

# Standardizing the double-observer survey method for estimating mountain ungulate prey of the endangered snow leopard

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**Abstract** Mountain ungulates around the world have been threatened by illegal hunting, habitat modification, increased livestock grazing, disease and development. Mountain ungulates play an important functional role in grasslands as primary consumers and as prey for wild carnivores, and monitoring of their populations is important for conservation purposes. However, most of the several currently available methods of estimating wild ungulate abundance are either difficult to implement or too expensive for mountainous terrain. A rigorous method of sampling ungulate abundance in mountainous areas that can allow for some measure of sampling error is therefore much needed. To this end, we used a combination of field data and computer simulations to test the critical assumptions associated with double-observer technique based on capture–recapture theory. The technique was modified and adapted to estimate the populations of bharal (*Pseudois nayaur*) and ibex (*Capra sibirica*) at five different sites. Conducting the two double-observer surveys simultaneously led to underestimation of the population by 15%. We therefore recommend separating the surveys in space or time. The overall detection probability for the two observers was 0.74 and 0.79. Our surveys estimated mountain ungulate populations

(±95% confidence interval) of 735 (±44), 580 (±46), 509 (±53), 184 (±40) and 30 (±14) individuals at the five sites, respectively. A detection probability of 0.75 was found to be sufficient to detect a change of 20% in populations of >420 individuals. Based on these results, we believe that this method is sufficiently precise for scientific and conservation purposes and therefore recommend the use of the double-observer approach (with the two surveys separated in time or space) for the estimation and monitoring of mountain ungulate populations.

**Keywords** *Capra ibex* · Bharal · *Pseudois nayaur* · Ovis · Central Asia

## Introduction

The availability of wild ungulate prey is one of the most important determinants of large carnivore density (Karanth et al. 2004). Ungulates also play an important role in maintaining ecosystems by influencing the vegetation structure, plant species composition and nutrient cycling (McNaughton 1979; Bagchi and Ritchie 2010). Maintaining and monitoring ungulate populations is therefore an important objective of conservation management. Although several techniques have been developed for monitoring ungulate and large herbivore populations (e.g. distance sampling using line transect or point counts, Burnham et al. 1980; strip transect, Eberhardt 1978; track count, Sulkava and Liukko 2007; dung count, Laing et al. 2003; for review, see Seber 1992), these methods appear to perform differently under different field conditions (Singh and Milner-Gulland 2011). Estimating ungulate abundance in mountainous areas especially remains a challenge (Singh and Milner-Gulland 2011).

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Distance sampling has been one of the most popular methods for assessing the density of large herbivores in tropical and temperate forests (Buckland et al. 2001). However, this method is subject to many assumptions that are hard to meet in mountainous landscapes (Singh and Milner-Gulland 2011). Wingard et al. (2011) found this method to be imprecise in estimating the densities of argali *Ovis ammon* even in a relatively accessible mountainous terrain in south-west Mongolia. These authors also discuss the difficulty in obtaining random samples, the potential for unrecorded evasive movement and imprecision in recording perpendicular distances in mountainous terrain. Alternatively, Reading et al. (1997) successfully used distance sampling using aerial surveys to estimate the density of argali in the Gobi Desert of Mongolia. However, the aerial surveys are expensive and may even be dangerous in mountainous areas (Singh and Milner-Gulland 2011).

All of the continents have extensive mountain systems. In some cases, such as the Southern Alps of New Zealand, introduced ungulate species have become invasive and are detrimental to the native flora of the region (Tustin 1990). Several mountain ungulate species, such as the markhor (*Capra falconeri*) [Red List category, ver. 3.1: endangered C1 + 2a(I)], Nubian ibex (*Capra nubiana*) [vulnerable C1 + 2a(I)], dwarf blue sheep (*Pseudois schaeferi*) (endangered A2), are also threatened and in need of immediate conservation attention (IUCN 2011). Many are endemic to the mountains where they occur, such as the Nilgiri tahr (*Nilgiritragus hylocrius*) and the Ethiopian ibex (*Capra walie*) (Mishra and Johnsingh 1998; Yalden and Lagen 1992). Carnivore species, including the endangered snow leopard (*Panthera uncia*), puma (*Puma concolor*) and Tibetan wolf (*Canis lupus chanco*), depend almost exclusively on these mountain ungulates for prey. Thus, reliable population estimation and monitoring are necessary to devise effective conservation strategies for these ungulates and the carnivores that depend on them.

