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Habitat Ecology, Trophic Interactions, and Distribution of Endangered Himalayan Musk Deer in the Nepal Himalaya

A dissertation submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy in Biology

by

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December 2017
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Abstract

This dissertation seeks to explore and assess the habitat selection, trophic interactions and distribution of Himalayan musk deer. Chapter one deals with seasonal diet analysis of musk deer along with the overlap in consumption with livestock during summer. Microhistological technique was employed to assess dietary consumption. Results showed that *Abies spectabilis, Pinus wallichiana*, and *Berberis* species constituted the major portion of musk deer's diet. Dietary breadth measured by the Shannon index was found higher in winter compared to summer. Although musk deer and livestock shared a considerable number of plant species in their diets, the consumption however was significantly different in terms of abundance of the species consumed.

Chapter two deals with habitat selection at the 2nd order in terms of physical and vegetational attributes within the home range. It also assesses the impacts of livestock presence in habitat selection of musk deer. Logistic regression of musk deer's presence/absence with binomial error structure and logit link function was employed to determine the physical and vegetational characteristics that likely affected the habitat selection by musk deer. Results found that elevation, aspect, canopy-cover, and tree species significantly affected the habitat selection of musk deer. Moreover, presence and absence of livestock was not found to have any significant effect on the habitat section of musk deer suggesting the selection as an evolutionary adaptation rather than an outcome of interspecific interactions with the livestock.

Chapter three deals with habitat selection at the scale of geographic range. This chapter seeks to predict the area that is climatically suitable currently and in the future in context of climate change. Maxent modeling technique with occurrence records (i.e., latitude and longitude) of the species and bioclimatic variables as inputs was employed. Annual mean temperature was

found as the significant climatic variable affecting habitat selection at the scale of geographic range and the model predicted an expansion of climatically-suitable area at the northern limit of the species’ range in Indian and Tibetan regions. It is expected that the understanding of habitat selection of musk deer at different scales could help in the conservation and management of the species.

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I feel lucky to be surrounded by very talented and helpful people during my academic career. My academic achievements would not have been possible without the help and support of these people. I will take a moment to acknowledge all the ones for whom any words of acknowledgment would look poor and insufficient. Yet, I will try to accommodate them all into the following paragraphs.

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Dedication

I would like to dedicate this dissertation to my parents, Komal Khadka and Maya Devi Khadka, for their constant support and tireless effort to provide the best education to their children. Despite numerous ups and downs in their life, they always supported and motivated me in the best possible way one can imagine of. Thank you so much, Mom and Dad.

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Introduction:

Species have some optimal requirements in terms of resources and conditions for survival, reproduction, and persistence and are thus adapted to such optimal conditions as invoked by niche theory (Grinnell, 1917; MacArthur, 1970; Tilman, 1982). Conservation of declining and threatened species requires the identification of those necessary resources and conditions, i.e. habitat that produces occupancy and support their survival and persistence (Hutchinson, 1957; Levins, 1968; Hall et al. 1997). However, the conditions that appear important for the distribution and persistence of species are scale dependent and selection of resources and conditions by individuals of a given species occur in a hierarchical process (Johnson, 1980). Hence, our understanding of resources that appear important could be greatly influenced by the scale context of the study. Understanding the factors that produces occupancy, drive their distribution, and support survival and persistence of the species at different spatial scales could greatly aid in the management and conservation. For example, Johnson (1980) has reported four hierarchical order of habitat selection ranging from the scale of geographic range of a species to procurement of diet at microscale within the home range. While physical and vegetational characteristics of the habitat, and biotic interactions could be important at a finer scale, climatic factors are considered important at a broader scale and are powerful determinants of species distribution at the scale of geographic range (Andrewartha and Birch 1954; Pearson and Dawson, 2003; Benton, 2009; Wiens, 2011).

With human induced climate change, selection of habitat and distribution of species at a scale of geographic range could change with cascading effect at lower and/or finer scale. Hence, understanding the factors that drive the selection of habitat and distribution of species at different hierarchical order could aid in better and effective management of species with immediate conservation concern. Moreover, such information could assist in habitat management and conservation planning in the context of climate change as well since the predicted climate change could shift the distribution and change the geographic range of the species as has been documented for many other species (Chen et al., 2011;

Himalayan musk deer (*Moschus leucogaster*) and Alpine musk deer (*Moschus chrysogaster*) are typically confined to mountain forests and alpine environments of Asia (Whitehead, 1972; Flerov, 1952). According to the literature, both the species are interchangeably treated as Himalayan musk deer or Alpine musk deer. It is probably due to their morphological similarities and overlapping habitat Nevertheless, owing to their small and declining population size with restricted geographic range, both the species are listed in Appendix I of CITES and as endangered in the IUCN red list. Thus, they require immediate conservation actions before their extinction in the wild. In Nepal, musk deer are found in the birch, pine and rhododendron forest of the Himalayan region at an altitude of 2400-4300 m (Shrestha, 1998). Although protected by the Department of National Park and Wildlife Conservation Act since 1973 (Green and Kattel, 1997), musk deer populations in Nepal remain susceptible to poaching, potential competition with livestock, and habitat alteration; all factors that likely contribute to further decline and fragmentation of remaining populations.

Despite of the understanding about the threats and necessity of their conservation concerns, little is known regarding habitat conditions driving the distribution and supporting the survival of musk deer populations at different hierarchical order and/or process. Also, potential threats from sympatric livestock during summer in terms of resource exploitation and habitat utilization is largely unknown. With this information in mind, this study seeks to fulfill the knowledge gap regarding the selection of habitat at different hierarchical scale and potential impacts of livestock in terms of diet and spatial habitat overlap. Moreover, the study also aims The findings could assist in developing and implementing the conservation strategies for the species at different hierarchical order. The first chapter is concerned with the dietary assessment of musk deer and evaluate the dietary composition and overlap with livestock. I analyzed the dietary composition using the microhistological technique. The second chapter is concerned with the habitat conditions in terms of physical characteristics and vegetational characteristics that are selected and utilized by the musk deer and evaluate any effects of livestock in terms of selection. The third chapter is concerned with the bioclimatic conditions driving the distribution of the species at the scale of geographic range of the species. Besides, this chapter also aims to predict the climatically-suitable geographic area in the future in the context of projected climate change.

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Chapter II: Dietary composition, breadth, and overlap between seasonally sympatric Himalayan musk deer and livestock: conservation implications

Abstract:

Livestock in high altitudes of Nepal and elsewhere, frequently and freely, use the potential habitat of native wildlife for foraging. Such intrusion of ecologically similar domestic species is supposed to negatively impact the resident wildlife via ‘perceived’ and/or ‘real’ competitive interactions. Hence, assessment of dietary composition and overlap between herbivores is crucial to gain insight into the potential impacts via resource exploitation by foraging livestock. Also, evaluation of dietary composition of resident wildlife across seasons is important to decipher their seasonal resource needs. Within this context, microhistological technique, that makes use of fecal pellets for the identification of plant species through comparison with reference slides of plant materials in the area, was used to assess dietary composition, breadth, and overlap between seasonally sympatric Himalayan musk deer and livestock in the Nepal Himalaya. Musk deer and livestock were found to have significantly different dietary consumption and that partition was contributed by different species; meaning different plant species were associated to the diets of these two groups. Of notable, however, was a considerable ‘number’ of species (i.e., species richness) shared in diets by musk deer and livestock raising a concern of unchecked number of livestock with a potential to exploit and reduce the availability of shared plant species for musk deer. Also, seasonal dietary composition of musk deer significantly varied, with increased dietary breadth in winter, suggesting a potential for intraspecific competition for forage in winter because of limited availability of resources mediated by retarded growth and harsh conditions.

1. **Introduction**

Coexistence of sympatric species, despite extensive overlap in ecological requirements, is a function of resource partition (Hutchinson, 1959; MacArthur & Levins, 1967; MacArthur, 1972). Such differential use of resources such as food and space can potentially be attributed to a response to interspecific competition over evolutionary time, where selection would favor the separation of resources to increase fitness (Schoener, 1974; Ricklefs, 2008). Introduction of ecologically similar species into a system can disrupt the system, if resident and introduced species do not share a long evolutionary history for resource partitioning and coexistence (Voeten & Prins, 1999; Prins, 2000). The severity of such introduction amplifies when introduced species are domesticated livestock with artificial supplementation of diet and are thus potentially competitively superior (Prins, 1992; Mishra *et al.*, 2002). The gravity of the situation is even more severe when residents are declining endangered species confined within the boundary of Conservation areas (Mishra *et al.*, 2004). Thus, understanding the extent of resource use by native wildlife and resource overlap with introduced species is a crucial conservation concern for declining wildlife populations.

Wildlife and livestock share the rangelands worldwide (Prins, 2000). High altitudes in the Himalayas, in particular, experience heavy grazing by livestock because of substantial pastoralism practices in these areas. Livestock grazing in these areas can potentially result in competitive interactions between the herbivores, and such interactions are predicted to be the most severe when the introduced species have similar feeding style with the native herbivore. Although demographic rates of the interacting species are desirable to confirm the existence of competition (Prins, 1996), incidences of significant spatial segregation between native wildlife and livestock have been reported in the literatures (Acevedo, Cassinello & Gortazar, 2007; Loft

Menke & Kie, 1991; Stewart *et al*., 2002) as evidence for competition between them. However, spatial segregation alone cannot be a consistent response to interactions between the herbivores. Understanding dietary breadth and overlap appears to be an additional important yardstick for understanding interactions (MacArthur & Levins, 1967; Gauze, 1971), and gauge the potential impacts of livestock-grazing on native wildlife species.

Himalayan musk deer (*Moschus leucogaster)* and alpine musk deer (*Moschus chrysogaster),* in particular, are confined to high-altitude forests of Bhutan, northern India, Pakistan, Nepal, and China (Green, 1986; Grubb, 2005; Yang *et al.*, 2003). The species are listed on Appendix I of CITES and as endangered on International Union for Conservation of Nature (IUCN) red list. Taking expert-based range map of IUCN red list as a reference, the species of concern in this study is treated as *Moschus leucogaster*, although literatures indicate that both the species are interchangeably treated as Himalayan musk deer and/or alpine musk deer. It is probably due to their overlapping habitat, difficulties in species identification from their morphology because of their elusive nature, and lack of genetic studies for species identification (i.e., species concept conundrum, see de Queiroz, 2007). In Nepal, musk deer are found in birch, pine, and fir forests at an altitude of 2400–4300 m (Khadka & James, 2016) and considerably share their potential habitat with seasonally-sympatric livestock that are the means of sustenance for people (Metz, 1990; Fox, Yonzon & Podger, 1996). Yet the likely impacts of livestock grazing in the potential musk deer habitats appear to be overlooked and still remains largely unexplored. An earlier study (Khadka & James, 2016) found a spatial segregation between musk deer populations and livestock in study area considered here. However, that separation could not be attributed as a response to competition, due in part to independent selection of habitat conditions by two groups. Moreover, the species do not share a co-existing evolutionary history for such niche segregation. So, it was hypothesized that the spatial separation between livestock and musk deer is due to significant overlap in dietary composition between them. Hence, the present study is directed towards the assessment of seasonal diet composition, diet breadth, and diet overlap between livestock and musk deer. It is expected that the findings of the study shed light on the likely impacts of livestock on musk deer populations in the area, and potentially aid in management and conservation of species. Besides, it is also anticipated that such well-informed management approach helps to address the interests of both Conservation area and people, and reduce the probable conflicts between two.

2. Methods

2.1 Study area

This study was conducted in Jomsom, Mustang area of Nepal (Fig. 1); it lies in the central North region of the country in the rainshadow part of Annapurna and Dhaulagiri Himalaya ranges. The altitude ranges from 2750 m above sea level to 6700 m and average annual precipitation is 250–400 mm. The study site is located in the Annapurna Conservation Area Project (ACAP), the largest protected area, covering 7629 sq. km in Nepal. Vegetation of the area is characterized by temperate coniferous forests and alpine meadows, while the northern boundary of the area consists of arid landscape and long steep bare slopes cut by deep river gorges (Ives, 2006). Livestock comprises cattle, goats, sheep, and are the major sources of sustenance for the local people. These livestock forage freely in the potential habitat range of musk deer from April to October (i.e., summer) and stay in the livestock-sheds built at higher elevation. They move down to human settlements in winter where they are provided supplemental forage during that season.

