To this end, mother-calf pairs were observed for an hour during daylight active period (7:00–18:00) i.e., morning, afternoon, dusk. Observations were repeated at weekly intervals for about a month. Suckling and grooming durations for calves which died before 6 months, were excluded from the study.

Statistical analysis

All statistical analyses were performed using ver.20.0 SPSS and ver. 8.4.3 GraphPad Prism. Quantitative data regarding activity budgets and behavioral frequencies were expressed as mean ± standard deviation (SD). Two-way ANOVA followed by a post-hoc Tukey's multiple comparisons test was employed to assess the diurnal and demographic effects on activ-

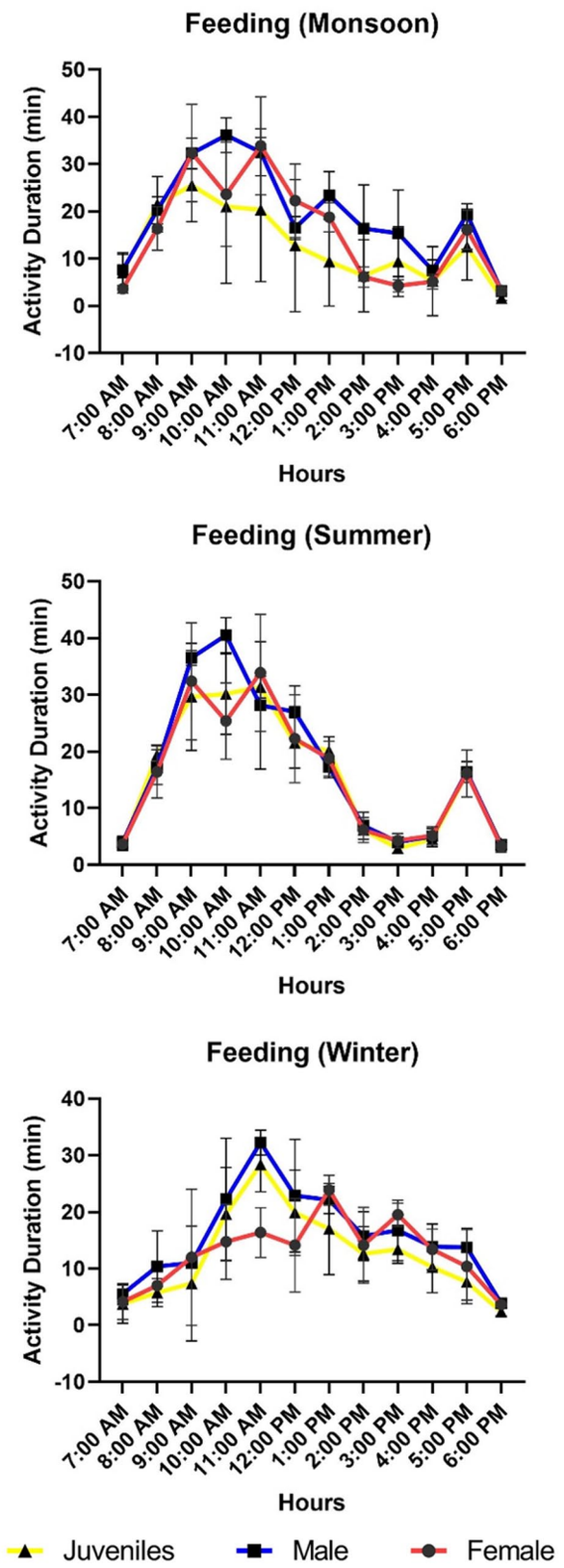


Fig. 3. Temporal variation in feeding duration (mean ± SD) among male, female, and juvenile blue bulls across monsoon, summer, and winter seasons.

ity patterns. Activity budgets for focal animals within the three study sites were averaged to obtain independent data snapshots for activity durations at a specific time period and season, representative of different blue bull demographics indigenous to Cholistan Desert, therefore measures were not repeated while performing statistical analysis. Mean frequencies of territorial marking, sparring bouts and grunt calls amongst male blue bulls were also analyzed using two-way ANOVA, while one-way ANOVA was utilized to analyze gestation periods and calving intervals. Fisher's exact test was used to assess the relative risk of calf mortalities within different habitats. $p < 0.05$ was determined to be statistically significant for all tests.

