Thinley, P., Rajaratnam, R., & Shrestha, R. (2018). Establishing baseline estimates of blue sheep (Pseudois nayaur) abundance and density to sustain populations of the endangered snow leopard (Panthera uncia) in Western Bhutan. *Wildlife Research*, 45(1), 38-46. doi: 10.1071/WR16218

Establishing baseline estimates of blue sheep (*Pseudois nayaur*) abundance and density to sustain populations of the endangered snow leopard (*Panthera uncia*) in Western Bhutan

Authors:

1. **Leki,** Lingzhi Park Range, Jigme Dorji National Park, Department of Forests and Park Services, Gasa, Bhutan

2. **Phuntsho Thinley** (Corresponding Author)

Ugyen Wangchuck Institute for Conservation and Environment Research, Department of Forests and Park Services, Bumthang, Bhutan

Email: pthinley@uwice.gov.bt, chetsho78@gmail.com

3. **Rajanathan Rajaratnam**, Geography & Planning, University of New England, Armidale, New South Wales, Australia

4. **Rinjan Shrestha**, World Wildlife Fund, Toronto, Canada

Abstract

Context. Advances have been made on developing reliable methods for estimating the abundance and density of large endangered mammalian predators, but there is little progress on developing population estimates for their principal prey. No standardized protocol for estimating prey populations exists, and hence, different researchers use different methods. As such, there is a little information on key prey species of the endangered snow leopard (*Panthera uncia*) such as the blue sheep (*Pseudois nayaur*), and this has hindered the preparation of effective snow leopard conservation plans.

Aims. We established an estimated seasonal baseline population abundance and density of blue sheep in the Lingzhi Park Range (LPR) of Bhutan's Jigme Dorji National Park over winter and summer. We also assessed the number of snow leopard individuals that the current blue sheep population can sustain in the study area.

Methods. We used a refined double-observer survey method and walked transect lengths of 414 km in winter and 450 km in summer to estimate blue sheep abundance with the aid of 8 x 30 binoculars and 15 x 45 spotting scopes.

Key results. We estimated 1,762 (*SE* ±199) blue sheep individuals in winter at a density of 8.51 individuals per km^2 and 2,097 (*SE* ±172) individuals in summer at a density of 9.32 individuals per km^2. Mean group size of blue sheep was 38.12 individuals (*SE* ± 6) in winter and 52.36 individuals (*SE* ± 4) in summer. LPR was estimated to sustain 11 to 17 snow leopards in winter and 15 to 21 in summer

Key conclusions. LPR can be a hotspot for snow leopard conservation in western Bhutan and regionally in the eastern Himalayas, because the comparatively higher estimated blue sheep abundance and density possibly supports the highest density of snow leopards in Bhutan. Our modified double-observer method used to assess blue sheep population estimates is inexpensive, robust, and practical in the mountainous terrain of the Himalayas.

Implications. We recommend the adoption of our modified double-observer method as a standard technique for estimating blue sheep populations in the snow leopard range countries of the Himalayas. Snow leopard conservation plans should, additionally, include efforts to minimize threats to blue sheep populations. Our modified method is also highly applicable for future surveys of gregarious mammalian taxa like ungulates and primates in difficult mountainous terrain elsewhere in the world.

Additional keywords: double-observer survey, Eastern Himalayas, Jigme Dorji National Park, mountain ungulates, snow leopard conservation

Introduction

Studies on endangered mammalian apex predators have largely focused on estimating their population abundance in an effort to save them from extinction. In the last fifteen years, there has been a marked increase in the number of studies refining the methods for estimating predator populations. For instance, the method for estimating the populations of naturally marked animals (Jackson *et al.* 2006; Karanth and Nichols 1998) such as the tiger (*Panthera tigris*) and the snow leopard (*Panthera uncia*) has been improved with advances in survey equipment and computer processing capabilities (Royle *et al.* 2013). Hence, there are empirically robust estimates of tiger (Karanth *et al.* 2004a; Khan 2012; Simcharoen *et al.* 2007; Thinley *et al.* 2015a; Wang and Macdonald 2009) and snow leopard (Jackson *et al.* 2006; Lham *et al.* 2016) populations within parts of their geographical range. However, there has been a lack of progress in refining the methods for reliably estimating their prey populations, resulting in little reliable information on the abundance of their key prey species.

Dearth of information on the abundance of key prey species has greatly hindered viability assessments and conservation planning for the snow leopard (MCCarthy and Chapron 2003; Wikramanayake *et al.* 2006). This elusive cat species is classified as "endangered" by the IUCN (Jackson et al. 2008) and is currently distributed in 12 Asian countries: Afghanistan, Bhutan, China, India, Kazakhstan, Kyrgyz Republic, Mongolia, Nepal, Pakistan, Russia, Turkmenistan, and Uzbekistan (Jackson *et al.* 2006). In all of these range states, it faces threats from prey base depletion, poaching, illegal trade, and habitat destruction (Jackson *et al.* 2008). It is not known how much of the prey population exists to sustain a viable snow leopard population in most of these countries. Without a baseline population estimate, the impacts of anthropogenic factors such as poaching, habitat reduction, habitat degradation, human intrusion, and fodder competition from domestic ungulates on prey populations remain unknown.

Since predator density is directly correlated to prey density (Karanth *et al.* 2004b; Karanth and Stith 1999), adequate knowledge about prey populations is highly relevant to the conservation of their main predators. The principal natural prey of the snow leopard differs regionally ranging from the Siberian ibex (*Capra sibirica*) and argali sheep (*Ovis ammon*) in Mongolia (Shehzad *et al.* 2012), to the Siberian ibex and markhor (*Capra falconeri*) in northern Pakistan (Anwar *et al.* 2011). The blue sheep (*Pseudois nayaur*), also commonly known as bharal or naur, constitutes the principal prey of the snow leopard in China (Schaller *et al.* 1988; Xu *et al.* 2008), India (Bagchi and Mishra 2006; Fox *et al.* 1991), Nepal (Devkota *et al.* 2013; Oli 1994; Oli *et al.* 1993b; Wegge *et al.* 2012), and Bhutan (Shrestha and Tenzin 2015; Thinley *et al.* 2014). This aberrant goat with sheep-like traits (Schaller 1977) is distributed from the Central Asian Mountains to northern Myanmar (Harris 2014). It faces varying threats in different countries, ranging from localised hunting to habitat loss. In Bhutan, it is threatened by the increasing number of domestic yaks (*Bos grunniens*) with which it competes for fodder (Shrestha and Wegge 2008), and an increasing number of international trekkers and medicinal plant collectors within its foraging areas (Thinley *et al.* 2014) who escalate its alertness (Jiang *et al.* 2013), and possibly disrupt its foraging behavior thereby impacting fodder uptake. Currently, there is very little information on blue sheep abundance within its geographical range.