2.2 Data collection

For the purpose of fecal collection, the area was divided into five units (four forest patches and one meadow patch). Fresh fecal pellets (< *ca*15 days old) of musk deer and livestock were collected along the altitudinal transect (1 transect per season) from each patch during summer (June and July) and winter (December and January) of 2014 and 2015. Age of the fecal pellets was roughly estimated by observing the color and moisture content. Collected pellets were air dried for microhistological analysis. Although issues of biased estimates due to differential digestibility of plant materials have been documented, microhistological technique is widely used in assessing the diets of herbivores. Moreover, the technique is of particular significance for rare and declining species like musk deer. Fecal pellets from a total of 39 and 27 latrine sites of musk deer were collected from summer and winter season respectively. Likewise, for livestock fecal pellets from a total of 72 fecal sites (Goat = 28, Sheep = 20, Cattle= 22) were collected for summer. Fecal pellets of livestock were collected only from summer since they forage in the concerned area only during that season. Fecal pellets collected from each unit for each season for each herbivore group were mixed thoroughly to make a composite sample.

Air dried fecal samples were broken into smaller pieces and ground to pass through a 1-mm screen fitted to an electric mill. The ground material was sieved through Endecotts sieves of 595 and 210 µm mesh size to remove coarse unidentifiable material and dust. Five slides from each composite sample for each season for each herbivore group (i.e., musk deer and livestock) were prepared following the method used by Sparks & Malechek (1968) and Anthony & Smith (1974), as modified by Vavra & Holechek (1980).

In order to get a glimpse of resource distribution and availability in the area in summer and evaluate if the consumption was correlated to abundance, dominant plant species in terms of frequency and cover in each category of tree species (browse), shrub species (browse), and herb species (forb + graminoid) were recorded in each randomly laid plots (10m X 10m) (n=112) in the area. Also, thirty-four plant species considered as the potential diets were collected from the area for preparation of reference slides. Each plant species was also classified among 3 forage categories: graminoids (grass and sedge families), forbs (broad leaved herbaceous plants) and browse (woody plants). Plant fragments in the slides were identified using compound microscope at 200X magnification. Each prepared slide was marked into five longitudinal transects and the first ten non-overlapping fragments in each transect were identified, classified, and recorded. Fragments were classified at least to generic taxonomic level. Completely unidentifiable fragments were classified as unknown. A total of 1250 fragments from each season for each group of herbivore were recorded.

2.3 Data analyses

Sample-based species-accumulation curves were plotted using *vegan* package (Oksanen *et al.*, 2013) in R (R Core Team, 2016) to assess the sampling sufficiency for both the herbivore groups for each season. Bipartite package was used to build a bipartite network graph for depicting the links between the herbivores and their shared or exclusive plant taxa in their diet. Dietary breadth was measured using Shannon diversity index. Diet separation between groups and across seasons was calculated using Bray-Curtis dissimilarity index in *vegan* with values ranging from 0 (complete overlap) to 1 (complete separation). This index takes into account the abundance of the plant species in the diet. Sorenson index (0= all species common, 1= none species common) was also calculated to elucidate diet overlap in terms of shared ‘number’ of species (i.e., species richness) between the groups. Differences in diet composition between the groups and within musk deer population across seasons were analyzed using *adonis* with 999 permutations in *vegan*. In order to determine the plant taxa contributing most to diet partition between two groups and within musk deer across seasons, indicator species analysis was performed using *signassoc* function with 999 permutations and Sidak's correction for multiple comparisons in *indicspecies* v.1.7.2 (De Cáceres & Legendre, 2009). This analysis tested the one sided null hypothesis that the abundance of plant taxa in samples from one herbivore group and/or one season is not greater than its abundance in the other group and/or season.

3. Results

Sample-based species-accumulation curves for each herbivore group and for each season approached asymptotes, indicating sufficient sampling for the dietary analysis (Colwell et al., 2012). The distributions of abundant plant species in each category of trees, shrubs, and herbs were significantly different [tree (browse): $\chi2 = 24.7$, $P < 0.001$, d.f.=2; shrubs (browse): $\chi2 = 130.95$, $P < 0.001$, d.f.=8; herbs (gramonid + forbs): $\chi2 = 293.72$, $P < 0.001$, d.f.=4]. The distributions of tree, shrub and herb species were dominated by *Pinus wallichaina*, *Berberis asiatica,* and *Calamagrostis canescens* respectively.

A total of 19 species were found in the summer diet of musk deer (Table 1). Mean dietary breadth of summer consumption in terms of Shannon index was found to be 1.09 ± 0.58 (mean ± SD). Summer consumption was found to be dominated by browse (86.5 %) (Fig. 2), in which *Abies spectabilis* alone accounted for 47.8%. Similarly, a total of 22 species were found in winter consumption. Mean dietary breadth in terms of Shannon index was found to be 1.43 ± 0.44 (mean ± SD). Winter consumption was found to be dominated by browse (67.0%) and forbs (22.7 %) (Fig.2), where *Abies spectabilis* (25.8%), *Pinus wallichiana* (14.8%), and *Berberis asiatica* (10.6%) dominated the browse category. However, there was no significant difference in the proportions of forage categories between summer and winter consumptions ($\chi 2$ =0.093, P=0.95, d.f.=2).

A total of 26 species were found in the summer diet of livestock (Table 1). Mean Shannon diversity index of the consumption was found to be 1.41 ± 0.52 (mean ± SD). Summer consumption of livestock was dominated by browse (63.8%) and graminoids (28.4%), among which *Pinus wallichaina* (30.6%) and *Calamagrostis canescens* (19.7%) dominated the forage categories respectively. In terms of proportion of forage categories, there was no significant difference between summer consumptions of livestock and musk deer ($\chi 2$ =0.33, P=0.84, d.f.=2). Although there was considerable overlap in consumption (74% of the species common) between livestock and musk deer, they however, diverged in abundance (Fig.3). Bray-Curtis and Sorenson dissimilarity indices were found to be 0.65 and 0.22 respectively. Bray-Curtis dissimilarity between musk deer and livestock diet composition was statistically significant indicating significant difference in consumption (pseudo $F_{1, 49} = 22.5$, $R^2 = 0.31$, $P < 0.001$). Nonmetric multidimensional scaling (NMDS) showed clear separation of samples between livestock and musk diet composition (Fig. 4). Also, Shannon diversity indices of summer diet composition of livestock and musk deer were found to be significantly different (t = -2.2024, d.f. = 54.435, P = 0.03). Five species, namely: *Calamagrostis canescens*, *Hedysarum species*, *Betula utilis*, unknown, and *Kobresia species* were found to be significantly associated to summer diet of livestock. *Abies spectabilis*, however, was found to be significantly associated to musk deer's summer diet.

Likewise, Bray-Curtis and Sorenson dissimilarity indices between summer and winter diet of musk deer were found to be 0.36 and 0.26 respectively. Bray-Curtis dissimilarity between summer and winter diet was significant (pseudo $F_{1, 49} = 9.34$, $R^2 = 0.16$, $P < 0.001$), and nonmetric multidimensional scaling (NMDS) showed separation of samples between summer and winter diet composition of musk deer (Fig. 5). Also, Shannon diversity indices of summer and winter diet composition of musk deer were significantly different (t = -2.6133, d.f. = 62.38, P = 0.01). Five species, namely: *Lonicera species*, *Rhododendron lepidotum, Juniperus species, Caragana species,* and an unknown species were found to be significantly associated to winter diet contributing most to the diet partition across seasons in musk deer.

4. Discussion

Both livestock and musk deer in the area appear to be mixed feeders (i.e., graze and browse) in terms of forage categories, although browsing seems to be a major feeding mode in musk deer unlike livestock that have considerably both grazing and browsing feeding modes. However, plant species contributing to the forage categories differ for the two groups. Although musk deer and livestock use a wide range of plant species available in the area in summer, majority of their diets are comprised of only few species they eat (25% for livestock and 20% for musk deer). Of notable was a disproportionate consumption of available resources by musk deer suggesting them to be selective feeders. Livestock, however, appear to be generalist feeders since the consumption was proportionate to resource distribution in the area. Livestock forage in a group, and hence it should be profitable to consume the available resources in bulk rather than search for the preferable plant species, as predicted by optimal foraging theory. Also, musk deer seems to be more specialist feeders in terms of diet breadth compared to livestock although this difference might have been biased by lumping of different livestock species into a single group. Nevertheless, this study is directed towards the assessment of intergroup diet variation and/or overlap for the habitat management purpose. Hence, the finding should be of worth concern for the conservation of musk deer population in the area.

Although musk deer and livestock show considerable summer diet overlap in terms of ‘number’ of species shared (74% of the species shared), they however differ in composition in terms of abundance of the species present in their consumption; it is presumably a reflection of differential preference. Such a significant differentiation in diet composition in summer, which is a major growing season in the high altitudes with increased abundance of plant species and availability of plant material, indicates differential diet selection and a low potential for competition for food between the groups. Although assessment of demographic rates might be desirable to robustly conclude the degree of competitive interactions (Prins & Olff, 1998) for food between the groups, such a compositional discrepancy in consumption should in part explain the absence of competition for food, as musk deer are particularly active during the night (Meng et al., 2001) with an opportunity of unrestricted access to and consumption of available plant species and/or materials in the area. Moreover, currently detected diet partition cannot be explained as a response to competitive interactions in the past as these two groups do not share a considerable coexisting evolutionary history leading to significant niche partitioning to improve fitness (Connell, 1980). An earlier finding of independent habitat selection by musk deer and livestock (Khadka & James, 2016) and current finding of significant diet partition between them in the area so far sufficiently provide suggestive evidences for absence of competitive interactions between these two groups of herbivores (De Boer & Prins, 1990). Thus, it appears that spatial segregation and differential consumption are presumably the responses to evolutionary adaptation of musk deer rather than to the competitive interactions with the livestock. However, removal of livestock from the area to see any changes in diet composition and breadth of musk deer resulting to considerable positive effect on vital rates would add further accuracy and precision in understanding competitive interactions between them (Pianka, 1976; Prins & Olff, 1998). So, future studies directed to unearth such concerns are recommended for gaining a deep sense on competitive interactions.

Compared to summer, musk deer appear to increase their dietary breath with differing composition in winter. Moreover, intraspecific diet variation was considerably lower in winter compared to summer suggesting limited availability of diet and potential for intraspecific competition for food during winter in the area. However, diet composition in terms of forage categories did not differ significantly across seasons indicating consistency in foraging mode. Increased dietary breadth with differing composition in winter might be due to intraspecific competition for the limited available plant species and differential availability of plant species across seasons in the area. Niche expansion due to intraspecific competition with depletion of preferred resources is a key prediction of classical optimal foraging theory (Svanback & Bolnick, 2005), and has been reported in numerous taxa elsewhere (Werner & Hall, 1974; Svanback & Bolnick, 2007). Winters in the high altitudes are characterized by considerable snowfall, retarded growth of the plant species, and lowered availability of annual graminoids and forbs. Thus, it should be potentially beneficial to opportunistically forage on the available perennial browse species in the area in winter in order to avoid intraspecific competition (MacArthur & Pianka, 1966; Schoener, 1971; Pulliam, 1974). Thus, significant association of perennial browse like *Rhododendron species*, *Caragana species*, *Lonicera species*, and *Juniperus species* with winter diet of musk deer is probably because of their availabilities in winter as well. Musk deer significantly select pine and fir forest as their potential habitat (Khadka & James, 2016). Increased proportion of *Pinus species* in the winter diet might be due to the increased preference for pine forest during winter, where the thick blanket of pine leaves provide relatively warm bedding against low temperature of winter, potentially decreasing thermoregulatory cost

(Dussault *et al*., 2004). On the other hand, significant association of *Abies species* with summer diet provides a suggestive evidence for increased preference of fir forest during summer.