Results

Diurnal activity budgets

Feeding duration exhibited significant demographic heterogeneity within each season (monsoon: $F(2, 252) = 19.87$, $p < 0.001$; summer: $F(2, 252) = 3.514$, $p = 0.031$; winter: $F(2, 252) = 11.28$, $p < 0.001$). Adult males consistently spent more time to feeding than females or juveniles across all seasons (Fig. 3). A temporal shift in foraging was evident during summer. Feeding activity peaked in the morning and declined significantly post-midday, indicative of heat-avoidance behavior. Conversely, winter foraging patterns lacked this sharp midday depression, characterized instead by sustained feeding between 07:00 and 16:00 hours. Notably, females maintained consistent feeding activity during winter, likely a strategy to accrue energy reserves for gestation (Fig. 3). In terms of total diurnal budget, feeding was highest during summer (28.99%), followed by monsoon (28.34%) and winter (25.50%), respectively.

Like feeding, the average duration of locomotion also differed significantly across seasons (monsoon: $F(2, 252) = 5.845$, $p = 0.003$; summer: $F(2, 252) = 19.41$, $p < 0.001$; winter: $F(2, 252) = 26.68$, $p < 0.001$), with percentage budget activity ranging narrowly between 18.93% and 19.25%. A midday reduction in movement was observed year-round, coinciding with peak resting times. In summer, locomotion increased slightly in the late afternoon, likely driven by thermoregulatory movements toward shade or water. Juveniles generally exhibited the lowest locomotor activity (Fig. 4). Alertness durations exhibited strong demographic stratification (monsoon: $F(2, 252) = 16.14$, $p < 0.001$; summer: $F(2, 252) = 3.691$, $p = 0.026$; winter: $F(2, 252) = 101.9$, $p < 0.001$). Adult males and females displayed heightened vigilance during early morning and late afternoon hours, whereas juveniles showed reduced alertness, particularly between 10:00 and 15:00 hours (Fig. 5).

Resting behavior showed reciprocal relationship with activity. In summer, adult males exhibited peak resting durations during late afternoon hours. In winter, bimodal resting pattern emerged with peaks in the early morning (07:00–08:00) and late evening (17:00–18:00).