A reason for the lack of baseline population data on key prey species for the snow leopard could be attributed to the lack of a standardized method for estimating their populations. This is true for blue sheep although several methods exist for surveying and monitoring of large herbivores based on direct methods such as distance sampling (Burnham *et al.* 1980), strip counts (Eberhardt 1978), and fixed-point counts (Jackson and Hunter 1996); and indirect methods such as track counts (Dzieciolowski 1976; Mandujano and Jones 2005) and dung counts (Laing *et al.* 2003; Marques *et al.* 2001). Seeing the limited applicability and reliability of these methods for gregarious mountain ungulates in relatively large areas, Suryawanshi *et al.* (2012) recently improved on the double-observer survey technique developed by Forsyth and Hickling (1997) by separating each observation in space or time. This technique also allowed an estimation of sampling error that enabled assigning a level of confidence to the population estimates. Hence, this inexpensive but rigorous method tested in the geophysical conditions of the Indian State of Himachal Pradesh in Western Himalaya, provided robust estimates of blue sheep and ibex abundance (Suryawanshi *et al.* 2012) with appropriate measures of error and detection probability. Yet, the applicability of this method has not been assessed and employed in the neighboring snow leopard range countries such as Nepal and Bhutan where similar topographic conditions exist. Therefore, the objectives of this study were to assess the applicability of the double-observer survey technique for estimating seasonal blue sheep abundance in Bhutan, and to estimate the number of snow leopards that could be supported by the current blue sheep population. We also observed how population estimates and group compositions seasonally differed between winter and summer. Based on our experience, we discuss some of the limitations of the technique and suggest further improvements.

Materials and methods

Study area

We conducted this study in the Lingzhi Park Range (27º 59' N, 89º 40' E; hereinafter referred to as LPR) in the biodiversity-rich Jigme Dorji National Park (Fig. 1; hereinafter referred to as JDNP). Situated in western Bhutan and measuring about 4,316 km^2, JDNP is a unique global protected area where the tiger and the snow leopard overlap in their respective ranges (Thinley *et al.* 2015c). Encompassing an area of 745 km^2 and adjoining the Tibetan Autonomous Region of China in the north, LPR is the fourth largest of the six park ranges in JDNP. LPR mostly falls within the upper catchment of Wangchhu River basin in Western Bhutan. The vegetation is dominated by alpine meadows above the tree line (i.e., > 3,800 m a.s.l.) and by sub- alpine and mixed conifer forests below the tree line. The terrain is highly rugged with deep valleys and steep hills. The precipitation comprises rain in summer and snow in winter. The altitude in LPR ranges from 3,250 to 6,794 m a.s.l.

LPR is an ideal place to study the population dynamics between blue sheep and snow leopards. During the recent nationwide camera-trap survey of snow leopards in Bhutan (Lham *et al.* 2016), 31 individuals were identified in JDNP of which 16 (52%) were located in LPR. In addition, LPR has the largest populations of blue sheep judging from the number of sighted herds and frequency of sightings. LPR also harbors other predators such as the tiger, dhole (*Cuon alpinus)*, clouded leopard (*Neofelis nebulosa*), leopard cat (*Prionailurus bengalensis*), Asiatic golden cat (*Catopuma temminckii*), marbled cat (*Pardofelis marmorata*), red fox (*Vulpes vulpes*), Asiatic black bear (*Ursus thibetanus*), and Pallas's cat (*Otocolobus manul*; Thinley 2013; Thinley *et al.* 2015b). The ungulate community is represented by the Bhutan takin (*Budorcas taxicolor whitei*), blue sheep, Himalayan musk deer (*Moschus leucogaster*), alpine musk deer (*Moschus chrysogaster*), sambar (*Rusa unicolor*), Himalayan goral (*Naemorhedus goral*), muntjac (*Muntiacus muntjac*) and Himalayan serow (*Capricornis thar*).

Approximately 700 pastoralists reside in LPR (NSB 2005), subsisting primarily on raising domestic yaks (*Bos grunniens*) and the sale of medicinal plants, including cordyceps, the highly-priced caterpillar fungus (*Ophiocordyceps sinensis*; Cannon *et al.* 2009). On average, each household owns 30 yaks (DoL 2013).Yak herders have also been permitted to collect cordyceps for one month (mid-June to mid-July) every year for sale to local exporters to supplement their household income. The LPR is also a prominent tourist destination with hundreds of international tourists trekking there every year.

Field methods

Fieldwork was conducted in winter (December 2014 to February 2015) during the blue sheep's mating season, and in summer (May 2015 to July 2015) during its parturition period (Wegge 1979; Wilson 1981). Prior to field visits, all potential areas of blue sheep occurrence in the LPR characterised by frequent sightings, known alpine grassland habitats, and minimal human presence were identified through staff interviews and consultation with local yak herders who provided information on where blue sheep groups were regularly seen. By plotting the names of potential sites on contour maps and Google Earth™, a total of 29 blocks were selected for surveys. Each block was separated from the rest by mountain ridges or large rivers which geophysically isolated several blue sheep groups. Using the double-observer survey technique (Forsyth and Hickling 1997; Suryawanshi *et al.* 2012), we conducted our surveys in the study area from east to west to be consistent. In each block, we randomly laid a transect along an altitudinal gradient, starting from the base of a hill with a drinking water source, usually a river or a large stream, and ending on the rocky outcrops on the hill top. This was to closely coincide with the movement pattern of blue sheep which are known to gradually descend to a hill base in the early morning for drinking water and progressively ascend the hill as they forage, reaching the hill top at dusk (Schaller 1973). On each survey day, the observers slowly (1.5 km/hour) walked a chosen transect uphill, commencing at 0600 hrs (first observer) till 1030 hrs. The second observer followed the same transect exactly one hour after the first observer, as suggested by Suryawanshi *et al.* (2012), finishing at 1130 hrs. Breaks were taken from 1130 hrs to 1400 hrs when blue sheep rested on the rocky cliffs, and surveys were resumed along a similar staggered timing from 1400 hrs to 1730 hrs. Each observer stopped to record observations whenever blue sheep herds were sighted. Surrounding areas were also additionally scanned for the occurrence of sub-groups. Observer 1 and observer 2 were the same in both the seasons.

We met all three critical assumptions of the double-observation method (Forsyth and Hickling 1997; Magnusson *et al.* 1978) which rests on the principle of a mark-recapture estimate of population (Nichols 1992). In order to fulfill the method's population closure assumption, we conducted the survey during a relatively short period in each season, ranging from 30 to 35 days. In addition, survey blocks were separated by ridges and big rivers, and it was unlikely that movements of individuals in and out of the survey sites occurred during the survey duration. All surveys in a block ended at a ridgeline that served as natural barrier for blue sheep to cross over to the adjacent block.