Niche partitioning as a response to interspecific competition is a mechanism for the coexistence for sympatric species (Hutchinson, 1959; Schoener, 1974). However, it is notable that partitioning of dietary composition between musk deer and livestock is presumably not a response to competitive interactions (see above). But, musk deer and livestock appears to share a considerable ‘number’ of plant species in their diets. Hence, the finding of significant partitioning in dietary composition cannot be completely-interpreted and expected as without any effect to musk deer population in the area. Numerical supremacy of livestock can potentially exploit the shared resources limiting their availability to musk deer. Moreover, being a generalist feeder livestock can potentially increase their dietary breadth as a response to intragroup competition for food (MacArthur & Pianka, 1966; Schoener, 1971) with their increase in number in the area. It can negatively affect the availability of plant species that constitute the major portion in diets of musk deer. Thus, it appears that the current finding of diet partition between musk deer and livestock in the area should be considered with caution. Additionally, possibility of indirect effects mediated by the compositional change of plant species due to the introduction of livestock in the area (Augustine & McNaughton, 1998; Fleischner, 1994) deserves a significant attention as well. Hence, further study directed towards an assessment of compositional change of vegetation in the area due to the presence of livestock would precisely decipher the possible negative impacts on musk deer. Undoubtedly though, findings of the current study are expected to aid in habitat management and species conservation via well-informed decision to focus on the availability and abundance of plant species that make the diets of musk deer in the area and elsewhere where the species share their potential habitat with livestock.

Park-people conflict is ubiquitous due to conflicting interests between the park manager and local people. Such conflicts, in particular, are common in countries where the local herders have huge dependencies on forest resources for livestock rearing (Nepal &Weber, 1993). However, complete barring of local people from the protected areas does not seem to be an effective tactic to conservation (Sekhar, 2003). Thus, approaches that accommodate and address the interests of both park and people are of utmost importance for a "win-win" outcome. Conception and development of such approaches for habitat management require a well-informed understanding of resource use and overlap of native species with livestock. Findings from the present study suggest for a partition and designation of livestock grazing area limiting them within it rather than letting them move freely and forage in the whole habitat range. Livestock removal and/or restriction from the area with significant availability of resources to musk deer could potentially benefit the species as has been reported for other wild herbivores elsewhere (Khan *et al*., 1996; Mishra *et al*., 2004). Also, the area that supports plant species (for example, *Abies species, Pinus species, Rhododendron species, Juniperus species, Caragana species, Lonicera species*) that are significantly associated to summer and winter diet of musk deer should be prioritized and protected from anthropogenic disturbances for the conservation of musk deer.

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Table 1: Percentage contribution of plant species in the diets of livestock and musk deer across seasons in the area

	Summer		Winter
Plant species	Livestock	Musk deer	Musk deer
Abies spectabilis	0.8	61.28	28.43
Anaphalis spp	0.24	-	0.06
Artemisia spp	0.16	-	-
Berberis asiatica	5.33	9.12	12.61
Betula utilis	4.28	1.3	0.3
Bistorta spp	-	-	0.36
Calamagrostis canescens	17.54	0.81	-
Caragana spp	0.08	-	1.96
Carex spp	0.16	0.08	-
Clematis barbellate	-	0.24	15.69
Cotoneaster spp	3.07	1.46	0.67
Festuca spp	1.21	-	-
Geranium spp	0.16	0.08	-
Hedysarum spp	7.51	0.32	0.18
Iris goniocarpa	0.16	0.08	0.06
Juniperus spp	2.18	1.71	4.3
Kobresia spp	6.3	0.08	-
Lonicera spp	4.28	1.05	6.03
Moss	-	-	0.06
Oxytropis spp	0.32	-	0.06
Pinus wallichiana	27.16	15.56	17.35
Polygonatum spp	0.24	-	0.06
Potentilla fruticose	0.16	-	-
Rhododendron lepidotum	0.24	-	1.96
Rosa sericea	0.64	1.14	1.41
Salix spp	0.24	-	0.24
Spiraea spp	0.32	0.08	-
Syringa emodi	0.56	0.08	0.18
Taraxacum spp	-	0.16	0.24
Thalictrum spp	0.08	0.24	0.43
Unknown a	8.73	4.8	7.01
Unknown b	7.76	0.24	0.24

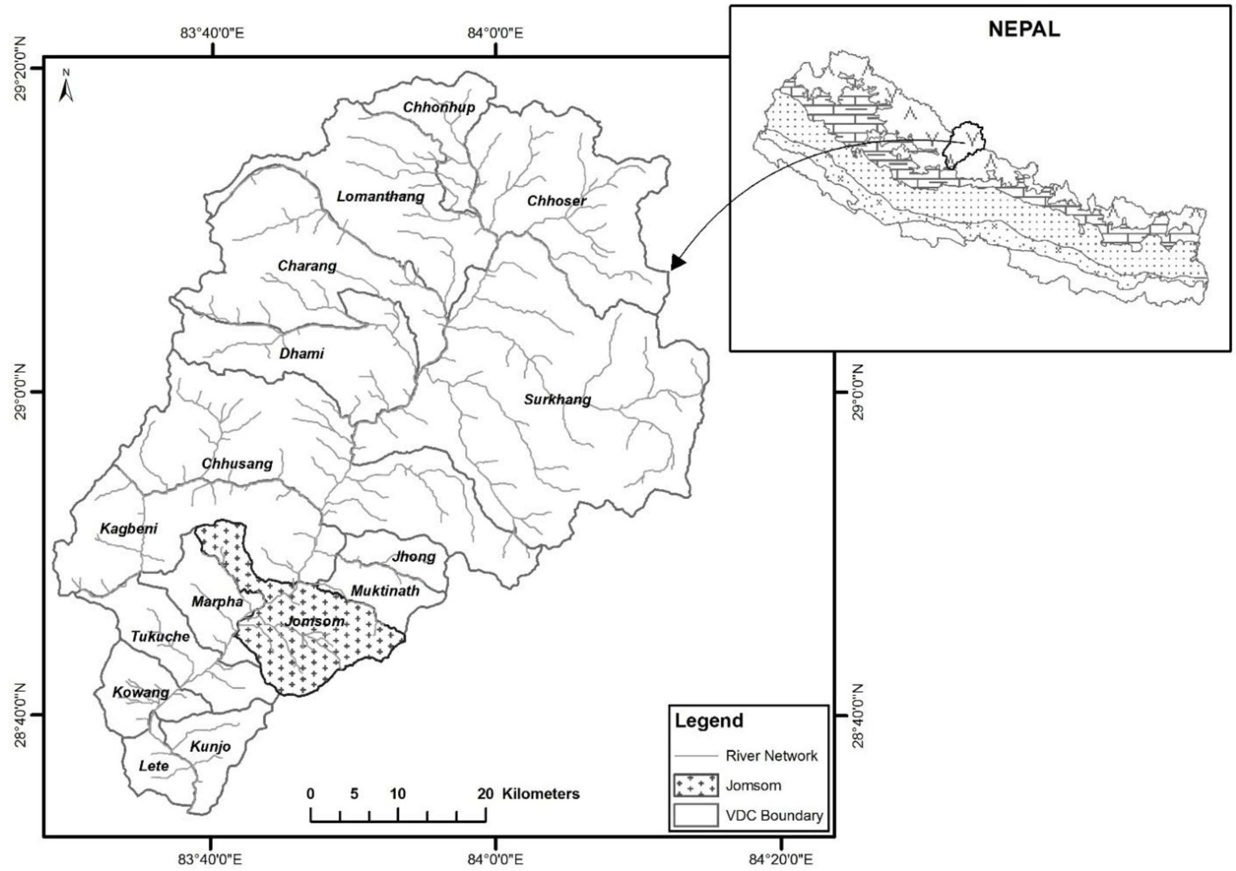

Figure 1. Mustang district of Nepal with river network and VDC boundary. Village Development Committee (VDC) is the lower administrative part in Nepal. Study site is labeled as Jomsom.

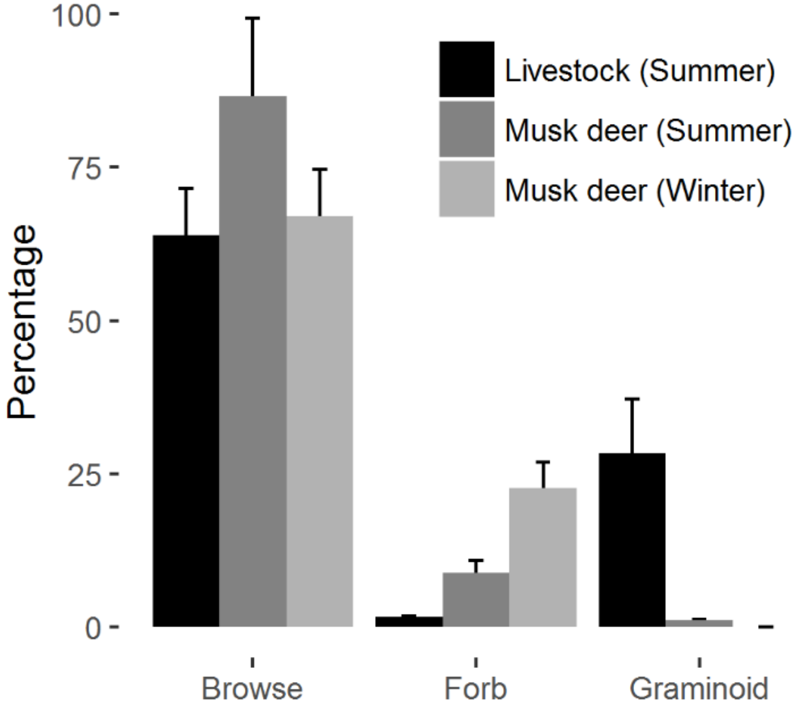

Figure 2. Percentage of forage categories (Browse, Forb, and Graminoid) in the summer and winter diet of musk deer, and summer diet of livestock.

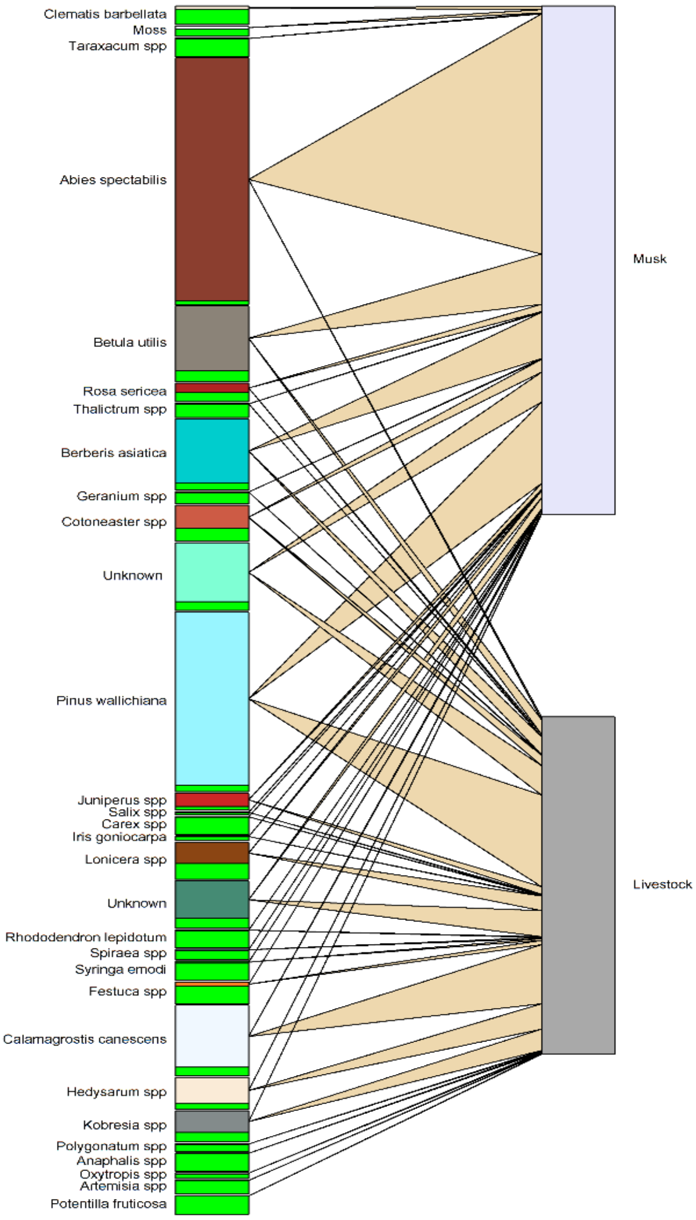

Figure 3. Bipartite network depicting dietary composition and overlap of summer diet of musk deer and livestock. Lines connect herbivore group (upper boxes) to dietary plant species (lower boxes), which are colored by plant species. Widths of upper boxes reflect the abundance of each plant species detected across all samples from the herbivore group.