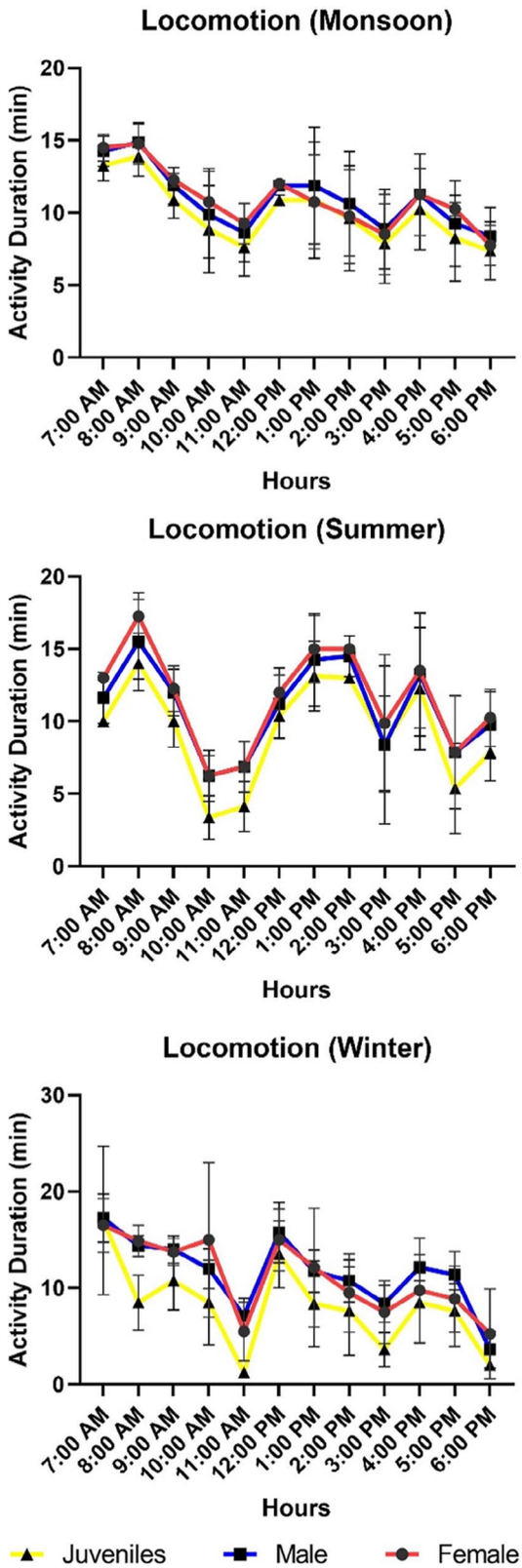


Fig. 4. Temporal variation in locomotion duration (mean ± SD) among demographic groups across three seasons.

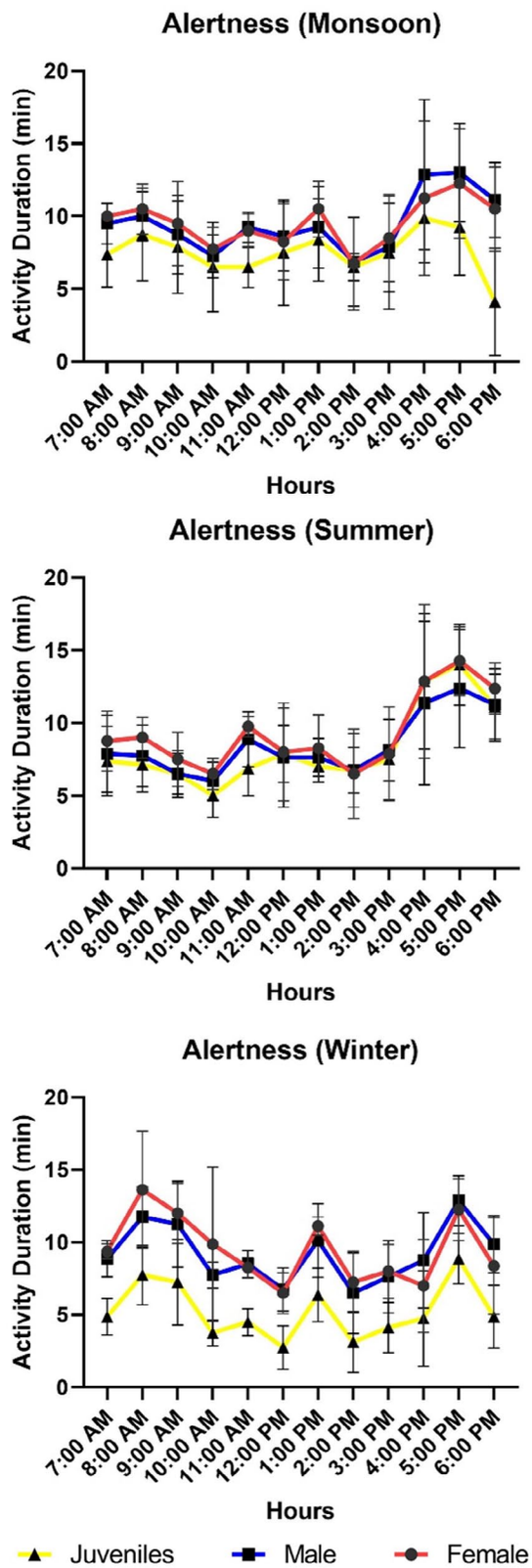