Most studies of ungulates in mountainous terrain have depended on total counts of the population or used some indirect index of abundance (e.g. Schaller et al. 1988; Oli 1994; Mishra et al. 2004; Bagchi and Mishra 2006; McCarthy et al. 2008; Lovari et al. 2009a, b; Suryawanshi et al. 2010). Although it may be possible to make a total count of a population with reasonable precision over relatively smaller areas (up to 100 km<sup>2</sup>) if the survey season is chosen carefully (Mishra et al. 2004), the precision of this approach can be questioned when attempted over larger areas (see Wingard et al. 2011). Also, censuses do not allow for an estimation of error to enable statistical comparison of changes in population over time (Yoccoz et al. 2001). On the contrary, although indirect indices of herbivore abundance allow statistical comparison, they do not provide reliable estimates of population number, which is

often the goal of monitoring programmes (Yoccoz et al. 2001). Thus, an inexpensive but rigorous, reliable and replicable method of sampling ungulate abundance in mountainous terrain, which can allow for some measure of sampling error, is much needed.

The double-observer technique for population estimation was originally developed to estimate the detection probabilities of aerial surveys of various taxonomic groups (Caughley 1974; Cook and Jaconson 1979; Graham and Bell 1989). Magnusson et al. (1978) modified the original equation proposed by Caughley (1974) to allow for observer differences in the ability to detect the target species. This technique is based on the principles of mark-recapture theory. In general, the technique involves two observers searching for and counting animals simultaneously, while ensuring that they do not cue each other on the locations of the animals. The technique capitalizes on the fact that theory allows for population size to be estimated based on just two surveys (Electronic Supplementary Material).

Forsyth and Hickling (1997) made an important contribution to the population estimation literature by applying the double-observer approach for estimating the abundance of Himalayan tahr (*Hemitragus jemlahicus*) in New Zealand. The technique also appears to be potentially useful for monitoring the populations of snow leopard prey in the mountainous areas of the Himalayas and Central Asia. However, some aspects of the use of this technique for mountain ungulates and associated assumptions remain untested (Table 1). Using a combination of field data and computer simulations, we have assessed the general suitability of this method and suggest improvements in this technique for the long-term monitoring of mountain ungulate populations.