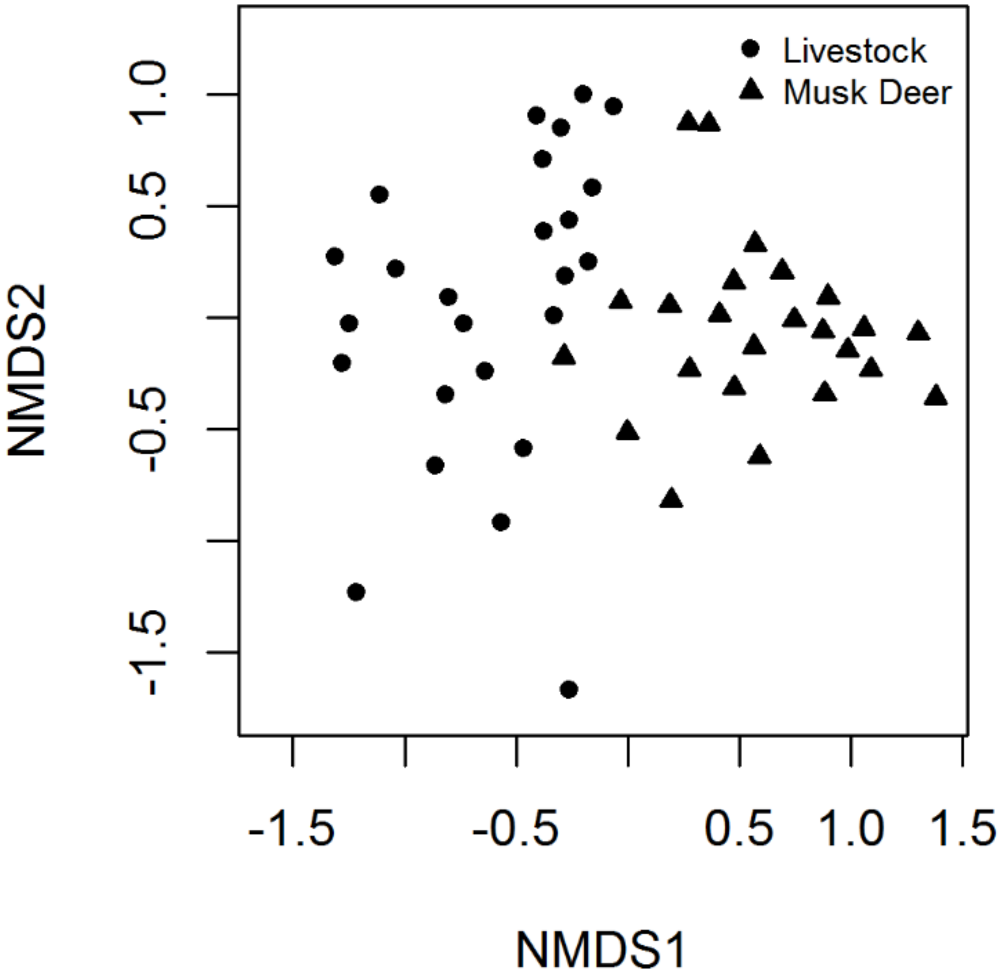

Figure 4. Summer diet partitioning between musk deer and livestock. NMDS of Bray–Curtis dissimilarity of samples from musk deer and livestock.

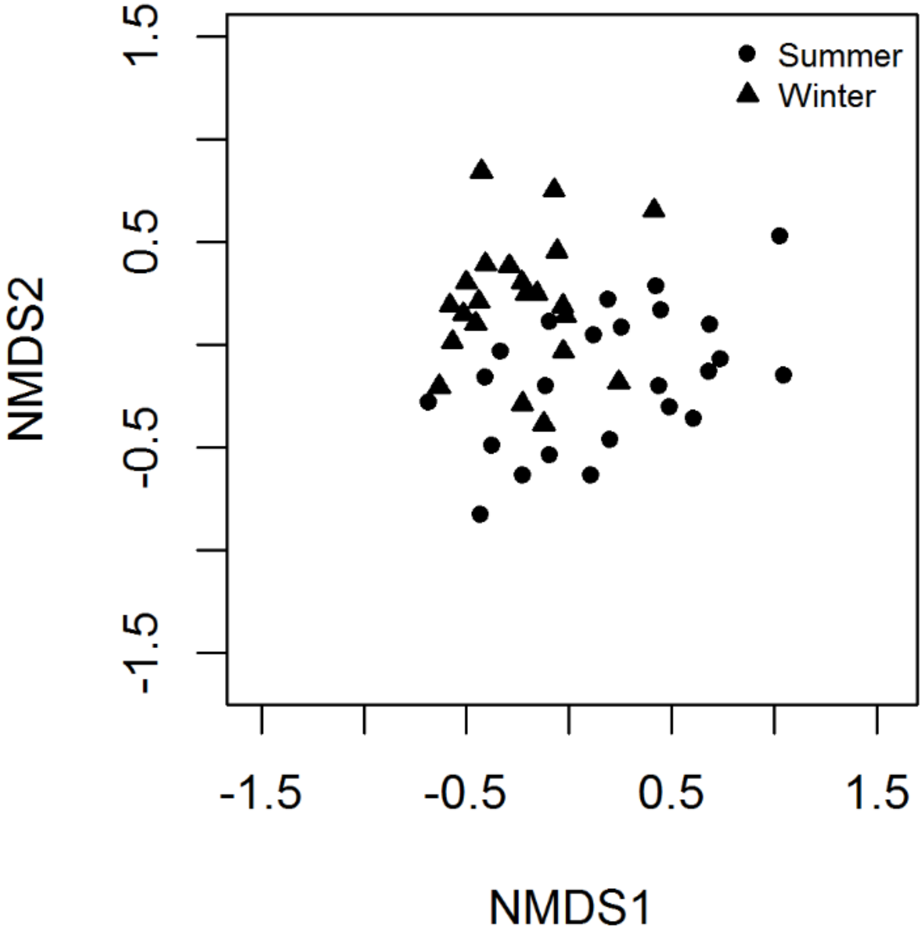

Figure 5. Diet partitioning of musk deer between summer and winter season. NMDS of Bray–Curtis dissimilarity of samples from summer and winter diet.

Chapter III: **Habitat selection by Himalayan musk deer and impacts of livestock grazing in Nepal Himalaya**

Abstract:

Habitat management within and outside the protected areas is a key to effective conservation of wildlife. It is particularly more vital for a declining wildlife population confined within the boundary of conservation area, yet sharing their potential habitat range with foraging livestock. To understand the habitat use by Himalayan musk deer (*Moschus chrysogaster*) and explore any potential impacts of livestock grazing on them, I conducted the present study in four forest patches of central Nepal Himalaya. I recorded data on musk deer and/or livestock presence/absence (based on signs of fecal pellets, footprints, and resting site) along the altitudinal transect with associated topographic features (altitude, slope, aspect, and distance to water) and vegetation features (tree sp., shrub sp., herb sp., and canopy-cover). I found that altitude, aspect, canopy-cover, and tree sp.in the area significantly affect the likelihood of habitat selection by musk deer. In particular, they selected the southern aspect of the area with altitude ≥3529 m, canopy-cover ≥42 %, and with stands of *Pinus* sp. and *Abies* sp. Slope and canopy-cover significantly affected the grazing areas selection by livestock. They used the gentler slopes in the northern aspect of the area with altitude <3529 m and canopy-cover <42%. These selections are possibly the response to morphological and behavioral adaptations than to impacts and interactions between these two groups of herbivores. I suggest avoiding any disturbances and livestock grazing on the area that are likely used and occupied by musk deer population.

1. Introduction:

Increasing anthropogenic pressures and their consequent impacts on wildlife have been well recognized globally (Millenium Ecosystem Assessment, 2005). High altitudes in the Himalayas, in particular, experience heavy grazing by livestock because of substantial pastoralism practice in these areas. Therefore, impacts of livestock grazing on native wildlife species in these areas are crucial conservation concerns (Fleischner, 1994; Noss, 1994; Mishra et al., 2004), as habitat overlap with foraging livestock can spatially displace wildlife with reduced foraging opportunities and low quality food via exploitative and interference competition leading to reduced fitness. Hence, it requires exploration, identification, and understanding of key habitat conditions that limit distribution and/or produce occupancy of the species (Morrison et al., 2006). This information can potentially act as yardstick to gauge the impacts imposed by migratory livestock on native wildlife, and can be effectively applied for habitat management which is a root to wildlife conservation (Lindenmayer et al., 2006). This can be accomplished via empirical modeling that correlate species presence and/or occupancy to resources and conditions potentially required for species survival and persistence (Pearce & Ferrier, 2000).

Himalayan musk deer (*Moschus chrysogaster*) (hereafter musk deer), characterized by the lack of antlers and presence of a pair of tusk like teeth (canines), is an ecologically and economically (for the invaluable musk male musk deer produces) important species of the family *Moschidae* (Order: Cetartiodactyla). This species is typically confined to mountain forests of Bhutan, northern India, Nepal, and China (Green, 1986, 1987; Grubb, 2005). In Nepal, the species is found in birch and rhododendron forests at an altitude of 2400-4300 m (Green, 1980; Shrestha, 1998). The species has been listed in Appendix I of CITES and as endangered by

IUCN suggesting that population is declining primarily due to habitat loss and poaching (Yang et al., 2003; Wang & Harris, 2008).

In Nepal, the species is protected by the Department of National Park and Wildlife Conservation Act since 1973. Despite conservation efforts implemented through enactment of law and designation of protected areas, the species remains susceptible to likely negative impacts of livestock grazing in their range (Aryal et al., 2010). Protected areas although play an important role in conservation, their effectiveness is limited by human-induced stresses. In high altitudes of Nepal, people depend on livestock rearing and forest resources for their sustenance. Livestock experience transhumance foraging systems where they move to different pastures and forests in the high altitudes for foraging (Metz, 1990; Fox et al., 1996) which are presumably the potential habitat for native wildlife including musk deer.

However, impacts of livestock grazing on mountain ungulates including musk deer habitat appear to be overlooked and their repercussions have received little attention recently (Mishra et al., 2004; Namgail et al., 2007). Thus, it’s crucial to identify habitat (topographic and vegetation features) use by both musk deer and migratory livestock in the areas to understand any impacts, and explore the conditions that characterize their habitat selection and use (Boyce et al., 2002). This information can act as guiding principles to develop management strategies for musk deer conservation in the high altitudes. With this understanding in mind, the present study aims to explore and identify the habitat conditions (topography and vegetation categories) that likely produce occupancy of musk deer and livestock to test whether habitat use of these two groups are characterized by similar habitat conditions in the area leading to potential impacts (Stewart et al., 2002; Bagchi et al., 2004). Although both physical and biotic factors shape the distribution of species (Benton, 2009), here we focus on physical habitat parameters since wild musk deer and domesticated migratory livestock do not share a co-existing evolutionary history that potentially leads to resource partitioning in response to their interactions (Connell, 1980).

2. Methods

2.1 Study area

I conducted this study in Jomsom, Mustang area of Nepal (Fig 1). It lies in the central North region of the country in the rain-shadow part of Annapurna and Dhaulagiri Himalaya ranges. The altitude ranges from 2750 m to 6700 m above sea level and average annual precipitation is 250-400 mm. The study sites (4 forest patches in Lupra and Thini village) are located in Annapurna conservation Area Project (ACAP), the largest protected area, covering 7629 sq. km. in Nepal. Vegetation is characterized by temperate coniferous forests and alpine meadows, whereas the northern boundary consists of arid landscape and long steep bare slopes cut by deep river gorges (Ives, 2006). Livestock comprises cattle, goats, sheep, and horses that forage in the forests and meadows of the area.