The first and second surveys were separated by one hour to fulfill the second assumption of independence in that surveys by both observers were independent random samples of the entire population. The spacing of one hour was deemed adequate to capture changes in detection that resulted from changes in group activity and locations (Suryawanshi *et al.* 2012). The first observer made minimal disturbance to avoid drastic changes in blue sheep behavior so that the sighting probability of the second observer was not affected.

In order to meet the third assumption that all blue sheep groups and their members were identifiable, unique features of group members such as broken horn tips, furless patches on the body, and injured individuals, were noted by each observer. Observers noted the characteristics of observation sites such as distinct geophysical features, herder's camps, lakes, and other landmarks to help in unique characterization of a group and to check if observed groups were the same or distinctly separate. Observations were made with the aid of 8 x 30 binoculars and 15 x 45 spotting scopes to record the number of individuals in a group and classify them into different sex and age categories. Group members were sexed and aged according to the classification method employed by Wegge (1979): *young* (<1 year), *yearling* (1-2 years), *adult female* (≥ 2 years), *young male* (2 – 3 years) with horn length measuring between 15 – 35 cm, *medium male* (4 – 6 years) with horn length ranging between 35 – 45 cm, and *big male* (≥ 7 years) with fully grown horns measuring 45 – 50 cm. With the use of binoculars and spotting scopes from various distances, observers were trained to precisely estimate horn lengths through prior first-hand knowledge of actual horn lengths from a collection of blue sheep horns from various age groups at LPR office.

At the end of each day, both observers tallied the number of blue sheep groups seen in common and exclusively seen by each observer based on the number of individuals counted, group composition, and the unique features of group members. For groups of less than 10 individuals, a group was treated as seen in common if the difference in the number of individuals recorded by both observers was less than the lowest observed group size (i.e., 2 in our case). Otherwise, the groups were treated as exclusive and seen separately by each observer. When groups were treated as seen in common, the group sizes and number of individuals in each age/sex class were averaged (and rounded to whole numbers) to avoid overestimation or underestimation. Both observers exercised extreme caution in agreeing to the unique features of a group, because a slight variation in the number of groups and group size would give rise to biases in estmating the total number of groups and mean group size, consequently affecting the estimation of abundance and density.

Geographical coordinates of the blue sheep herd centers were recorded using GPS (Global Positioning System) units (Fig. 1). In order to not disturb blue sheep, and also to estimate locations in situations when there were steep gorges and lakes between the observers and blue sheep groups, the coordinates of the group centers were projected using the way point projection tool in the GPS unit.

Estimating blue sheep abundance and density

We used the population abundance estimation method for the double-observer survey developed by Forsyth and Hickling (1997) to estimate the abundance of blue sheep in the study area. The estimate of blue sheep abundance was computed as the product of the estimated number of observed blue sheep groups ($\hat{G}$) and the mean group size ($\hat{\mu}$) computed by averaging all group sizes. The estimated number of groups was computed as:

$$\hat{G} = \left(\frac{(B + S_1 + 1)\,(B + S_2 + 1)}{(B + 1)}\right) - 1$$

where: B = the number of blue sheep groups seen in common by both observers,

S_1 = the number of blue sheep groups exclusively seen by the first observer, and

S_2 = the number of blue sheep groups exclusively seen by the second observer

We computed the sampled area by multiplying the total transect length with a 250 m maximum observation distance on either side. We used a total sampled area of 207 km^2 in winter (with a total transect length of 414 km) and 225 km^2 in summer (with a 450 km transect length) for estimating the density of blue sheep in the respective season.

Computing blue sheep detection rate

In accordance with Suryawanshi *et al.* (2012), we computed the detection rate (p) of each observer as the ratio of the sum of the number of groups commonly seen (B) and number of groups only seen by the particular observer to the estimated number of groups in the population. For example, the detection probability (p_1)of the first observer was computed as:

$$p_1 = \left(\frac{B + S_1}{\hat{G}}\right)$$

Comparing estimated abundances and mean group sizes between seasons

For assessing statistical significance of change in estimated abundance between winter ($\hat{N}_1$) and summer ($\hat{N}_2$), we used the z-test (Forsyth and Hickling 1997):

$$z = \frac{\left(\hat{N}_2 - \hat{N}_1\right)}{se\left(\hat{N}_2 - \hat{N}_1\right)}$$

where:

$$se\left(\hat{N}_2 - \hat{N}_1\right) = \sqrt{Var\left(\hat{N}_1\right) + Var\left(\hat{N}_2\right)}$$

Please refer to Forsyth and Hickling (1997) for computing $Var\left(\hat{N}\right)$.

We used a Student's t-test to compare the mean group size of blue sheep between two seasons. Significance of both the tests was determined at $\alpha = 0.05$. The tests were performed in Microsoft Excel™ using the inbuilt statistical tool.

Results

Survey effort

In a 30-day survey period during winter, a total of 1,635 blue sheep belonging to 43 groups were sighted by the first observer, while the second observer counted 1,643 individuals belonging to the same number of groups (Table 1). In summer with 35-day survey period, the first observer observed 2,042 blue sheep belonging to 39 groups whereas the second observer recorded 2,064 individuals belonging to 38 groups.

Population abundance, density, and detection rate

The total number of blue sheep in LPR was estimated at 1,762 (*SE* ± 199) individuals in winter (Table 1) and 2,097 (*SE* ± 172) individuals in summer. The estimated abundance did not significantly vary from winter to summer ($z = 1.27$, two-tailed test, $p = 0.202$). Density of blue sheep based on the total sampled area and population abundance was estimated at 8.51 individuals per km^2 in winter and 9.32

individuals per km^2 in summer. The overall detection rate of both the observers was 0.93 in winter, but the rates were 0.97 and 0.95 for the first and second observer respectively in summer (Table 1).

Estimated number of groups

The number of blue sheep groups ($\hat{G}$) was estimated at 46.22 in winter and 40.05 in summer, with a mean group size of 38.12 ($SE \pm 6$) individuals in winter and 52.36 ($SE \pm 4$) individuals in summer (Table 1). There was a weak evidence for a difference in mean group size between winter and summer ($t = 1.796$, $df = 80$, $p = 0.076$). Small herds of two to 10 individuals were most frequently seen in winter (Fig. 2) accounting for 34.8% of total groups, whereas larger groups of 51 to 70 individuals representing 37.5% of total groups were most frequently seen in summer.

Population structure and sex ratio

In winter, 1,524 blue sheep were classified as 478 adult females, 266 as lambs, 305 as yearlings, 117 as young males, 109 as medium males, and 249 as big males. In summer, 1,996 blue sheep were classified as 627 adult females, 289 lambs, 314 yearlings, 219 young males, 230 medium males, and 317 big males. With 475 males and 478 females observed in winter, we computed a sex ratio of 99 males to 100 females. In summer, the sex ratio was 122 males to 100 females based on 766 males and 627 females.