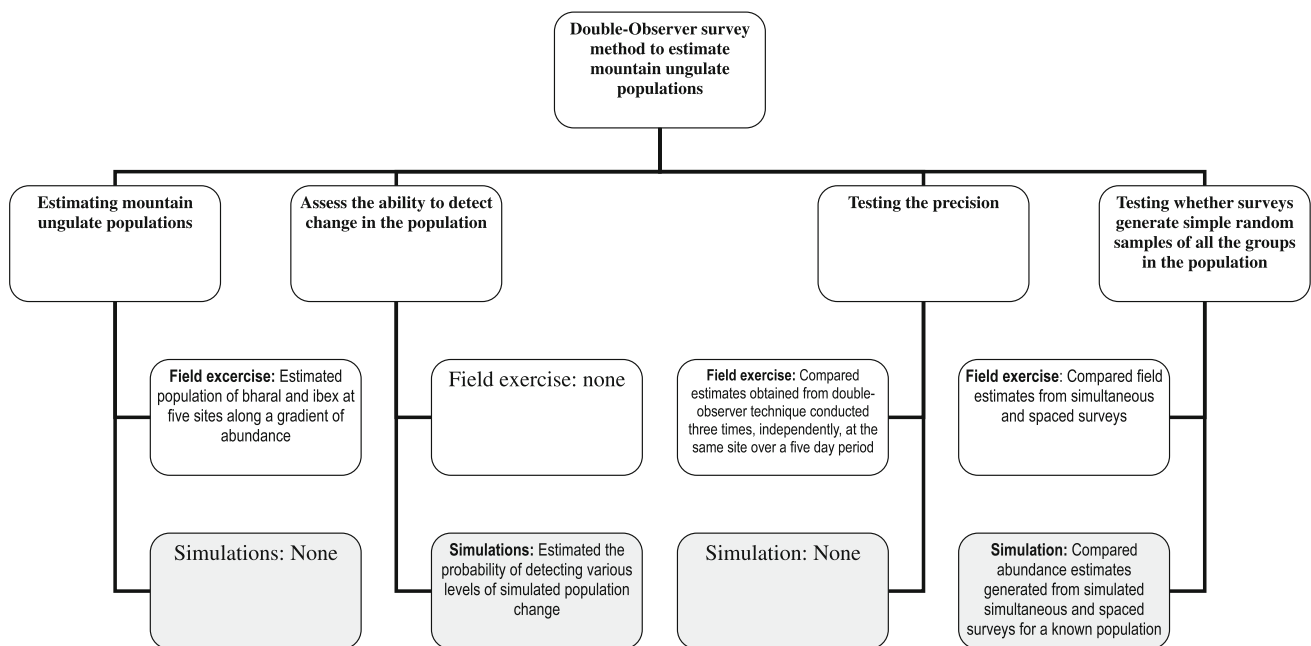
In our study, we used bharal (*Pseudois nayaur*) and ibex (*Capra sibirica*)—two of the most important prey species of the snow leopard—as our model taxa. Forsyth and Hickling (1997) allow for simultaneous as well as temporally spaced surveys in the double-observer technique, and we tested and compared the results of both these methods (Fig. 1). The precision of the population estimates was assessed and the ability or ‘power’ of the double-observer technique to detect varying levels of change in any population was evaluated (Fig. 1). Based on our results, we are able to suggest ways of enhancing this ability. Lastly, our results indicate the robustness of the technique by reliably estimating mountain ungulate populations across a gradient of population abundance.

## Study area

The study was carried out in the Spiti River Valley (32°00′–32°42′N; 77°37′–78°30′E), Lahaul and Spiti

**Table 1** List of critical assumptions involved in obtaining unbiased estimates of a population using the double-observer survey method (Caughley 1974; Magnusson et al. 1978) and our approach to address these

Assumption	Our approach
Each animal group detected can be individually identified (Otis et al. 1978; Seber 1982)	We relied on post-survey discussion between the two observers to ascertain the unique identity of each herd sighted during each pair of surveys using information on group size, age–sex classification of the groups and location and time of sighting each group, following Forsyth and Hickling (1997)
The population being surveyed should be closed during the period of the two surveys	1. Study areas are delineated by high mountain ridges (approx. 5,700 m a.s.l.) 2. Each study area was further divided into survey sites of 20–30 km <sup>2</sup> 3. Each of these smaller areas was surveyed separately to ensure that no gaps larger than daily movement of the species were left out of the survey 4. Surveys were conducted within a few hours of each other to ensure that groups did not split or merge between the two surveys, leading to a change in the number of groups present.
The surveys generate simple random samples of all the groups in the population	We tested this assumption using field data and computer simulation (Fig. 1)



**Fig. 1** Summary of the objectives and methods employed in our study designed to assess the general suitability and suggest improvements to the double-observer technique for long-term monitoring of mountain

ungulate populations. *Shaded boxes* indicate use of computer simulations

District, Himachal Pradesh, India. The river valley is approximately 12,000 km<sup>2</sup> in size and contains two protected areas: the Pin Valley National Park and the Kibber Wildlife Sanctuary. In this large landscape, we selected five sites, denoted Pin, Lossar, Tabo, Lingti and Kibber (approx. 350 km<sup>2</sup> each), with an expected gradient of wild ungulate densities. The study area has an altitudinal range from 3,300 to 6,000 m a.s.l. The terrain is rugged with rocky ridges and rolling hills broken occasionally by rocky cliffs and outcrops. During winter the temperature drops down to –35°C, and in the summer the mean maximum temperature is around 25°C. Precipitation is mainly in the form of winter snow. The winter snow starts to melt around late March.