2.2 Data collection and analysis

The procedure followed design I and sampling protocol D of Mcdonald, Alldredge, Boyce, and Erickson, (2005), meaning I categorized the sampling plots as used or unused by musk deer and livestock at a population level. The study was conducted during summer (June and July) and winter (December and January) of 2014 and 2015 (1 transect per unit per season). I laid plots (N = 209), each of 10 m × 10 m, at intervals of 100 m along the transect in elevational gradient, and recorded presence or absence of livestock and musk deer based on signs (fecal pellets, footprints, resting sites). I intensively searched each plot for any signs of presence or use to maximize the probability of detection. Also, at each plot the following variables were assessed and recorded:

elevation (m), slope (degree), canopy-cover (%), distance to vantage point (m) (rock, cliff, and wooden log), aspect, distance to water (m), dominant herb spp., shrub spp., and tree spp. Tree spp., shrub spp., and herb spp. were categorized into 3 (1 = *Betula* spp., 2 = *Abies* spp., 3 = *Pinus* spp.), 5 (1 = *Berberis* spp., 2 = *Juniperus* spp., 3 = *Anaphilis* spp., 4 = *Rosa* spp., 5 = *Caragana* spp.), and 2 (1 = Grass, 2 = Others) genus levels respectively for analyses. Likewise, I categorized aspect into 2 levels (1 = North, 2 = South). Also, years (1 = 2014, 2 = 2015) and seasons (1 =Winter, 2 = Summer) were categorized and used as explanatory variables to check the consistency in habitat use across years and seasons. Multicollinearity of continuous variables were checked and when I found a significant correlation of vantage point distance with slope (Pearson's $r = -0.3$, $p < 0.05$) and cover (Pearson's $r = 0.15$, $p < 0.05$), I excluded it from analysis. I performed a binomial logistic regression with presence or absence of musk deer and livestock as a response variable and aforementioned variables as inputs to explore the habitat selections. Also, I included the presence or absence of livestock in the logistic regression model for musk deer (and vice versa) to check whether the habitat selection is independent of the other group. I scaled (subtracted the mean and divided by SD) all the continuous variables prior to analysis (Draper & Smith, 1998) to improve model convergence. Also, I built a partition tree taking the plots exclusive to musk deer and livestock presence as class for partition and the associated variables in those plots as partitioning factors. I conducted all the analyses in statistical tool R (R Core Team, 2015).

3. Results

Of the plots surveyed, 19% were used exclusively by livestock and 35% by musk deer while 13% were found to be used by both. Musk deer presence signs were found in the area with average (±SD) elevation, canopy-cover, slope, and water-distance of 3685 ± 115 m, 55 ± 23%, 47 ± 14◦, and 440 ± 253 m respectively. Likewise, livestock presence signs were found in the area with average (±SD) elevation, canopy-cover, slope, and water distance of 3634 ± 198 m, 46 ± 29%, 42 ± 14◦, and 420 ± 198 m respectively. Maximum detected distance between musk deer and livestock was 580 m, while the mean detected distance between them was 51 m. Elevation, aspect, canopy-cover, and tree spp. (*Pinus* spp. and *Abies* spp.) were found to be the significant predictors for likelihood of habitat selection by musk deer. I determined the best predictive reduced model using a stepwise model selection (direction = 'both') approach which employs the Akaike's Information Criteria for decision making (Table 1). The reduced model was not different from the full model (Likelihood ratio test: 2 = 8.93, df = 6, p = 0.25). Likewise, I found slope and canopy-cover as the significant predictors for likelihood of habitat selection by live stock (Table 2). Again, reduced model was not different from the full model with all the variables included (Likelihood ratio test: 2 = 7.18, df = 4, p = 0.61). Also, I found that presence or absence of livestock does not have any significant effect (Tables 3 and 4) on the likelihood of habitat selection by musk deer (and vice versa), and made insignificant differences in the habitat coefficients of the habitat selection models (i.e. Tables 1 and 2). Finally, I built a partition tree taking livestock and musk as categorical classes and associated variables as partitioning factors. I found elevation (≥3529 m for musk deer and <3529 m for livestock), canopy-cover (≥42% for musk deer and < 42% for livestock), and aspect (South for musk deer and North for livestock) as the important classifiers for the classification of musk deer and livestock on habitat selection in the area (Figure 2).

4. Discussion

The present study depicts a broad yet important picture of habitat selection by musk deer and livestock in the study area. Musk deer populations appear to use the area characterized by presence of stands of *Pinus* sp. and *Abies* sp. trees with relatively dense canopy-cover (≥42 %) on higher elevational zone (≥3529 m) of the southern aspect. These selections are presumably the response to the behavioral and morphological adaptations (Futuyma & Moreno, 1988) to increase the fitness. Musk deer are elusive and shy animals (Kattel, 1992) characterized by longer hind limbs compared to forelimbs adapted for efficient movement and climbing rugged terrain of high elevation. Moreover, thick blanket of pine leaves on ground provide warmth and presumably reduces the thermoregulatory cost (Dussault et al., 2004; Maloney et al., 2005) in high altitudes. Besides, bark of *Abies* sp. contribute a significant portion to the diet of musk deer (Green, 1980) during winter. Selection for relatively dense vegetation with higher canopy-cover (Yang et al., 2003) is possibly a response to predator avoidance.

On the other side, livestock tends to use the area characterized by moderate canopy cover (<42 %) on relatively gentler slope and lower elevation (<3529 m) of the northern aspect. This presumably is a response to their foraging strategy to maximize forage intake and profitability (Pyke et al., 1977). It is energetically costly to travel to high altitudes and steep slopes for foraging. Moreover, livestock forage in a group and hence potentially select areas with high forage availability. It’s likely that moderately open canopy provides comparatively more foraging opportunities to the livestock, as increasing density of canopy cover of woody plants decreases the herbaceous standing crop (Jameson, 1967; Dahl et al., 1978).

Findings of the present study, thus far, offer suggestive evidence that habitat selection by musk deer and livestock in the area is independent ofthe other species, and do not provide evidence to current interactions and impacts to musk deer populations. Although musk deer are active particularly during the night (Meng et al., 2001), this behavior however cannot be attributed as a response to interactions with livestock. This is because such behavioral changes are expected to evolve as a response to interactions (in particular competition) for co-existing species in the same habitat competing for the same limited resources. Habitat selections by these two groups, however, are characterized by a combination of different vegetation categories and topographic features, and are spatially separated. Additionally, these selections are less likely to be the response to past impacts and interactions (Connell, 1980), as these two groups do not share co-existing evolutionary history that potentially leads to habitat differentiation and adaptive resource partitioning (Behmer & Joern, 2008).

Nevertheless, this does not completely eliminate the possibility of any form of effects on musk deer population by livestock grazing on the area because of possible imperfect detection of used and unused plots during the survey. Moreover, population trend of musk deer in the area is unknown. The present study depended on indirect evidence of presence. Hence, further study directed towards the assessment of vital rates and population trajectory of the species is recommended to shed more light on potential impacts by livestock. Northern aspect of the area is closer to human settlement and hence the reason for using the southern aspect by musk deer could also be a response to human disturbance and livestock avoidance. This side of the area is often visited by villagers for fuel wood and fodder (personal observation) and is therefore comparatively more disturbed, possibly leading to displacement of musk deer population from the area. Significant spatial displacement of mountain ungulates by livestock elsewhere is reported in the literatures (Acevedo, Cassinello, & Gortazar, 2007; Loft, Menke, & Kie, 1991; Stewart et al., 2002). Therefore, it would be interesting to see if the musk deer population in the area expands their habitat selection when livestock are stopped foraging from this part of the area.

Our results can help meet a ‘win-win’ condition to both the managers and livestock owners. Avoidance of livestock grazing and restriction of any form of disturbances on high elevation (≥3529 m) of the southern aspect, where dense stands of *Pinus* sp. and *Abies* sp. trees with canopy-cover ≥42 % potentially provide the resources and conditions for musk deer occupancy, can promote the conservation of musk deer in the area. On the other hand, limiting livestock grazing on lower elevation (<3529 m) of the Northern aspect with canopy-cover <42 % can assist the sustenance of livestock owners. Wildlife conservation in a developing country like Nepal, where majority of people depend on agriculture and natural resources, is often in serious conflict with the necessities for sustenance by local people. Efficacy of any conservation approach, therefore, depends on the support and participation of the people. So, complete restriction of livestock grazing for the conservation of musk deer in the area can potentially create a park-people conflict. We suggest for a management approach with dual goals of regulation of livestock grazing and amelioration of habitat conditions for musk deer in the area.

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Table 1. Habitat parameters in the final logistic regression model with the presence of musk deer as the response as revealed by stepwise regression.

	Estimates	SE	Z-value	P – value
Intercept	-1.48	0.4	-3.62	<0.01
Elevation	0.81	0.2	3.93	<0.01
Canopy-cover	0.33	0.16	2.02	0.04
South aspect	1.47	0.41	3.55	<0.01
Abies spp Tree	0.97	0.49	1.96	0.04
Pinus spp Tree	1.46	0.5	2.92	<0.01

Table 2. Habitat parameters in the final logistic regression model with the presence of livestock as the response as revealed by stepwise regression.

	Estimates	SE	Z-value	P – value
Intercept	-0.59	0.17	-3.31	<0.01
Slope	-0.52	0.17	-3.07	<0.01
Canopy-cover	-0.38	0.15	-2.41	0.01
North aspect	-0.56	0.38	-1.48	0.13

Table 3. Logistic regression model with the presence of musk deer as the response and presence/absence of livestock added as an explanatory variable to check the effect of livestock on habitat selection by musk deer.

	Estimates	SE	Z-value	P – value
Intercept	-1.65	0.45	-3.62	<0.01
Elevation	0.8	0.2	3.89	<0.01
Canopy-cover	0.31	0.16	1.85	0.06
South aspect	1.47	0.41	3.52	<0.01
Abies spp Tree	0.93	0.5	1.86	0.06
Pinus spp Tree	1.44	0.5	2.88	<0.01
Livestock [absence]	0.29	0.32	0.9	0.36

Table 4. Logistic regression model with the presence of livestock as the response and presence/absence of musk deer added as an explanatory variable to check the effect of musk deer on habitat selection by livestock.

	Estimates	SE	Z-value	P – value
Intercept	-0.45	0.21	-2.08	0.03
Slope	-0.52	0.17	-3.07	<0.01
Canopy-cover	-0.36	0.16	-2.3	0.02
North aspect	-0.48	0.39	-1.22	0.22
Musk deer [presence]	-0.33	0.31	-1.07	0.28

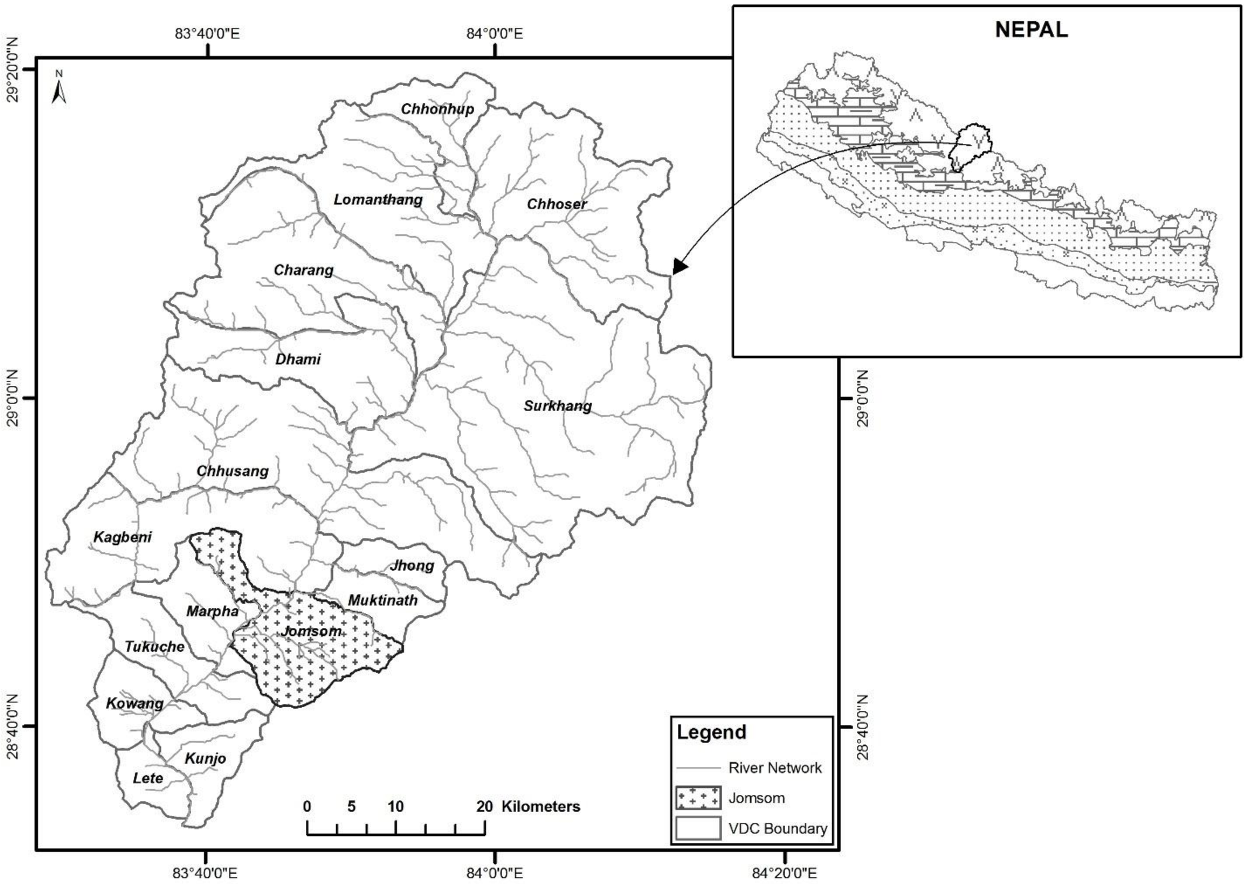

Figure 1. Figure 1. Mustang district of Nepal with river network and VDC boundary. Village Development Committee (VDC) is the lower administrative part in Nepal. Study site is labeled as Jomsom.