Number of snow leopards that can be sustained

We estimate that blue sheep numbers in LPR could sustain between 11 – 17 snow leopards in winter and 15 – 21 in summer based on an assumed snow leopard to blue sheep ratio of 1 : 98 – 143 estimated by Jackson (1996) in Nepal. Our estimated number of snow leopards was comparable to the estimated range of 13 to 17 individuals obtained by Thinley *et al.* (2014) in the west part of JDNP which also included the adjacent Soe Park Range.

Discussion

Study limitations and improvements in the method

In our study area, there were adequate physical barriers to prevent the movement of blue sheep from one survey block to another. In areas without such barriers, the method's assumption of population closure may not be met especially if surveys are done for longer periods by few observers, as individuals may move between areas and group sizes may thus differ due to formation of sub-groups. There could also have been limitations to our survey method if the first observer disturbed blue sheep herds through chance encounters when the random transect was close to their foraging or resting places, thereby subsequently affecting the second observer's detection probability. We ensured that such limitations were minimized through diligence on the part of the first observer to be quiet, cautious, and not initiating eye contact when in close proximity to blue sheep groups. It was also unlikely that the first observer would disturb blue sheep groups located distantly, thereby necessitating the use of spotting scopes.

In our study, we observed movement of males from one group to another in some survey blocks during the mating season. Hence, double-counting of individuals or groups may have occurred which will cause positive biases in the estimation of average group size and even the total number of groups. In such cases, an alternative is to train and deploy a large number of observers in multiple survey blocks to conduct simultaneous surveys within a very short period. The double observer method may also underestimate abundance when some target groups shelter in rocky outcrops or on precipitous cliffs (Wilson 1981), especially when there is a predator in the area. We observed predators such as the snow leopard and the dhole in our study area, and therefore surmise that our true N may be higher. Nevertheless, our seasonal estimates of blue sheep population ($\widehat{N}$) in LPR were reliable with reasonable error margins.

Forsyth and Hickling (1997) and Suryawanshi *et al.* (2012) did not explain how observers arrived at a consensus on both common and exclusively observed groups. Such ambiguity may result in over or underestimating the number of groups and group sizes which will affect the abundance estimates. We developed a new rule using the minimum group size to distinguish between these two categories especially when groups were identified based on group sizes, particularly for small groups of less than 10 individuals. Forsyth and Hickling (1997) and Suryawanshi *et al.* (2012) also did not explain how group sizes were determined when there were differences in the number of individuals of a supposedly group observed in common. In such cases, we offer an alternative by averaging (rounded to whole number) the two counts to avoid over or under estimates. We additionally improved the precision of the observation technique by closely following the movement patterns of blue sheep in our study area. We consistently used the same technique in all transects and seasons. This prevented the likelihood of selecting observation routes that had an unlikelihood of encountering blue sheep.

Variability of estimates across seasons

The lower estimated number of blue sheep groups in summer relative to winter could be possibly attributed to observers missing groups that could have been resting in shadows or rocky crevasses in hotter temperatures during summer. In contrast, winter is the breeding season for blue sheep during which they congregate in large groups for mating, thereby improving their chances of being detected by observers. Smaller herds (2 – 10 individuals) were also more prevalent in winter than in summer (51-70 individuals) although largest groups (> 90 individuals) were detected in winter (Fig. 2). Cao *et al.* (2004) similarly observed smaller blue sheep herds of 2 to 8 individuals which constituted 94.8% of winter herds in the Helen Mountains of China. A possible explanation is that winter is the mating season during which small heterogeneous groups of two to three individuals are commonly seen. Alternately, smaller herds could possibly be more common in winter when forage is poor (Liu *et al.* 2007).

Our mean group sizes of 38 (*SE* ± 6) individuals in winter and 52 (*SE* ± 4) individuals in summer were comparatively higher than those observed in other parts of the Himalayas: 15.6 (*SE* ± 1.3) individuals in Nepal's Annapurna Conservation Area (Oli *et al.* 1993a); 7 (*SE* ± 5.5) individuals in Nepal's Dhorpatan Hunting Reserve (Aryal *et al.* 2010); 9.87 (*SE* ± 1.24) individuals in India's Gangotri National Park (Bhardwaj *et al.* 2010); and 11.6 individuals in Bhutan's Wangchuck Centennial National Park (Shrestha *et al.* 2012). We attribute this to the existence of large intact and undisturbed tracts of alpine meadows (approximately 596 km^2) in our study area that provide adequate foraging areas for blue sheep and hunting prohibitions imposed by the Forest and Nature Conservation Act of Bhutan 1995, which is strictly enforced. The field staff of LPR are to be credited for rigorous anti-poaching patrols and effective law enforcement

Our observed sex ratio of 99 males to 100 females in winter was similar to the 102 males to 100 females in Bhutan's WCNP (Shrestha et al. 2012), 90 males to 100 females in Nepal's Kanchenjunga Conservation Area (Khatiwada et al. 2007), and 93 males to 100 females in Nepal's Annapurna

Conservation Area, Nepal (Oli *et al.* 1993a). Sex ratio in our study was almost equal in winter albeit a negligibly higher number of females than males. This could be attributed to 14% unidentified blue sheep, particularly the young. However, in summer, there was a slightly higher number of males than females. Sex ratios from both seasons indicate the absence of trophy hunting in the area, as we did not observe any signs of blue sheep hunting. Local residents also did not report any incidence of blue sheep hunting in the study area within the last five years. In Nepal's Dhorpatan Hunting Reserve, low male to female ratio was attributed to poaching and selective hunting (Aryal *et al.* 2010). We also observed many large groups (> 30 individuals) in both seasons especially in winter, when there were seven groups with more than 90 individuals. Occurrence of such large groups is indicative of predation pressure in the study area (Zhang *et al.* 2012). During our blue sheep survey in the lower part of LPR, we sighted a group of three snow leopards in the survey area which was possibly a mother accompanied by two cubs. We also sighted a pack of five dhole in the eastern part of LPR which could be hunting blue sheep and yaks in the area. An existence of dietary overlap between dholes and snow leopards needs to be investigated to determine the existence of inter-specific competition between these two predators.

Comparisons with density estimates from other regions

Our estimated densities of blue sheep in both winter (8.51 per km^2) and summer (9.32 per km^2) were much higher than those reported in the neighboring regions, although the estimates may be not comparable because of different estimation methods. Blue sheep density was recorded at only 1.8 individuals per km^2 (n = 638) in Bhutan's Wangchuck Centennial National Park by Shrestha *et al*. (2012) due to intensive predation by multiple predators such as grey wolf (*Canis lupus chanco*), dhole, and snow leopard. Wilson (1981) reported a density of 2.6 blue sheep per km^2 (n = 1,000) in Nepal's Dhorpatan Shikar Reserve where the population was heavily poached by humans. A higher density of 3.63 individuals per km^2 (n = 367) was observed in the Helan Mountain Region of China by Liu *et al*. (2007), while a very high density of 9.4 blue sheep per km2 (n = 213) was reported by Shrestha and Wegge (2008) in the Phu Valley in Nepal. A possible reason for a higher density in our study area was the lack of human-induced mortality such as hunting. In Nepal's Dhorpatan Hunting Reserve, a low male to female ratio was attributed to poaching and selective hunting (Aryal *et al.* 2010).