The vegetation is ‘dry alpine steppe’ (Champion and Seth 1968). Very few shrubs exceed a height of 1 m. The vegetation is mainly dominated by shrubs, such as *Caragana brevifolia* and *Lonicera spinosa*, and graminoids, such as *Stipa*, *Carex* and *Kobresia*. People of the region are mainly agro-pastoralists. Green peas *Pisum sativum*, black peas (local variety of peas) and barley *Hordeum vulgare* form the main agricultural crops. Domestic livestock includes goat *Capra hircus*, sheep *Ovis aries*, horses *Equus caballus*, donkeys *E. asinus*, cows *Bos indicus* and yak *B. grunniens* and *dzomo* (cow–yak hybrid). Wild herbivores of the region include ibex, bharal and hare *Lepus oiostolus*. Predators include snow leopard, wolf, red fox *Vulpes vulpes* and golden eagle *Aquila chrysaetos*.

## Methods

### Addressing basic assumptions

While Forsyth and Hickling (1997) suggest that both the surveys can be conducted simultaneously, our preliminary surveys indicated that this approach could lead to the violation of the assumption that the two surveys should represent simple random samples of the entire population (Table 1). In the field, the probability that an observer detects a group largely depends on the activity of the animals in that group, the distance of the group from the observer and the local topography. Note that the probability being discussed is  $p_{sI}$ , which is the probability of observer 's' detecting the 'Ith' group (henceforth referred to as 'group-specific detection probability'). In simultaneous surveys, even though the observers do not cue each other, both the distance of the animal group to both of the observers and the activity of the animals is similar for both sets of observers. Thus, the probability of any group being detected by each of the set of observers is similar ( $p_{s1I} \approx p_{s2I}$ , where s1 and s2 are the two observers, respectively; i.e. the group-specific detection probability is similar for both observers). This can lead to overestimation of 'observer-specific detection probability' and thus underestimation of the number of groups. We tested for this potential bias and violation of assumption by conducting simultaneous and spaced surveys of the same animal population.

### Simultaneous or spaced surveys

Whether simultaneous surveys could indeed lead to an underestimation of the population through computer simulations were tested and field data were used to validate the results.

### Simulations

In a computer simulation, we created 50 groups that were randomly assigned group-specific detection probabilities drawn from a uniform distribution between 0.1 and 0.9 at each step. We ran two scenarios 1,000 times each. In the first scenario, the observers (s1 and s2) detected groups based on these detection probabilities that remained the same for both of them ( $p_{s1I} = p_{s2I}$ ), i.e. the group-specific detection probability remained the same for both observers. This represents a field situation where both observers conduct surveys simultaneously, and the probability that a particular group is detected remains similar between both surveys. Estimates obtained from these surveys were then tested against the known abundance of 50 groups in this simulated exercise.

In the second scenario, both observers detected the groups based on the randomly generated detection proba-

bilities as described earlier, but the group-specific detection probabilities in this exercise were randomly generated twice from a uniform distribution: once for each observer (thus,  $p_{s1I} \neq p_{s2I}$ ). This scenario represents a situation where the two surveys are separated in time and the probability that a particular group is detected is different for both observers.