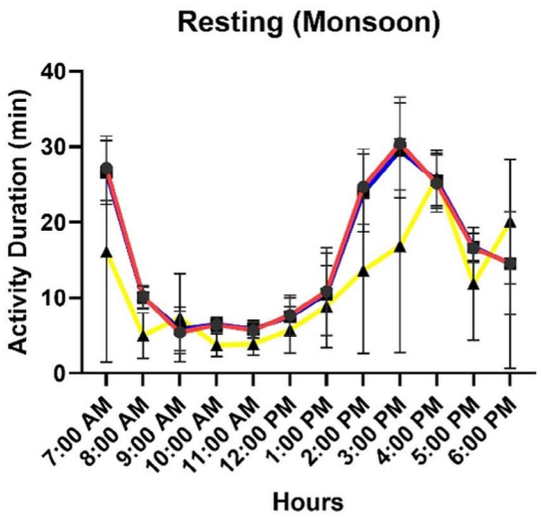
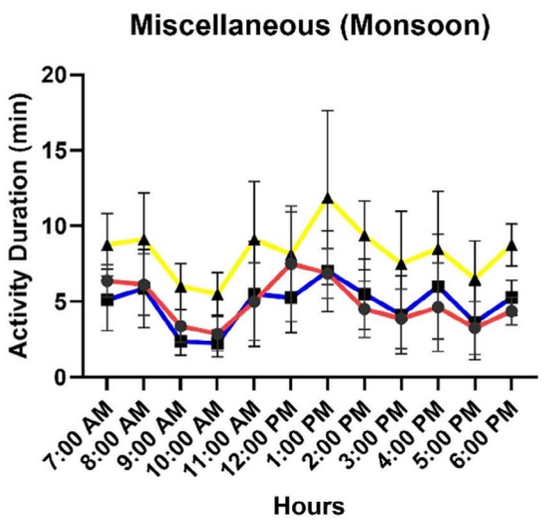
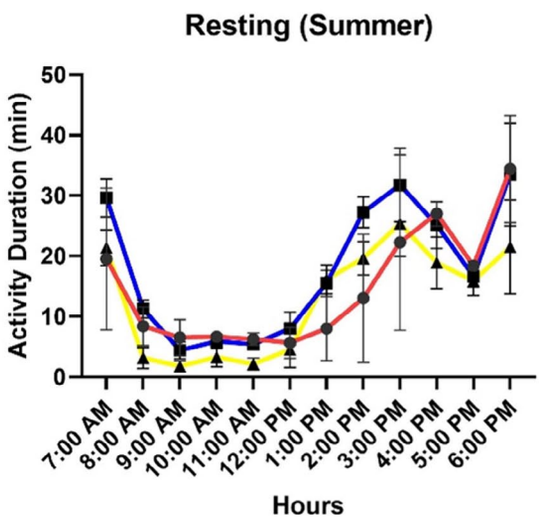
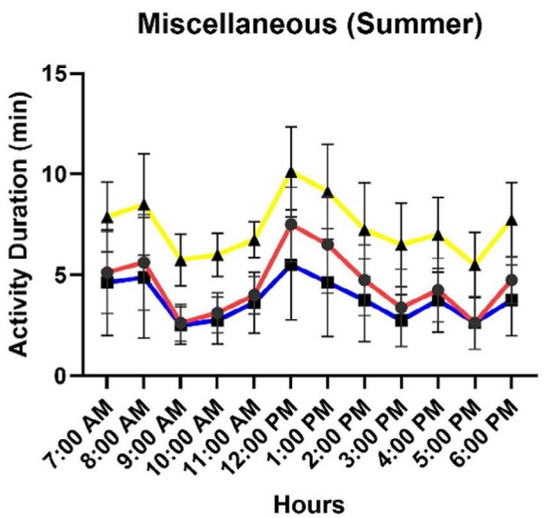