Implications for snow leopard conservation

Our study firmly established a baseline estimate of blue sheep abundance and density in LPR for future monitoring of population trends and for conservation planning. Additionally, our estimates of abundance, density, and average group size were much higher than in other parts of the Himalayas. Despite a small area of 745 km^2 comprising merely 490 km^2 of suitable habitat for the snow leopard, the current blue sheep population in LPR can sustain a maximum of 21 snow leopards which is a viable population size for a relatively small area. This is plausible, because LPR recorded the nation's highest density of snow leopard (6.1 individuals per 100 km^2) with 16 distinct individuals observed during the recent nation-wide camera trap survey of snow leopards (Lham *et al.* 2016). All of these indicate that LPR within JDNP is a hotspot for snow leopard conservation in the Bhutanese Trans-Himalaya, and further highlight its localized regional importance in sustaining a high snow leopard population supported by a healthy prey population.

In most of the snow leopard range countries, there are no reliable estimates of blue sheep populations. Various researchers used different survey methods influenced by range of varying factors. We consider the double-observer survey method as a relatively simple, fast, and highly robust technique in estimating blue sheep populations as proposed by Suryawanshi *et al.* (2012). As discussed, we made an improvement in the observation methods of this survey technique to increase its precision. We strongly recommend the use of this improved method as a standardized technique to survey blue sheep in all the range states. This is especially important in light of the global call for securing all snow leopard populations in the priority landscapes by 2020 (Snow Leopard Working Secretariat 2013), including the Himalayan countries. We additionally recommend extending the application of our modified double-observer survey method for gregarious mammalian species in mountainous terrain elsewhere. It is particularly relevant to the survey of mountain ungulates and also primate taxa that are territorial which allows for proper blocking of survey sites and identification of specific animal groups.

A snow leopard conservation plan in Bhutan should include efforts to minimize threats to blue sheep populations. We recommend a comprehensive study on the impact of cordyceps collection and tourism on blue sheep populations, as these activities occur during blue sheep's birthing period.   We also noted plastic bottles, plastic bags, snack covers, and empty metal cans recklessly dumped by illegal medicinal plant collectors from across the border with China as well as by the local collectors. Bhardwaj *et al.* (2010) made similar observations in India's Gangotri Natinal Park where tourists and pilgrims degraded blue sheep habitat with a multitude of garbage. In addition, we observed many large herds of domestic yaks collectively grazing with blue sheep in almost all our surveyed areas with the potential for zoonotic disease transmission across species. In fact, the domestic livestock population in the LPR gradually increased from 9,645 in 2006 (DoL 2006) to 10,984 in 2013 (DoL 2013). Mishra *et al.* (2004) and Shrestha (2007) while studying grazing competition between blue sheep and domestic livestock in the Indian and Nepal Trans-Himalaya, observed dietary and habitat overlap between these two taxa, more intensely in winter when fodder availability was low. We further recommend studies to investigate the occurrence of such overlaps in Bhutan and elsewhere in the region. This has direct implications for snow leopard conservation through future potential prey depletion.

Acknowledgements

We express our deepest appreciation to the Royal Government of Bhutan, particularly the Wildlife Conservation Division of the Department of Forests and Park Services, for kindly permitting us to carry out the study and also for providing financial support. We also thank the Rufford Foundation and the Royal Society for Protection of Nature, Bhutan, for their supplemental funding.

Likewise, we sincerely acknowledge our field staff, particularly Dagay, Kinley Sithup, and Gyeltshen, and local guides for their hard work and sacrifice in the harsh climatic conditions of the study area. We also thank Om Katel and Ugyen Thinley of the College of Natural Resources, Lhendup Tharchen of Jigme Dorji National Park, Sonam Wangchuck and Dechen Lham of Wildlife Conservation Division, and Namgay Wangchuk of Jigme Khesar Strict Nature Reserve for their support and guidance.

We appreciate the critical comments provided by Paul D. Curtis of Cornell University in the US and all anonymous reviewers.

References

Anwar, M. B., Jackson, R., Nadeem, M. S., Janecka, J. E., Hussian, S., Beg, M. A., Muhammad, G., and Qayyum, M. (2011). Food habits of the snow leopard *Panthera uncia* (Schreber, 1775) in Baltistan, Northern Pakistan. *European Journal of Wildlife Research* **57**, 1077-1083.

Aryal, A., Gastaur, S., Menzel, S., Chhetri, T. B., and Hopkins, J. B. (2010). Estimation of blue sheep population parameters in the Dhorpatan Hunting Reserve, Nepal. *International Journal of Biodiversity and Conservation* **2**, 051-055.

Bagchi, S. and Mishra, C. (2006). Living with large carnivores: predation on livestock by the snow leopard (*Uncia uncia*). *Journal of Zoology* **268**, 217-224.

Bhardwaj, M., Uniyal, V., Sanyal, A., and Sanyal, A. K. (2010). Estimating relative abundance and habitat use of Himalayan Blue Sheep *Pseudois nayaur* in Gangotri National Park, Western Himalaya, India. *Galemys: Boletín informativo de la Sociedad Española para la conservación y estudio de los mamíferos* **22**, 545-560.

Burnham, K. P., Anderson, D. R., and Laake, J. L. (1980). Estimation of density from line transect sampling of biological populations. *Wildlife Monographs*, 3-202.

Cannon, P. F., Hywel-Jones, N. L., Maczey, N., Norbu, L., Samdup, T., and Lhendup, P. (2009). Steps towards sustainable harvest of Ophiocordyceps sinensis in Bhutan. *Biodiversity and Conservation* **18**, 2263-2281.

Cao, L., Liu, Z., Wang, X., Hu, T., Zhai, H., and Hou, J. (2004). Winter group size and composition of blue sheep (*Pseudois nayaur*) in the Helan Mountains, China. *Acta theriologica sinica* **25**, 200-204.

Devkota, B. P., Silwal, T., and Kolejka, J. (2013). Prey density and diet of snow leopard (*Uncia Uncia*) in Shey Phoksundo National Park, Nepal. *Applied Ecology and Environmental Sciences* **1**, 55-60.

DoL (Department of Livestock) (2006) 'Livestock Statistics 2006.' (Department of Livestock, Ministry of Agriculture and Forests: Thimphu, Bhutan.)

DoL (Department of Livestock) (2013) 'Livestock Statistics 2013.' (Department of Livestock, Ministry of Agriculture and Forests: Thimphu, Bhutan.)