We analysed four different versions of this simulation exercise, each with different randomly assigned detection probabilities: (1) version 1, the groups were randomly assigned detection probabilities of between 0.1 and 0.9; (2) version 2, randomly assigned detection probabilities ranged between 0.3 and 0.9; (3) version 3, randomly assigned detection probabilities ranged between 0.45 and 0.9; (4) version 4, randomly assigned detection probabilities ranged between 0.6 and 0.9. The first version depicts a situation where the observers are not familiar with the landscape or the distribution of animals, leading to very low detection probabilities for at least some of the animal groups. The fourth version depicts a situation where observers are familiar with the landscape, and thus almost all groups have a high probability of being detected (e.g. areas with long-term monitoring). Versions 2 and 3 depict intermediate situations. The estimates obtained from both scenarios of the four versions were compared with each other and with the actual number of groups.

### Field exercise

We chose a relatively isolated area of approximately 250 km<sup>2</sup> in the Pin Valley National Park and conducted double-observer surveys to estimate the abundance of ibex in this area. The exercise was conducted twice. In the first exercise, both observers conducted the survey simultaneously, ensuring that they did not cue each other on the location of the groups. In the second exercise, both observers chose their own best path to survey the study area as long as they ensured complete visual coverage, with the second observer starting the survey 1 h after the first observer. Each survey site was surveyed for 5 h at an average walking speed of 2 km per hour. Thus, in the second exercise, both observers were separated in time and space (i.e. the survey route), although both counted in the same study area. We compared the population abundance obtained in each of the exercises to see if the population estimate obtained from simultaneous surveys was indeed lower than that obtained when the surveys were spaced.

### Assessing the precision of abundance estimates

To test if repeated double-observer surveys yielded consistent estimates, we chose an area of approximately 150-km<sup>2</sup> in the Kibber Wildlife Sanctuary. We repeatedly conducted

double-observer surveys to estimate the abundance of bharal in this area on three different occasions separated by 2 days each. Both observers were free to choose their path of search during all three surveys. On all three occasions the second observer started 1 h after the first observer.

#### Estimating populations across a gradient of abundance

Bharal and ibex populations were estimated in five different areas in the catchment of the Spiti River (Pin, Lossar, Tabo, Lingti, and Kibber). Independent estimates of bharal and ibex abundance were obtained for each of these five areas. Each study area was further divided into smaller survey sites of 20–30 km<sup>2</sup> depending on the size and topography of the area, with Pin, Lossar, Tabo, Lingti and Kibbe divided into 16, 7, 14, 11 and 14 survey sites and surveyed within 2, 1, 2, 3 and 2 days, respectively. A survey site was considered to be a set of adjoining sub-catchments, separated from the next survey site by a ridge. Data from all smaller survey sites for each area were pooled for analysis. Since the surveys were conducted in late winter and early spring (March–June 2010), all of the ridges were covered with snow, allowing minimum movement of animals across them. Two observers surveyed each of these survey sites by walking along predetermined trails and scanning surrounding areas using a pair of 8 × 40 binoculars from predetermined points. The second observer started the survey 60 min after the first. This protocol precluded any visual cue that an observer could provide unintentionally; for example, prolonged interest in a particular direction by one observer could otherwise tip the other observer on the location of a group. The observers recorded the group size, age–sex classification, the pasture name where the group was encountered and any other comments that could help in a distinct identification of the observed groups. At the end of the survey the observers discussed and identified the groups seen by both of them. All available information, such as group size, age–sex classification, location (pasture name) and other comments, were used in the identification of individual groups. Care was taken to end the day's survey at a natural boundary, such as a ridgeline or river where animals were unlikely to cross over.

#### Ability to detect population trends

We conducted computer simulations informed by field data to assess the ability of the field technique to detect actual changes in a given population over time. We simulated 10, 35, 70 and 165 groups with a mean group size of 12 individuals and a variance of 0.02. The groups correspond to populations averaging 120, 420, 840, and 1,980 individuals, respectively. A population comprising 10, 35 and 75 groups represent small, moderate and large populations, respec-