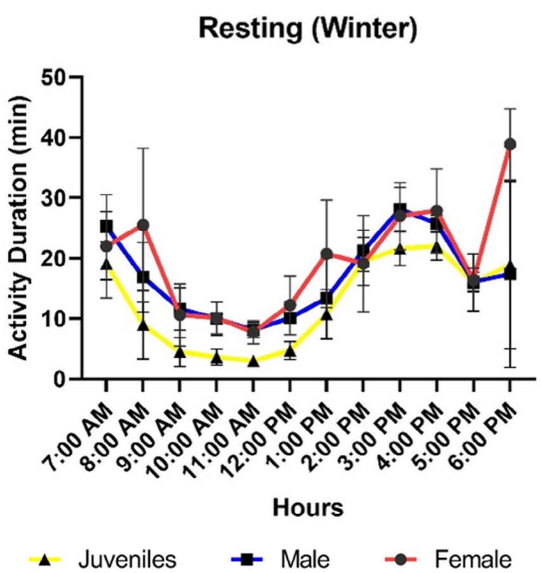
Fig. 5. Temporal variation in alertness duration (mean ± SD) among demographic groups across three seasons.











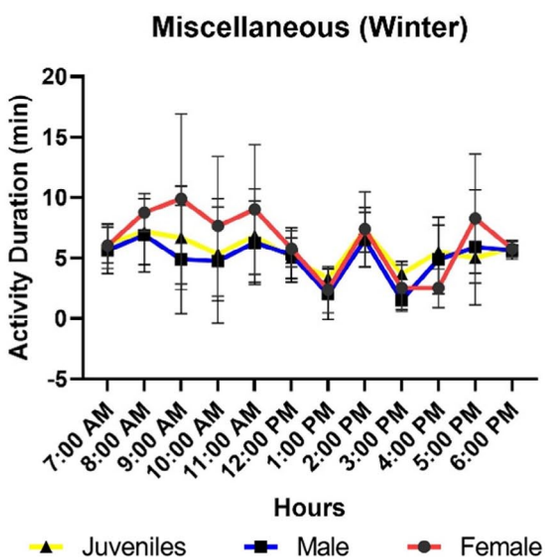


Fig. 6. Temporal variation in resting duration (mean ± SD) among demographic groups across three seasons.

Fig. 7. Temporal variation in miscellaneous activity duration (mean ± SD) among demographic groups across three seasons.

Table 1. Hourly frequency (mean ± SD) of male reproductive behaviors across three distinct habitat types.

Habitats	Territorial marking		Sparring bouts		Grunt calls		Column factor
	mean	±SD	mean	±SD	mean	±SD	
Dry deciduous forest	6.26	2.59	2.36	1.69	7.84	3.02	<0.001
Irrigated croplands	5.99	2.67	2.10	1.68	7.43	2.87	
Desert scrubs	5.63	2.59	2.56	1.64	7.33	2.85	
Row factor	0.8815						

Females consistently rested longest during evening hours (Fig. 6). Resting behavior exhibited strong demographic stratification as well (monsoon: $F(2, 252) = 12.39$, $p < 0.001$; summer: $F(2, 252) = 24.78$, $p < 0.001$; winter: $F(2, 252) = 35.63$, $p < 0.001$).

Miscellaneous activities (social interactions, grooming) occupied the smallest portion of the budget (9.43%–11.09%). While generally stable, juveniles exhibited increased engagement in miscellaneous behaviors (exploratory/play) during winter mornings and afternoons compared to adults (monsoon: $F(2, 252) = 57.39$, $p < 0.001$; summer: $F(2, 252) = 99.09$, $p < 0.001$; winter: $F(2, 252) = 4.105$, $p = 0.018$) (Fig. 7).

Reproductive behavior and biology

Analysis of male rutting behaviors revealed that grunt calls were the most frequent activity (7.33–7.84 calls/hour). A two-way ANOVA indicated that while the frequency of specific behaviors (calling vs. marking vs. sparring) differed significantly ($F(2, 57) = 25.23$, $p < 0.001$), there was no significant variation in these behaviors across the three habitat types ($F(2, 57) = 0.126$, $p = 0.882$). Male reproductive strategies appear consistent regardless of habitat structure (Table 1).

Gestation length and calving intervals were analyzed to determine environmental influence. The mean gestation period was consistent across habitats ($F(2, 69) = 0.331$, $p = 0.720$), ranging from 244.00 ± 2.69 days in irrigated croplands to 244.57 ± 1.87 days in dry deciduous forests (Fig. 8A). Calving intervals showed marginally non-significant trend ($F(2, 69) = 3.022$, $p = 0.055$), being shortest in desert scrubs (15.67 ± 1.78 months) and longest in irrigated croplands (18.00 ± 2.03 months) (Fig. 8B).

Habitat type appeared to influence reproductive outcomes. The dry deciduous forest supported the highest birth rate (100%; $n = 13/13$) and the highest juvenile survival rate (46.15%). Conversely, irrigated croplands yielded birth rate of 92.86% but the lowest survival rate (38.46%). Desert scrubs recorded birth rate of 83.33% with a 40.00% survival rate (Table 2).