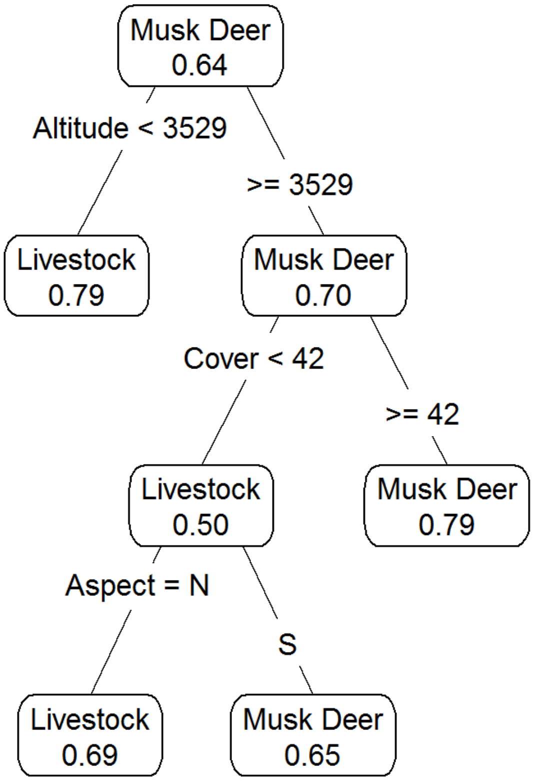

Figure 2**.** Partition tree for musk deer and livestock based on habitat parameters. Figures inside the boxes indicate probability of fitted class.

Chapter IV: Modeling and mapping the current and future climatic-niche of endangered Himalayan musk deer

Abstract:

Conservation and management of environmentally suitable areas, that support survival and persistence of species, are keys to protect wildlife in their natural habitat. Populations of Himalayan musk deer *Moschus leucogaster,* an endemic species in Asia, are listed as endangered in the IUCN red list, requiring immediate conservation actions before their extinction in the wild. In order to model and map the current and future (under projected climate change settings) climatically-suitable areas for the species, Maxent modeling technique, that requires presence-only records, was employed. As predictors, I extracted 19 bioclimatic variables from ‘WorldClim’ database with a ~1km spatial resolution and used 10 uncorrelated bioclimatic variables as inputs. As indicated by a high area under ROC curve (AUC) value (> 0.9), Maxent well performed and predicted climatically-suitable habitat for the species along the Hindukush Himalaya, where the species is known to occur. Annual mean temperature appeared to most influence the distribution of potential habitat for the species. An expansion of species’ habitat was noticed in the Indian and Tibetan part of species range, suggesting a potential future effect of climate change on the species distribution. The findings of this study could assist wildlife managers in devising conservation plans for the current and future conservation of the species in the context of climate change. This is the first study to model and map the current and future distribution of the species in its range.

Introduction:

With different levels of biodiversity increasingly being endangered or threatened with extinction by manifold factors (both deterministic and stochastic), one of the biggest challenge conservationists face today is to turn this tide and maintain integrity and functionality of ecosystems (Millennium Ecosystem Assessment, 2005). This challenge has been further amplified by effects of climate change with an array of varying consequences over space and time (Parmesan and Yohe, 2003; Thomas et al., 2004; van Gils et al., 2016). Numerous conservation strategies, varying with type, scale, and magnitude of threats, have been developed by conservationists (Brooks et al., 2006). Within these contexts, species distribution models (SDMs) have been widely developed to estimate, predict, and map species geographic ranges over time (Elith and Leathwick, 2009).

Various algorithms, with increasing computational capabilities, have been devised for SDMs and their use vary with objectives, their data type and availabilities (Guisan and Zimmermann, 2000; Elith and Graham, 2009). These techniques establish relationships between sites of known species occurrences and environmental factors that are presumed to affect their presences or absences. These relationships allow to interpolate and extrapolate geographic distributions in novel areas and/or under a changed scenario setting (for example, scenarios predicted under climate change). Among the SDMs, Maximum Entropy Modeling (Maxent) technique, that requires presence-only records (i.e., latitude/longitude of species occurrence points) of the concerned species, is being widely used for estimation and prediction of a species' geographical range (Phillips et al., 2006). Moreover, increasing availabilities of species occurrence data have increased its application in conservation biogeography, especially regarding rare and declining species with incomplete information (for example, Himalayan musk deer in this study). Consequently, Maxent appears as an important tool to gain insights into current ranges and potential range-shifts due to climate change effects over time (see Phillips et al., 2006; Franklin, 2010).

Himalayan musk deer (*Moschus leucogaster)* inhabits high alpine environments of Bhutan, northern India, Pakistan, Nepal, and China (Green, 1986; Grubb, 2005, Yang et al., 2003); i.e., high altitude regions along the Hindukush Himalaya. This species is also treated as a subspecies of alpine musk deer (*Moschus chrysogaster*). So, literatures indicate that both *M. leucogaster* and *M. chrysogaster* are interchangeably treated as Himalayan musk deer and/or alpine musk deer in these regions. However, the range map from IUCN red list specifies that the musk deer species in this range is Himalayan musk deer (i.e., *M. leucogaster*). Hence, the species of concern in this study is treated as *M. leucogaster*. Populations of musk deer are declining primarily due to habitat loss and overexploitation (Yang et al., 2003; Timmins and Duckworth, 2015). Consequently, the species has been listed in Appendix I of CITES and as endangered in red list of International Union for Conservation of Nature (IUCN). Identification of climatically-suitable areas for the survival and persistence of the species could potentially aid in the current and future conservation of the species. Hence, the current study is directed towards modeling and mapping the current distributional range of the species, and attempts to predict the future range under projected climate change scenario. Besides, it also aims to provide qualitative insights into the climatic variables that potentially affect the habitat distribution of the species.

Methods:

Eighty-five unique geographic coordinates (i.e. Latitude/Longitude) of the species' occurrences were used in the study. These geographic coordinates represent presence locations of the species and were recorded based on sightings of fecal pellets of the species. Musk deer have easily recognizable ‘latrine-sites’ (with a heap of fecal pellets) that make recording of the species’ presence easy. These data were collected from randomly surveyed potential habitat of the species in Bhutan, Nepal, India, and Pakistan in between 2013-2015; hence the occurrence points are from the geographic range of the species along the Hindukush Himalaya from Pakistan to Bhutan (for details about the area and data collection see, Abbas et al., 2015; Ilyas, 2015; Khadka and James, 2016). Nineteen bioclimatic variables with a 30 arc-second spatial resolution (approximately 1 km resolution) for two time periods: ‘current’ and ‘future’ (for the year 2050), were used as predictors and extracted from the ‘WorldClim’ database (url: worldclim.org; Hijmans et al., 2005). The database consists of projected climate for the years 2050 and 2070, with four different scenarios of greenhouse gas trajectories i.e., Representative Concentration Pathways (RCPs). Because of varying level of greenhouse gas concentration trajectories envisioned for the future and their inherent effect on climate, climatic surfaces data for a modest scenario i.e., RCP6.0 averaged from three randomly selected General Circulation Models (GCM: BCC-CSM1-1, CCSM4, GISS-E2-R) for the year 2050 were used for projecting the future geographic range of the species.

Pearson’s correlation coefficients among the current nineteen bioclimatic variables in the database were determined, and when the correlation coefficient between the variables was found to be significant (i.e. $r \geq 0.9$, $p < 0.01$), only one variable from a set of highly correlated variables was used to reduce the problems due to multi-collinearity (Dormann et al., 2013). So, of the 19 bioclimatic variables extracted from ‘WorldClim’, 10 bioclimatic variables i.e. annual mean temperature, mean diurnal range, isothermality, temperature seasonality, mean temperature of wettest quarter, annual precipitation, precipitation of driest month, precipitation seasonality, precipitation of warmest quarter, and precipitation of coldest quarter were used as inputs for the model. Since the ecology of the species is largely unknown, I used all the 10 uncorrelated variables as inputs rather than filtering them out to variables that otherwise would be considerably linked to the survival of the species. Moreover, my major focus is to map climatically-suitable geographic area (i.e., prediction) rather than description of the process (i.e., explanation). I used Maxent (version 3.3.3k; http://www.cs.princeton.edu/~schapire/maxent/; Phillips et al., 2004, 2006) as a modeling platform (with auto features, 5000 iterations and default settings). For background samples (i.e. pseudo-absences), to estimate the bioclimatic layers across the entire extent, Maxent was made to select only the countries with presence locations (i.e., Bhutan, Nepal, India and Pakistan). In so doing, I limited the pseudo-absences to areas that were surveyed for the species, potentially providing the background samples with the same bias as presence locations (Elith et al., 2011).

Model was developed in Maxent using the occurrence points (i.e. latitude and longitude) and current climatic variables and was projected for the future climatic variables. The model was replicated 100 times in order to get an average estimate (since machine learning techniques are notorious for their inability to produce unique solutions), and hence the output is an average of 100 replications. Maxent produces a continuous raster map of habitat suitability with values ranging from 0 to 1 (0 indicating a non-suitability, 1 indicating a perfect suitability). Continuous map produced by Maxent was exported to ArcGIS (version: 10.4.1). A binary map of climatically-suitable and unsuitable geographical areas was created in ArcMap using 'maximum test sensitivity plus specificity logistic threshold' in the Maxent output file called 'maxentResults'. This threshold has been found or shown to perform considerably well as the 'presence/absence' models (see Liu et al. 2016). Performance of the model was evaluated using a metric called 'Area Under the ROC (receiver operating characteristic) curve' or 'AUC' (Swets,

1988) and test omission error (i.e., fraction of presences predicted absent). The AUC metric, whose value ranges between 0 and 1, is a threshold-independent measure of a model's ability to discriminate presence from absence (or background). An AUC value of 0.5 indicates that the model performance is not better than random, while value > 0.9 indicates high model performance (Peterson et al., 2011). 'Subsampling' procedure was executed in Maxent for model validation. Seventy percent of the occurrences data were used to train the model while the remaining 30 percent were used to test it. The relative contribution of different bioclimatic predictors to the distribution model was evaluated using percent variable contribution and jackknife procedures in Maxent (Elith et al., 2011)

Results

Average test AUC value for the model was 0.98 (± 0.003 SD) and average training AUC value was 0.992 (± 0.0007 SD). Average test omission error for the threshold used was 0.01. Annual mean temperature was the strongest predictor of musk deer habitat distribution with 71.4percent contribution. Similarly, the other climatic variables that were noted important for musk deer habitat distribution were precipitation seasonality (i.e., coefficient of variation), temperature seasonality, and annual precipitation (Table 1; Figs. 1,2,3,4). Jackknife results showed 'annual mean temperature' as the most useful information by itself, and having the most information that is not present in other variables, for model predictability (i.e., with highest regularized training gain and AUC value). Model predictions matched the collected occurrences of musk deer in Bhutan, Nepal, India, and Pakistan and also showed potential geographic range in China (Fig. 5 and 6). Future geographic distribution of the species is predicted to expand mostly in the Indian and Tibetan region of China (Fig. 6).