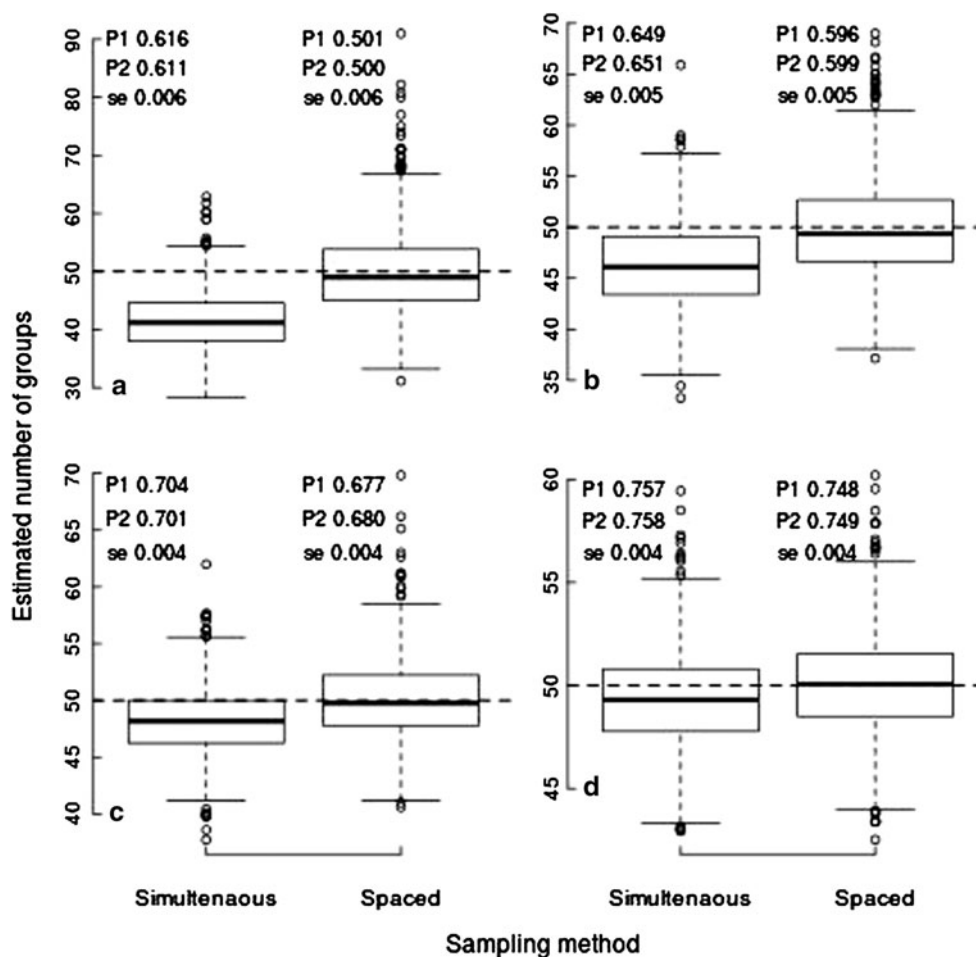
tively, in relation to our estimates from the field. 'Captures' of these groups were simulated by each of the two observers to estimate the population size using the double-observer survey framework. We then changed the population by a known percentage value and repeated the double-observer survey to estimate the new population size. These two estimates were then compared following Forsyth and Hickling (1997) to examine the probability of detecting the change at  $p < 0.05$ . The exercise was repeated 500 times, where the population was increased by 250-fold and decreased by 250-fold, respectively; we then calculated the proportion of times a change in the population was detected. We varied the detection probabilities of the observers from 0.05 to 1 at intervals of 0.05. The population was increased or decreased from 0 to 100% at intervals of 5%, and we then repeated the exercise 500 times for each combination of group size (10, 35, 70, 165), calculating the percentage change in the population (0–100% at each 5% interval; population was increased and decreased by the percentage value 250 times each), and each observer detection probability (0.05–1 at intervals of 0.05). For the combinations where we could detect an increase or decrease in the population for >95% of the time, we assumed that the probability of committing a type-2 error (i.e. falsely concluding that the population has not changed when in fact it has) was <0.05. The statistical significance of the differences in population abundance estimates were assessed using the  $z$  test following Forsyth and Hickling (1997).