Analysis of mortality causes using Fisher's Exact Test revealed no statistically significant difference in the relative risk of natural versus anthropogenic mortality across habitats ($p > 0.999$). In dry deciduous forests and irrigated croplands, mortalities were evenly split between natural causes (predation, disease) and man-made factors. In desert scrubs, only natural mortalities (predation, drought) were recorded (Table 3).

Maternal care behaviors differed significantly by type, with grooming frequency (2.05–2.25 bouts/hour) consistently exceeding suckling frequency (1.17–1.19 bouts/hour) ($F(1, 30) = 5.602$, $p = 0.025$). However, the frequency of these maternal behaviors did not vary significantly across habitat types ($F(2, 30) = 0.020$, $p = 0.980$) (Table 4).

Discussion

Wild animals engage in a diverse range of daily activities essential for survival in their natural ecosystems (Quasin *et al.*, 2014). However, the intensity and timing of these behaviors are rarely static; they are shaped by ecological constraints such as limited space (Khanal *et al.*, 2018), food availability, and anthropogenic disturbances.

Feeding and foraging dynamics

The main activity observed was feeding, which was lowest during the mid-day period and maximum during morning hours (9:00–11:00). These findings

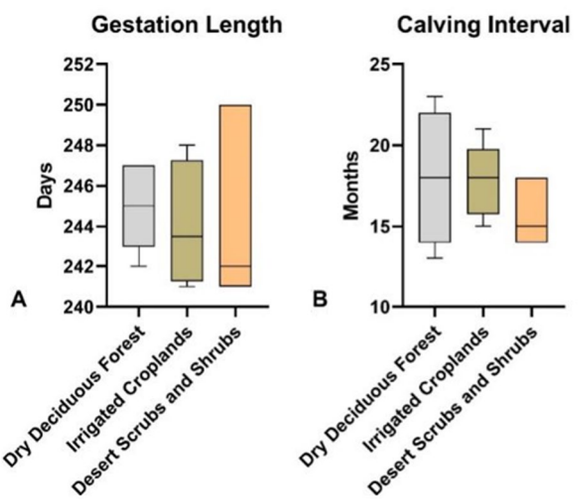


Fig. 8. Box-and-whisker plots representing gestation lengths (A) and calving intervals (B) of female blue bulls.

Table 2. Comparative birth rates and juvenile survival percentages (2023–2025) across three habitat types.

Birth rates	Habitats	Live births	Still births	Relative risk	95% CI	*p*-value
	Dry deciduous forest	13	0	1.11	0.84–1.95	0.51
	Irrigated croplands	13	1	0.98	0.71–1.24	>0.99
	Desert scrubs and shrubs	5	1	0.87	0.45–1.07	0.34
	Total	31	2			
Survival rate	Habitats	Juveniles survived (+6 months)	Early mortalities	Relative risk	95% CI	*p*-value
	Dry deciduous forest	7	6	0.88	0.44–1.61	0.72
	Irrigated croplands	8	5	1.1	0.58–2.02	>0.999
	Desert scrubs and shrubs	3	2	1.04	0.38–1.89	>0.999
	Total	18	13			

Table 3. Relative risk analysis of natural versus anthropogenic causes of calf mortality across habitats.

Habitats	Natural			Man-made	Relative risk	95% CI	*p*-value
	Predation	Disease	Drought	Human intervention			
Dry deciduous forest	2	2	0	2	0.933	0.390–2.072	>0.999
Irrigated croplands	2	1	0	2	0.8	0.292–1.729	>0.999
Desert scrubs and shrubs	1	0	1	0	1.571	0.509–13.27	>0.999
Total	5	3	1	4			

Table 4. Hourly frequency (mean ± SD) of maternal care behaviors (suckling vs. grooming) across three habitat types.