Dzieciolowski, R. (1976). Estimating ungulate numbers in a forest by track counts. *Acta Theriologica* **21**, 217-222.

Eberhardt, L. (1978). Transect methods for population studies. *The Journal of Wildlife Management*, 1-31.

Forsyth, D. M. and Hickling, G. J. (1997). An improved technique for indexing abundance of Himalayan thar. *New Zealand Journal of Ecology* **21**, 97-101.

Fox, J. L., Sinha, S. P., Chundawat, R. S., and Das, P. K. (1991). Status of the snow leopard *Panthera uncia* in northwest India. *Biological Conservation* **55**, 283-298.

Harris, R. B. (2014). *Pseudois nayaur*. The IUCN Red List of Threatened Species 2014: e.T61513537A64313015. http://dx.doi.org/10.2305/IUCN.UK.2014-3.RLTS.T61513537A64313015.en. Downloaded on 14 November 2016.

Jackson, R. and Hunter, D. O. (1996). Snow Leopard Survey and Conservation Handbook. pp. 154. (International Snow Leopard Trust, Seattle, and U.S. Geological Survey, Biological Resources Division: Seattle, U.S.A.)

Jackson, R., Mallon, D., McCarthy, T., Chundaway, R. A., and Habib, B. (2008). *Panthera uncia.* The IUCN Red List of Threatened Species 2008: e.T22732A9381126. http://dx.doi.org/10.2305/IUCN.UK.2008.RLTS.T22732A9381126.en. Downloaded on 14 November 2016.

Jackson, R. M. (1996). Home range, movements and habitat use of snow leopard (*Uncia uncia*) in Nepal. (University of London: London, United Kingdom.)

Jackson, R. M., Roe, J. D., Wangchuk, R., and Hunter, D. O. (2006). Estimating snow leopard population abundance using photography and capture-recapture techniques. *Wildlife Society Bulletin* **34**, 772-781.

Jiang, T., Wang, X., Ding, Y., Liu, Z., and Wang, Z. (2013). Behavioral responses of blue sheep (*Pseudois nayaur*) to nonlethal human recreational disturbance. *Chinese Science Bulletin* **58**, 2237-2247.

Karanth, K. U., Chundawat, R. S., Nichol, J. D., and Kumar, N. S. (2004a). Estimation of tiger densities in the tropical dry forests of Panna, Central India, using photographic capture-recapture sampling. *Animal Conservation* **7**, 285-290. doi: Doi 10.1017/S1367943004001477.

Karanth, K. U. and Nichols, J. D. (1998). Estimation of tiger densities in India using photographic captures and recaptures. *Ecology* **79**, 2852-2862.

Karanth, K. U., Nichols, J. D., Kumar, N. S., Link, W. A., and Hines, J. E. (2004b). Tigers and their prey: Predicting carnivore densities from prey abundance. *Proceedings of the National Academy of Sciences of the United States of America* **101**, 4854-4858. doi: DOI 10.1073/pnas.03062101.

Karanth, K. U. and Stith, B. M. (1999). Prey depletion as a critical determinant of tiger population viability. In 'Riding the tiger: tiger conservation in human dominated landscapes'. (Eds J. Seidensticker, S. Christie, and P. Jackson). (Cambridge University Press: Cambridge, U.K.)

Khan, M. M. H. (2012). Population and prey of the Bengal Tiger *Panthera tigris tigris* (Linnaeus, 1758)(Carnivora: Felidae) in the Sundarbans, Bangladesh. *Journal of Threatened Taxa* **4**, 2370-2380.

Khatiwada, J. R., Chalise, M. K., and Kyes, R. C. (2007). Survey of snow leopard (*Uncia uncia*) and blue sheep (*Pseudois nayaur)* populations in the Kangchenjunga Conservation Area (KCA), Nepal. (Snow Leopard Trust: Seattle, U.S.A.)

Laing, S., Buckland, S., Burn, R., Lambie, D., and Amphlett, A. (2003). Dung and nest surveys: estimating decay rates. *Journal of Applied Ecology* **40**, 1102-1111.

Lham, D., Thinley, P., Wangchuk, S., Wangchuk, N., Lham, K., Namgay, T., Tharchen, L., Tenzin, and Phuntsho (2016). National Snow Leopard Survey 2014-2016 (Phase II): Camera Trap Suvey for Population Estimation. (Department of Forests and Parks Services, Ministry of Agriculture and Forests: Thimphu, Bhutan.)

Liu, Z., Wang, X., Li, Z., Cui, D., and Li, X. (2007). Feeding habitats of blue sheep (*Pseudois nayaur*) during winter and spring in Helan Mountains, China. *Frontiers of Biology in China* **2**, 100-107.

Magnusson, W. E., Caughley, G. J., and Grigg, G. C. (1978). A double-survey estimate of population size from incomplete counts. *The Journal of Wildlife Management* **42**, 174-176.

Mandujano, S. and Jones, C. A. (2005). Track count calibration to estimate density of white-tailed deer (*Odocoileus virginianus*) in Mexican dry tropical forest. *The Southwestern Naturalist* **50**, 223-229.

Marques, F. F., Buckland, S. T., Goffin, D., Dixon, C. E., Borchers, D. L., Mayle, B. A., and Peace, A. J. (2001). Estimating deer abundance from line transect surveys of dung: sika deer in southern Scotland. *Journal of Applied Ecology* **38**, 349-363.

MCCarthy, T. M. and Chapron, G. (2003) 'Snow Leopard Survival Strategy.' (International Snow Leopard Trust and Snow Leopard Network: Seattle, Washington, U.S.A.)

Mishra, C., Van Wieren, S. E., Ketner, P., Heitkönig, I., and Prins, H. H. (2004). Competition between domestic livestock and wild bharal *Pseudois nayaur* in the Indian Trans-Himalaya. *Journal of Applied Ecology* **41**, 344-354.

Nichols, J. D. (1992). Capture-recapture models. *Bioscience* **42**, 94-102.

OCC (Office of the Census Commissioner) (2005). Population and Housing Census of Bhutan 2005. (National Statistics Bureau: Thimphu, Bhutan.)

Oli, M., Taylor, I., and Rogers, D. M. (1993a). Diet of the snow leopard (*Panthera uncia*) in the Annapurna Conservation Area, Nepal. *Journal of Zoology* **231**, 365-370.

Oli, M. K. (1994). Snow leopards and blue sheep in Nepal: densities and predator: prey ratio. *Journal of Mammalogy* **75**, 998-1004.

Oli, M. K., Taylor, I. R., and Rogers, M. E. (1993b). Diet of snow leopard (*Panthera uncia*) in the Annapurna Conservation Area, Nepal. *Journal of Zoology* **231**, 365-370.

Royle, J. A., Chandler, R. B., Sollmann, R., and Gardner, B. (2013) 'Spatial capture-recapture.' (Academic Press: Waltham, Massachusetts, U.S.A.)