Discussion

This is the first study to model and map the potential current and future distribution of climatically-suitable habitat of Himalayan musk deer in its whole range. Maxent accurately predicted the currently available occurrences; hence the maps created can be used reliably to design detailed surveys to explore populations of the species in the predicted geographic area. It appears that the species has a narrowly-distributed climatically-suitable habitat, along the Hindukush Himalaya, with majority of climatically-suitable current habitat in Indian and the Tibetan region of species' range. The current distribution of climatically-suitable area as predicted from the study did not completely match the expert-based IUCN range map of the species. Yet, notable is the potential habitat range in Pakistan and Tibetan region of China which is not encompassed in the IUCN range map although the species have been recorded in those areas (see Yang et al. 2003; Abbas et al. 2015). Hence, the current distribution map from this study offers an avenue for further exploration of the species in the area predicted suitable in this study. I believe that the current distribution map, as predicted from this study, meets the necessity of identifying potential areas that demand conservation concern. We recommend the protection and management of potentially suitable key areas predicted by the model even if the species don't currently occur there. This might require cooperation between countries and the design of a joint, international management plan.

The expansion of climatically-suitable habitat in future in Indian and Tibetan part of the species' range suggest a potential reshuffling of species' distribution in the future (see Parmesan and Yohe, 2003); presumably to track the optimum or adaptive climatic niches and keep pace with the effects of changing climate for survival. This is in accordance to the theoretical predictions of climate change on a wide variety of taxa and climates (Hersteinsson and Macdonald, 1992; Pounds et al., 1999, Warren et al., 2001; Parmesan and Yohe, 2003). The geographic range of the species is distributed in between the latitudinal range of 30^0-38^0 N (i.e. in temperate areas), where the magnitude of climate change effects is predicted to be greater (Parmesan, 2007), because of projected relatively high rise in temperature and variation in precipitation patterns at those latitudes and altitudes (IPCC, 1996; Hughes, 2000). Therefore, effects of climate change on the species are inevitable, since a narrow range of annual mean temperature, low precipitation seasonality, and low annual precipitation appear to be the major determinants to its habitat distribution. Temperature has been found as a major component in structuring distribution of Himalayan species of other taxa as well (Elsen et al., 2017). How and to what extent these climatic changes will affect the species, however, cannot be explained with certainty primarily because of knowledge gap and incomplete information about the ecology of the species. Yet we can hypothesize that the effects would be direct via physiological or phenological effects and indirect via cascading effects on resource bases or both. Since evidences suggest that temperate species have relatively broader thermal tolerance (Chan et al., 2016; but see Elsen et al., 2017), the latter hypothesis however would be more reasonable to test in the future studies to better understand the effects of climate change. Nevertheless, design of new conservation areas and expansion of existing conservation areas towards the predicted potentially suitable geographic area could aid in conservation of the species.

It is noteworthy that climatic variables are not the sole factors driving species distribution over space, although their crucial role in determining the geographic range of many species is undisputable (Andrewartha and Birch, 1954; IPCC, 1996; Venier et al., 1999). Other ecological factors like dispersal pattern and capacity, resource distribution and availability, ecological interactions, habitat selection etc. deserve well considerations, and better integrations within SDMs to comprehend a perfect and clear picture of their distribution over space (Guisan and

Thuiller, 2005; Elith and Leathwick, 2009). Incomplete availabilities of such data, to fully integrate the ecological theories of species into modeling process, have in part added some limitations to this study. Other factors that contribute to the uncertainties and limitations of SDMs are; sample size, sampling bias, spatial resolution of predictors including their choices, multi-collinearity; that deserve well considerations during modeling process (Stockwell and Peterson, 2002; Kadmon et al., 2004; Segurado et al., 2006). Maxent is robust to small sample sizes and has been found to have an optimal predictive power even with small sample size (see Wisz et al. 2008), and although I tried to deal with issues of multi-collinearity (by dropping highly correlated variables) and background sampling bias (by picking the background samples from the area of occurrences records only), yet I acknowledge the possible uncertainties in my findings, due in part to other potential issues (for example, biotic interactions, dispersal capacity, phenology) that could not be dealt and/or integrated into the modeling process. Inclusion of biologically relevant factors in modeling process in future would further refine the predicted distribution map of environmentally suitable habitat for the species. Yet, the predicted suitable area from the study is climatically-conducive to the survival of the species; hence the area deserves considerable concern for conservation of the species in the context of climate change.

SDMs are increasingly and diversely used in conservation biogeography with relatively good success (Austin et al., 1990; Elith and Burgman, 2002; Ferrier, 2002). Of notable beauty of these techniques is an easily understandable and interpretable output, in the form of binary maps (i.e. habitat-suitability maps), required by wildlife managers for conservation actions and risk analyses. Although interpreting habitat and its suitability from patterns of occurrence can sometimes be misleading (van Horne, 1983), which is usually the case with high population size; yet for a small population size of Himalayan musk deer, it is unlikely to misinform the suitability of habitat by the occurrence points of the species used here. This, however, requires exploration of musk deer populations in the predicted geographical space for validity. It is expected that the findings of the current study potentially assist wildlife managers and other stakeholders in conservation planning and sound management decisions of, declining and threatened, Himalayan musk deer in the context of climate change.

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Table 1. Relative contribution of different bioclimatic variables to Maxent model for climatically-suitable habitat distribution of Himalayan musk deer. Percent contribution values are averages over 100 replicate runs. General statistics show the bioclimatic profile of the species. Only the variables with contribution > 1% are shown.

Variable	Percent Contribution	Mean	Standard Deviation
Annual Mean Temperature (°C)	71.4	6.18	0.28
Precipitation seasonality (CV)	7.6	68.2	0.8
Temperature seasonality (SD*100)	5.5	5690	179
Annual precipitation (mm)	5.3	721	52
Mean Diurnal Range (°C)	1.7	10.5	0.09
Precipitation of Coldest Quarter (mm)	2.8	124	6.48

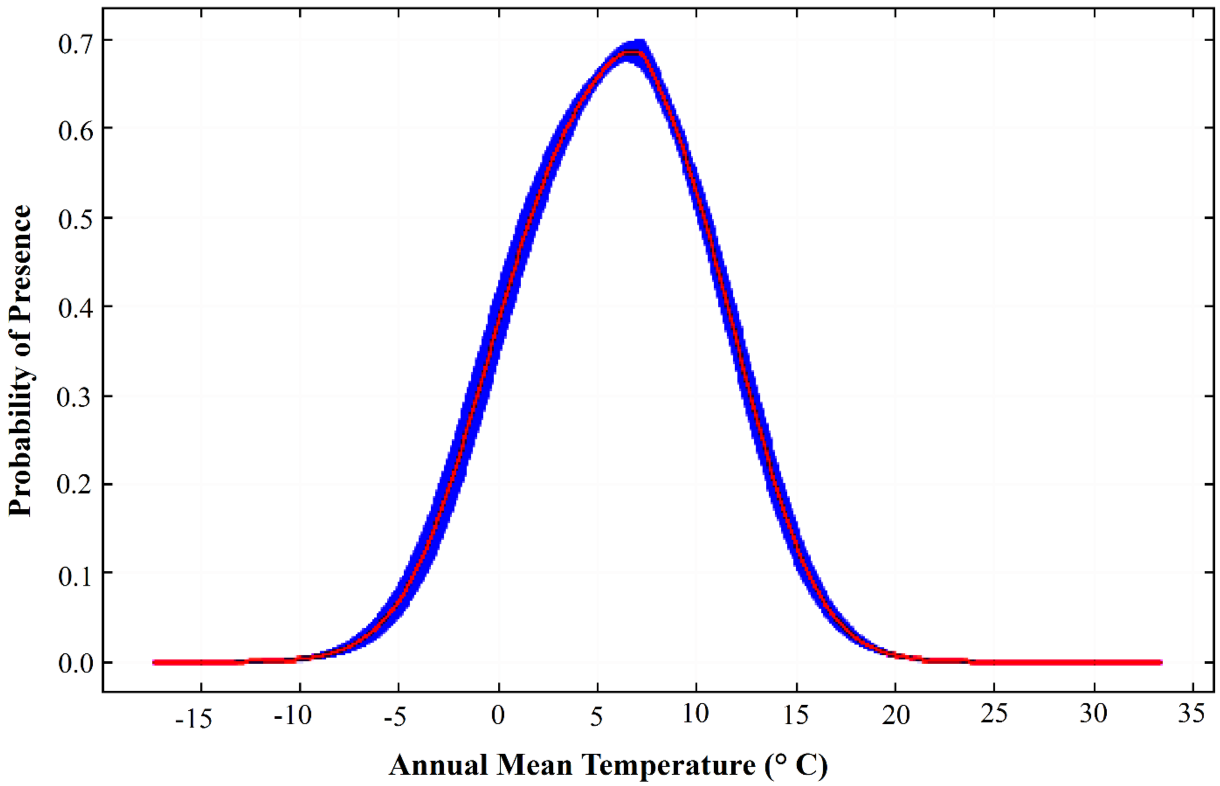

Figure 1. Relationship between annual mean temperature and probability of presence of musk deer. The curve depicts the mean (± SD) response calculated over 100 replicates.

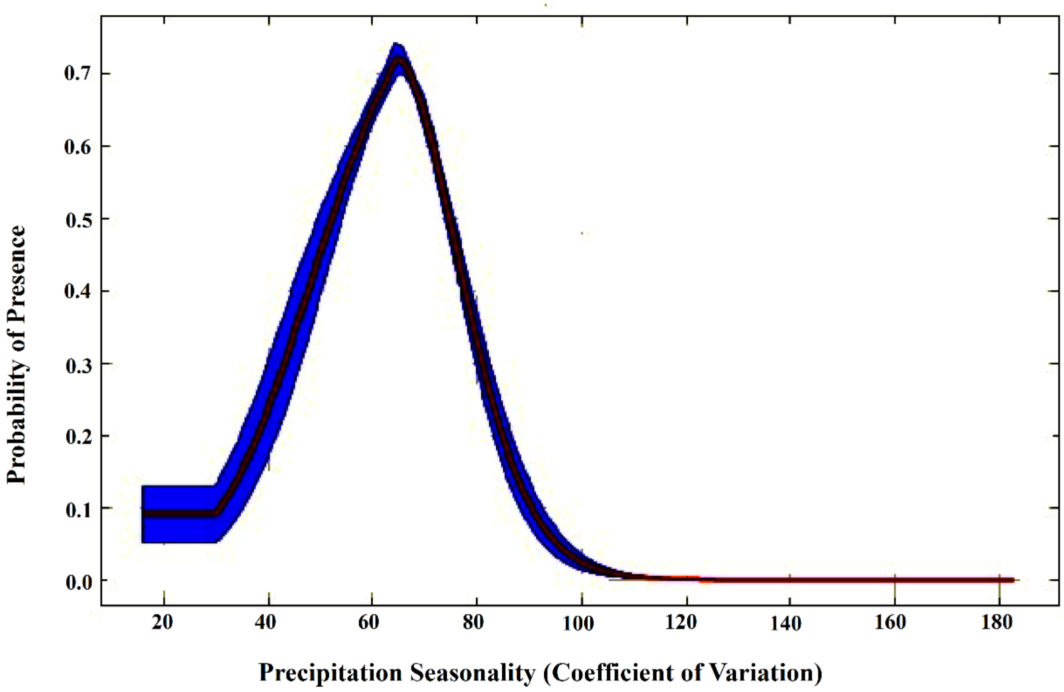

Figure 2. Relationship between precipitation seasonality and probability of presence of musk deer. The curve depicts the mean (± SD) response calculated over 100 replicates.