Habitats	Suckling		Grooming		Column factor
	mean	SD	mean	SD	
Dry deciduous forest	1.19	0.95	2.13	1.18	0.025
Irrigated croplands	1.17	0.95	2.05	1.33	
Desert scrubs	1.17	1.03	2.25	1.23	
Row factor	0.980				

confirmed various earlier studies on Blue bull activity patterns (Bajwa & Chauhan, 2019; Chandel *et al.*, 2024; Kushwaha *et al.*, 2024) corroborating the fact that feeding is the most seasonally and demographically variable activity (Jain *et al.*, 2022). In addition, during several observations in summer ($p = 0.031$), monsoon ($p < 0.001$), and winter ($p < 0.001$), major changes were noted among demographic groups (male, female, juvenile). Comparable to prior observations, males spent longer durations feeding than females and juveniles. This likely reflects their larger body size and associated higher nutritional requirements, as prolonged grazing and ruminating are necessary for large ungulates to maintain body mass and competitive status (Zoromski *et al.*, 2022). Seasonally, feeding was most pronounced during morning hours in the monsoon season, attributable to greater forage availability and favorable ambient temperatures. This supports the hypothesis that environmental pressure drives activity pattern shifts in wild ungulates (Rahman, 2024). Conversely, feeding declined with the day's progression, particularly during summer afternoons (Prasad *et al.*, 2021), phenomenon justified by behavioral thermoregulation to avoid heat stress (Khanal *et al.*, 2018). In winter, midday lull was followed by late afternoon resurgence in feeding across all groups, indicative of a strategy to balance energy acquisition with thermal comfort (Prasad, 2020). Similar adaptive foraging and heat-avoidance patterns have been documented in blackbucks indigenous to the Cholistan region (Bajwa & Chauhan, 2019; Prasad *et al.*, 2021; Sliwa *et al.*, 2023).

Locomotion, alertness, and resting behaviors

In contrast to feeding, overall locomotion means did not vary significantly amongst demographic groups ($p = 0.494$). This suggested that movement between water and food sources (Jain *et al.*, 2022), remained rather constant throughout the year and were influenced by the structure of the habitat rather than climatic changes (Prasad, 2022). Adult male and female individuals were able to travelled more than juveniles, who stayed closer to cover and their mothers, probably due to limited energy, or as predator avoidance strategy (Prasad, 2020). A midday depression in locomotion was evident across all seasons, consistent with the resting and ruminating phases reported in ruminants inhabiting harsh climates (Prasad *et al.*, 2021; Chandel *et al.*, 2024; Rahman, 2024). However, slight rise in summer locomotion during late afternoon suggests renewed activity as temperatures dropped. Regarding vigilance, males and females remained more alert than juveniles, particularly during morning hours. This elevated vigilance is attributed to increased predator activity and intergroup competition (Foley *et al.*, 2017; Granger, 2021; Baumgardt *et al.*, 2023). Furthermore, breeding and social interactions intensify during the monsoon, necessitating heightened visual and auditory awareness (Khanal *et al.*, 2018). Conversely, lower alertness in juveniles may be explained by their limited situational awareness (Mehta *et al.*, 2013). Resting behaviors followed patterns complementary to alertness and feeding, peaking during midday. This pronounced midday rest, particularly in summer, is critical strategy for water conservation and thermoregulation previously reported in arid-zone herbivores (Olafson *et al.*, 2018; Kritika *et al.*, 2023; Siddiq & Shahzad, 2023; Kushwaha *et al.*, 2024).

Reproductive behavior and vocalization

While typically described as a calm species (Sliwa *et al.*, 2023), all age groups are capable of producing forceful guttural sound resembling a cough or roar (Prasad, 2020). Current observations corroborated that adult males produce violent belching sounds termed «grunt calls» during territorial confrontations or mating rituals (Bajwa & Chauhan, 2019; Granger, 2021). In contrast, females vocalized more subtly (Prasad, 2022), utilizing low-pitched clicking sounds during nursing or estrus (Jordan, 2013). Polygynous mating systems were documented where top ranking males exerted dominance over aggregations of females through a repertoire of actions, including territorial marking and sparring bouts (Granger, 2021). Significant differences between mean hourly frequencies of grunt calls, territorial marking, and sparring behavior were observed in present settings. The grunt call represented the dominant behavior, indicative of the crucial role played by grunt calls in signaling of readiness for reproduction (Quasin *et al.*, 2014; Khanal *et al.*, 2018; Jain *et al.*, 2022; Prasad, 2022). Surprisingly, the use of two-way ANOVA exhibited no significant variation in male reproductive behaviors between different habitats ($p = 0.882$). Such a conserved pattern of territorial marking and sparring between habitats (Prasad, 2020) indicated that the drivers behind territorial marking and sparring behaviors could be hormonal stimuli and/or evolutionary factors instead of immediate ecological factors (Granger *et al.*, 2024). Moreover, courtship behaviors were observed such that the dominant male raised his tail while putting up its back; the responsive female would lower her neck head and perform a twisting gesture (Granger *et al.*, 2024).