Schaller, G. B. (1973). On the behaviour of blue sheep (*Pseudois nayaur*). *Journal of Bombay Natural History Society* **69**, 523-537.

Schaller, G. B. (1977) 'Mountain monarchs: wild sheep and goats of the Himalaya.' (University of Chicago: Chichago, Illinois, U.S.A.)

Schaller, G. B., Junrang, R., and Mingjiang, Q. (1988). Status of the snow leopard *Panthera uncia* in Qinghai and Gansu provinces, China. *Biological Conservation* **45**, 179-194.

Shehzad, W., McCarthy, T. M., Pompanon, F., Purevjav, L., Coissac, E., Riaz, T., and Taberlet, P. (2012). Prey preference of snow leopard (*Panthera uncia*) in south Gobi, Mongolia. *Plos One* **7**, 1-8.

Shrestha, R. (2007). Coexistence of wild and domestic ungulates in the Nepalese Trans-Himalaya: Resource competition or habitat partitioning? (Norwegian University of Life Sciences: Aas, Norway.)

Shrestha, R. and Tenzin (2015). Population Status and Distribution of Snow Leopard (*Panthera uncia*) in Wangchuck Centennial National Park, Bhutan: A Technical Report. pp. 46. (Wangchuck Centennial National Park: Bumthang, Bhutan.)

Shrestha, R., Wangda, T., and Tashi, N. (2012). A report on population status and habitat utilization of naur (*Pseudois nayaur*) in Wangchuck Centennial Park, Bhutan. (Wangchuck Centennial Park: Bumthang, Bhutan.)

Shrestha, R. and Wegge, P. (2008). Wild sheep and livestock in Nepal Trans-Himalaya: coexistence or competition? *Environmental Conservation* **35**, 125-136.

Simcharoen, S., Pattanavibool, A., Karanth, K. U., Nichols, J. D., and Kumar, N. S. (2007). How many tigers *Panthera tigris* are there in Huai Kha Khaeng Wildlife Sanctuary, Thailand? An estimate using photographic capture-recapture sampling. *Oryx* **41**, 447–453. doi: 10.1017/S0030605307414107.

Snow Leopard Working Secretariat (2013). Global Snow Leopard Ecosystem Protection Program: A New International Effort to Save the Snow Leopard and Conserve High-Mountain Ecosystems. pp. 71. (Global Tiger Initiative Secretariat: Bishkek, Kyrgyz Republic.)

Suryawanshi, K. R., Bhatnagar, Y. V., and Mishra, C. (2012). Standardizing the double-observer survey method for estimating mountain ungulate prey of the endangered snow leopard. *Oecologia* **169**, 581-590.

Thinley, P. (2013). First photographic evidence of a Pallas's cat in Jigme Dorji National Park, Bhutan. *CatNews* **58**, 27-28.

Thinley, P., Dagay, Leki, Dorji, P., Namgyel, C., Yoenten, S., Phuntsho, and Dorji, T. (2014). Estimating snow leopard (*Panthera uncia*) abundance and distribution in Jigme Dorji National Park using camera traps: A technical report. pp. 45. (Jigme Dorji National Park: Gasa, Bhutan.)

Thinley, P., Dorji, S., Tempa, T., Wangchuk, N., Tandin, Namgyel, U., Tshewang, S., and Lham, D. (2015a). Counting the Tigers in Bhutan: Report on the National Tiger Survey of Bhutan 2014 - 2015. (Department of Forests and Parks Services, Ministry of Agriculture and Forests: Thimphu, Bhutan.)

Thinley, P., Morreale, S. J., Curtis, P. D., Lassoie, J. P., Dorji, T., Leki, Phuntsho, S., and Dorji, N. (2015b). Diversity, occupancy, and spatio-temporal occurrences of mammalian predators in Bhutan's Jigme Dorji National Park. *Bhutan Journal of Natural Resources and Development* **2**, 19-27.

Thinley, P., Tharchen, L., and Dorji, R. (2015c). Conservation management plan of Jigme Dorji National Park for the period January 2015 - December 2019: Biodiveristy conservation in pursuit of Gross National Happiness. pp. 110. (Department of Forests and Park Services: Gasa, Bhutan.)

Wang, S. W. and Macdonald, D. W. (2009). The use of camera traps for estimating tiger and leopard populations in the high altitude mountains of Bhutan. *Biological Conservation* **142**, 606-613. doi: DOI 10.1016/j.biocon.2008.11.023.

Wegge, P. (1979). Aspects of the population ecology of blue sheep in Nepal. *Journal of Asian Ecology* **1**, 1-10.

Wegge, P., Shrestha, R., and Flagstad, O. (2012). Snow leopard *Panthera uncia* predation on livestock and wild prey in a mountain valley in northern Nepal: implications for conservation management. *Wildlife Biology* **18**, 131-141.

Wikramanayake, E., Moktan, V., Aziz, T., Khaling, S., Khan, A. A., and Tshering, D. (2006). The WWF Snow Leopard Action Strategy for the Himalayan Region. pp. 21. (The World Wildlife Fund: Thimphu, Bhutan.)

Wilson, P. (1981). Ecology and habitat utilisation of blue sheep (*Pseudois nayaur*) in nepal. *Biological Conservation* **21**, 55-74.

Xu, A., Jiang, Z., Li, C., Guo, J., Da, S., Cui, Q., Yu, S., and Wu, G. (2008). Status and conservation of the snow leopard *Panthera uncia* in the Gouli Region, Kunlun Mountains, China. *Oryx* **42**, 460-463.

Zhang, M., Wang, X., Ding, Y., Zhang, Z., Wang, Z., Li, Z., Hu, T., and Ma, B. (2012). Population dynamics of blue sheep *Pseudois nayaur* in Ningxia Helan Mountain National Nature Reserve, China. *Folia Zoologica* **61**, 121-128.