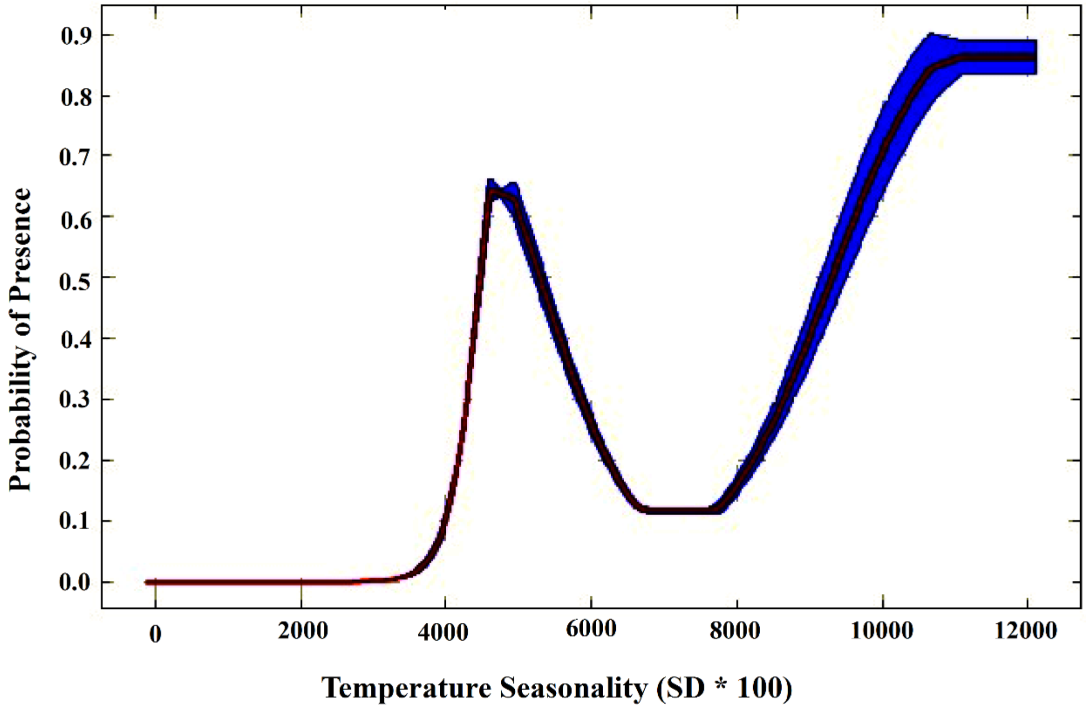

Figure 3. Relationship between temperature seasonality and probability of presence of musk deer. The curve depicts the mean (± SD) response calculated over 100 replicates.

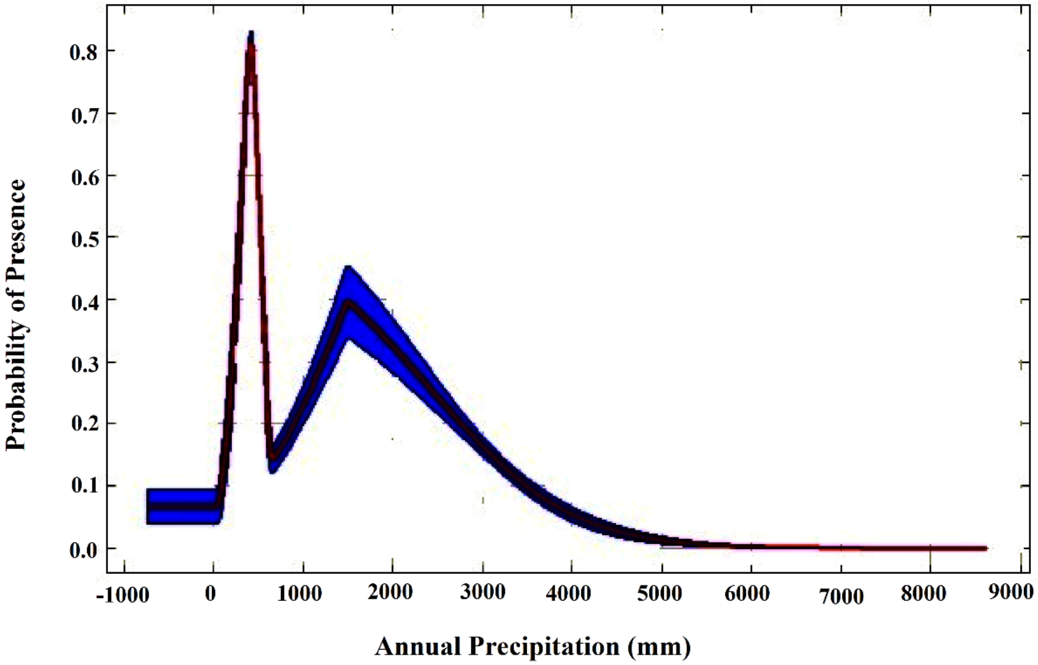

Figure 4. Relationship between annual precipitation and probability of presence of musk deer. The curve depicts the mean (± SD) response calculated over 100 replicates.

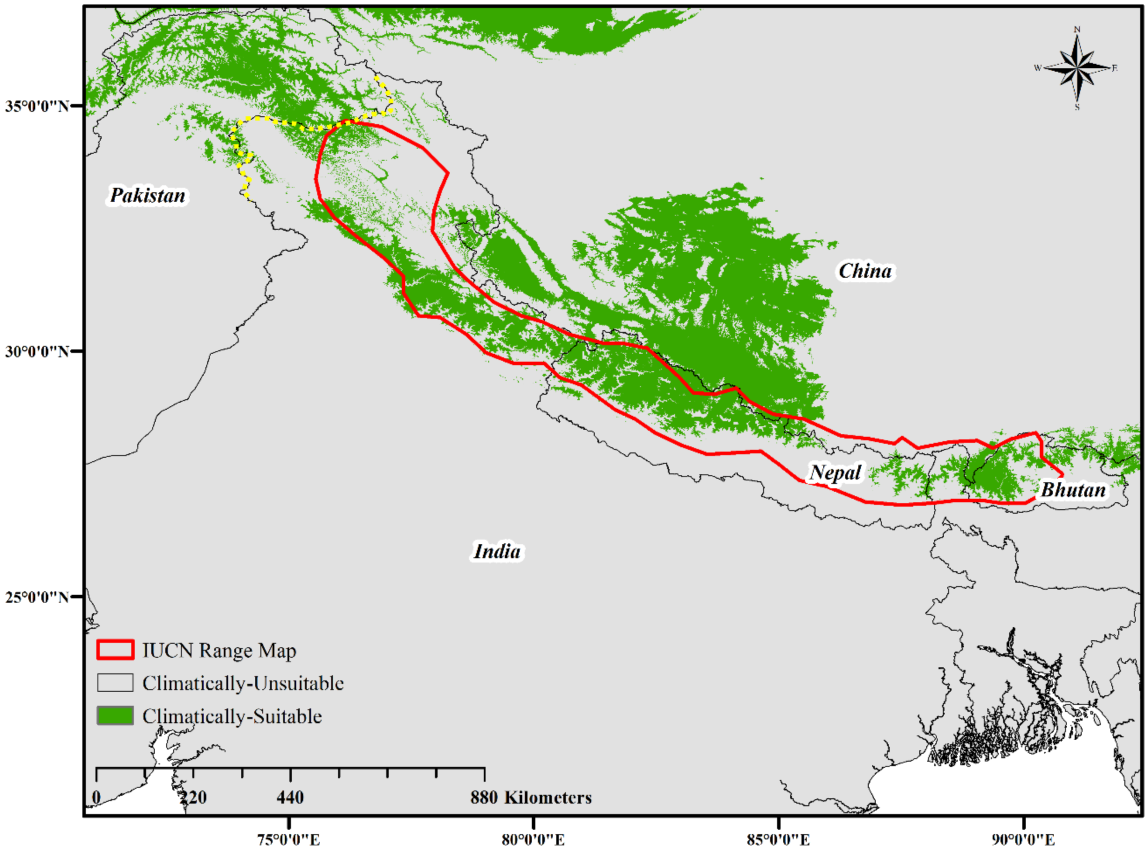

Figure 5. Current climatically-suitable area for Himalayan musk deer as determined by the model. Yellow boundary line shows the geographical boundary of conflict.

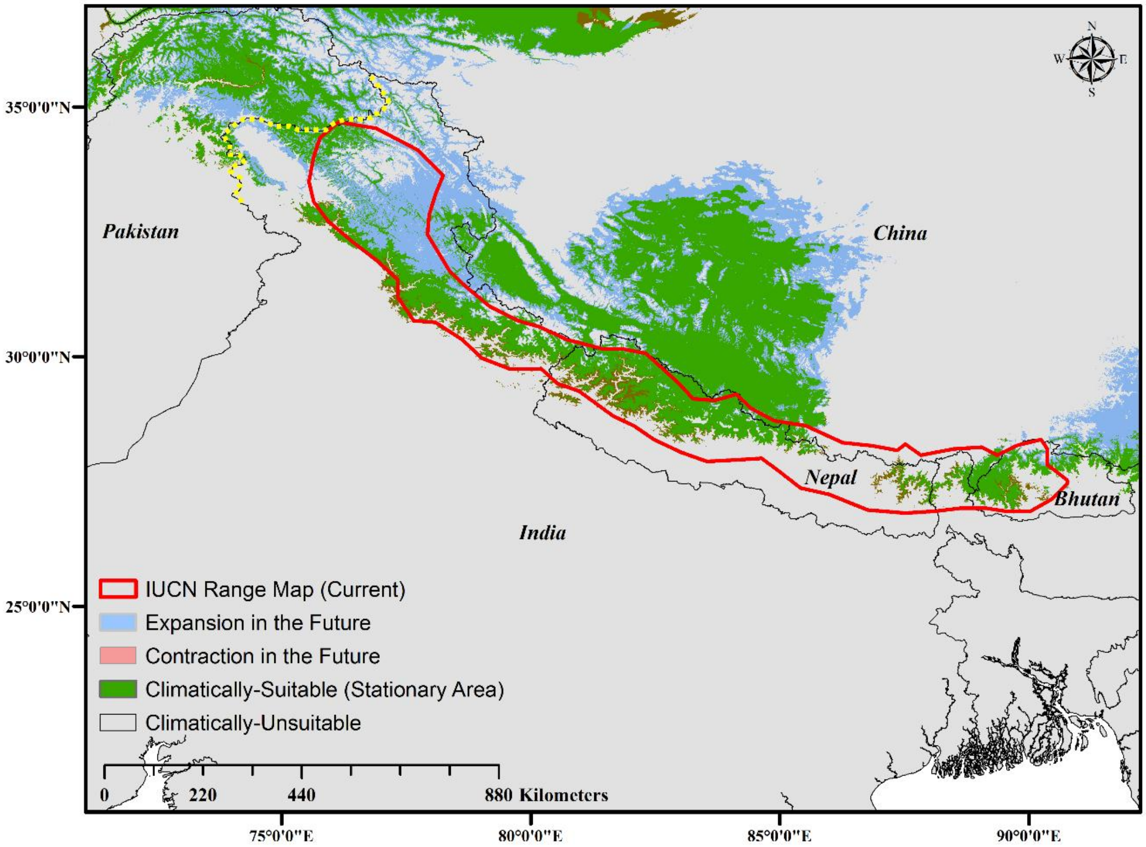

Figure 6. Future climatically-suitable area for Himalayan musk deer as predicted by the model along with the expansion and contraction of area under projected climate change.

Chapter V: Concluding remarks

To sum up, this dissertation highlights the importance of understanding habitat selection of a species at different hierarchical order. Conservation of biodiversity at species level requires well-informed decisions and planning. Development and execution of planning, however, demands scale specific understanding of the habitat selection process. It is expected that this dissertation could aid in the planning of Himalayan musk deer conservation at different scales of their range. Chapter 1 highlights the seasonal diet composition of musk deer along with the possible impacts of sympatric livestock if their number is not checked and are not assigned a separate foraging area. Similarly, the chapter highlights the habitat attributes in terms of physical and vegetational characteristics that are likely selected by Himalayan musk deer within their home range. Thus, management of habitat with due consideration of these habitat attributes could help in the conservation of the species. Chapter 3 predicts the potential future distribution of the species and highlights the possible range expansion at the northern limit of the current geographic range of the species. Consideration of the geographic area predicted climatically-suitable in the future during conservation planning would help mitigate the potential impacts of climate change. The findings, however, are not the panacea to the threats per se. Future studies regarding dispersal ecology and population dynamics would help in further understanding about the species and better management of the species before their extinction in the wild.