Reproductive physiology and juvenile survival

It takes about two years for wild females to reach sexual maturity (Granger *et al.*, 2024). Previous findings of 243–247 days were consistent with the presently reported mean gestation period of approximately 244 days (Khanal *et al.*, 2018). Females often regained receptivity within a year after calving, which took about 17 months (Oguya & Eltringham, 1991). Notably, gestation ($p = 0.720$) and calving ($p = 0.055$) lengths were not significantly impacted by ecological conditions, which supported the idea that these are species-specific characteristics controlled by internal cycles rather than external stressors (Siddiq & Shahzad, 2023). Habitat type, however, appeared to influence reproductive outcomes. Dry deciduous forests yielded the highest birth rates (100%) and survival rates (46.15%), suggesting that canopy coverage provides optimal microclimates and vegetation for calf rearing. Conversely, irrigated croplands showed the lowest calf survival (38.46%), likely due to anthropogenic disturbances such as machinery operation and human-wildlife conflict (Johnson *et al.*, 2024). Although twinning has been reported previously (Sliwa *et al.*, 2023), no instances were observed in this study. The primary breeding season extended from September to December, with calving peaking in May and June, consistent with regional patterns (Chandel *et al.*, 2024).

With respect to mortality, there was no significant difference observed using Fisher's exact test on the relative risk of natural versus man-made causes across habitats ($p > 0.999$). It should also be noted that, none of the natural or anthropogenic factors overwhelmed the others when considering mortality data (Prasad, 2020) and this indicated a multifactorial relationship among several types of stochastic occurrences. Maternal behavioral preferences were reflected in a notable degree of significance ($p = 0.025$) in favoring grooming over suckling however, no influence of habitat type was detected ($p = 0.980$). Further highlighting the duality of roles played by these activities ranging from basic hygienic needs and emotional bonding to nutrition through suckling (Granger *et al.*, 2024).

Conclusion

Current study clarified the complicated daily activity patterns of blue bull in the Cholistan Desert, therefore highlighting major chronological and demographic variation in basic activities like feeding, movement,

and resting. The observed activity budget showed important behavioral adaptation to the extreme heat of the dry Cholistani environment. Foraging activity peaked during early morning hours and plummeted during mid-day. These results indicted towards the behavioral plasticity of the species, in response to social dynamics, photoperiods, ambient temperature, and food availability. Although reproductive physiology and behavioral repertoires did not vary significantly among different habitat types, our findings suggested that spatial heterogeneity exerted critical influences on demographic success. While we failed to establish direct relationships between individual mortality processes and habitat type, authors detected enhanced juvenile survival probabilities in forested landscapes compared with those inhabiting agricultural zones. Reduced calf survival in cultivated areas suggested important ramifications pertaining to human-induced ecological changes. Authors also acknowledge certain limitations in present research endeavor. Currently, individual identification relied on natural morphological characteristics, which may have introduced minor identification errors despite repeated observations. Sample sizes for mortality analyses were relatively small, reducing statistical power. Future studies incorporating GPS collars and larger sample sizes would improve estimates of movement ecology and demographic parameters. Authors have endeavored to mitigate limitations associated with direct focal observation of wild and semi-captive populations by averaging activity budgets from different sites during the same season and diurnal time period. Thus, the obtained data represented the most precise inclinations of different blue bull demographics irrespective of the lapses for data recording of a particular focal individual considering limitations of direct observations.

Consequently, conservation strategies in the Cholistan region must prioritize the preservation of native vegetation, grazing corridors, and water access points. Future management efforts should focus on monitoring human-wildlife interfaces in agricultural landscapes to ensure the long-term resilience of this ungulate population against increasing climatic variability and anthropogenic pressures.

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