List of figures:

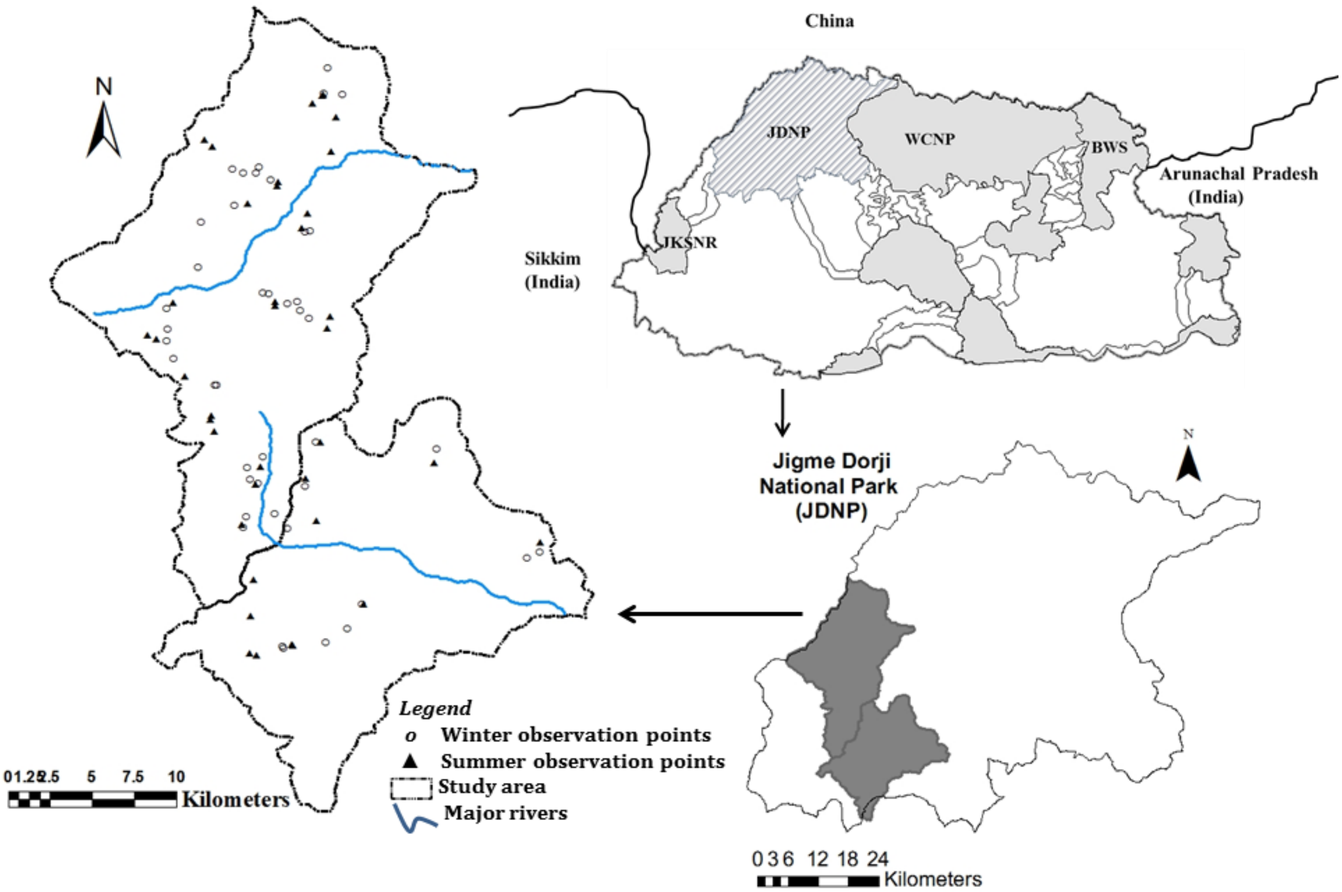

Figure 1. The map of Lingzhi Park Range in Bhutan's Jigme Dorji National Park, showing the survey areas and groups of blue sheep encountered during winter 2014 (hollow circles) and summer 2015 (filled triangles).

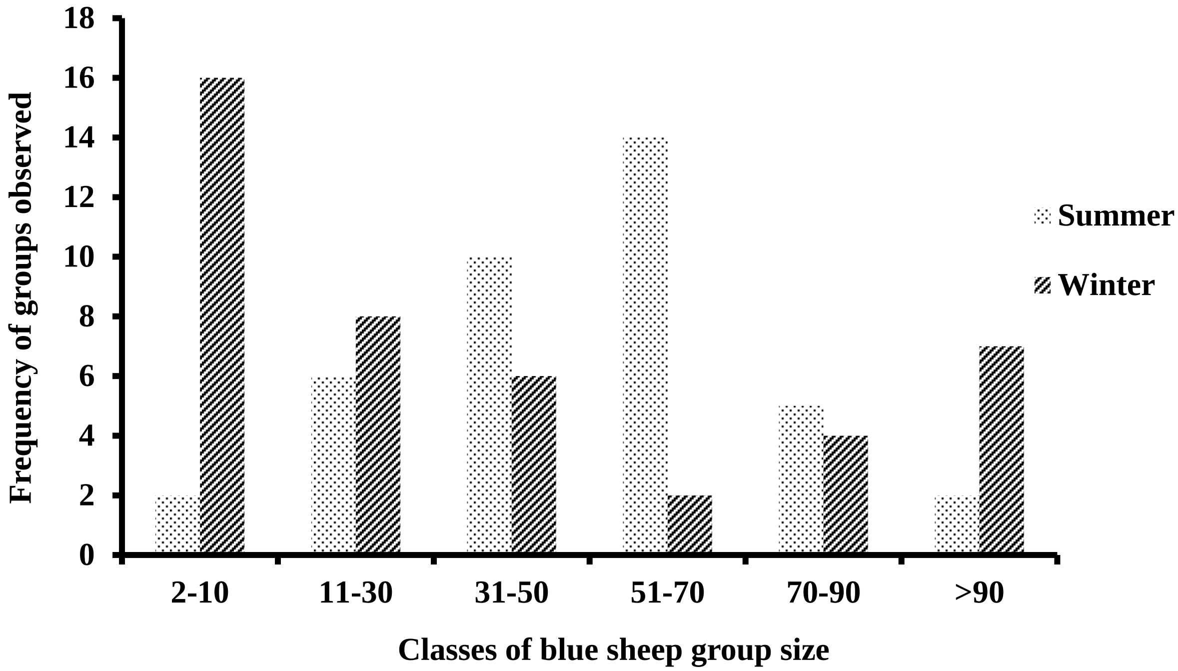

Figure 2: Blue sheep group sizes observed in winter of 2014 and summer of 2015 in Lingzhi Park Range of Jigme Dorji National Park, northwestern Bhutan.

List of tables:

Table 1. Summer and winter estimates of blue sheep population abundance ($\widehat{N}$) and detection rate (p) in Lingzhi Park Range of Jigme Dorji National Park using the double-observer survey and estimation method developed by (Forsyth and Hickling 1997). B represents the number of groups observed in common by both observers, while S_1 and S_2 represent the number of groups only observed by the first observer and second observer, respectively. $\hat{G}$ and $\hat{\mu}$ represent the estimated number of groups and average group size, respectively.

Variable	**Winter 2014 – 15**	**Summer 2015**
B	40	37
S_1	3	2
S_2	3	1
$\hat{G}$	46.22	40.05
Var($\hat{G}$)	0.25	0.06
$\hat{\mu}$	38.12	52.36
Var($\hat{\mu}$)	18	18
$\widehat{N}$	1,762	2,097
Var($\widehat{N}$)	39,511	29,566
SE ($\widehat{N}$)	199	172
SE ($\hat{\mu}$)	5.99	4.28
p_1	0.93	0.97
p_2	0.93	0.95