## Results

### Simultaneous or spaced surveys

Our simulation model showed that when both observers had the same probability of detecting a group (group-specific detection probability in simultaneous surveys) and groups were randomly assigned a probability between 0.1 and 0.9, the median of the estimated number of groups was 15% lower than the actual number of groups present, and the mean estimated observer-specific detection probability was 0.616 [standard error (SE) 0.006] and 0.611 (SE 0.006) for observer one and two, respectively. On the other hand, the median of number of groups was estimated precisely when the group-specific detection probability varied between the two observers and the estimated observer-specific detection probability was significantly lower than 0.501 (SE 0.006) and 0.500 (SE 0.006), respectively ( $t$  score = 23.01;  $p$  value <0.005; spaced surveys; Fig. 2a). In the second version, where groups were randomly assigned a detection probability of between 0.3 and 0.9, the median of the estimates obtained from the first scenario (depicting simultaneous surveys) was 10% lower than the

**Fig. 2** Box and whiskers plot of population abundance estimates obtained through two types of simulated double-observer surveys. *Simultaneous* represents the scenario where the probability of a group being detected is the same for both observers, *Spaced* represents the scenario where the probability of a group being detected varies between observers. The simulated herds were randomly assigned a detection probability between **a** 0.1 and 0.9, **b** 0.3 and 0.9, **c** 0.45 and 0.9, and **d** 0.6 and 0.9. See “Methods” for details. *Horizontal dashed line* Actual known population,  $P_1$ ,  $P_2$  mean of the estimated detection probability for observer one and two, respectively. The standard error (*se*) of both  $P_1$  and  $P_2$  were always the same to the third decimal and therefore are written only once



actual number of groups (Fig. 2b). In the third and fourth versions, the median of the estimates obtained from simultaneous surveys was only 5 and 1% lower than actual number of groups, respectively (Fig. 2c, d). In all four versions, the mean estimated observer-specific detection probability for simultaneous surveys was always significantly higher than that for spaced surveys (Fig. 2). On the contrary, in all four versions, the median of the estimates obtained from simulated spaced surveys always equalled the actual number of groups present (Fig. 2).

In the field exercise, simultaneous double-observer surveys conducted in Pin estimated the ibex population to be  $110 [\pm 12.6, 95\% \text{ confidence interval (CI)}]$  individuals, which was in line with our expectation but lower than that obtained for the same population ( $143 \pm 30.4, 95\% \text{ CI}$ ) through spaced surveys where the observers were separated by 60 min. The estimated observer-specific detection probabilities for the two observers were respectively 0.875 and 0.875 for the simultaneous and 0.75 and 0.66 for spaced surveys. Thus, in line with our expectation and as predicted by the simulation exercise, the population estimate obtained through simultaneous surveys was significantly lower than that obtained when observers were spaced in time

( $p = 0.02$ ,  $z$  score). Also, the observer detection probabilities were higher for simultaneous surveys than for spaced surveys.

#### Assessing the precision of the abundance estimates

Bharal abundance estimates for the same population using spaced double-observer surveys on three separate occasions were  $450 (\pm 39; 95\% \text{ CI})$ ,  $436 (\pm 39)$  and  $456 (\pm 30)$ , respectively.

#### Estimating bharal and ibex populations across a gradient of abundance

The abundance of bharal and ibex was estimated at five sites in Spiti Valley. These abundance data and data on other parameters are summarized in Table 2. The total count of individual observers was always lower than the estimate obtained from the double-observer technique ( $p < 0.05$ ,  $z$  test). The cumulative total count of both observers (based on all unique groups observed by either of the observers) was also always lower, although the difference was not statistically significant (Fig. 3). The overall

**Table 2** Abundance estimates of bharal and ibex populations obtained using spaced double-observer surveys in five different sites in Spiti Valley

Variable	Kibber (Blue sheep) <sup>a</sup>	Kibber (Ibex) <sup>a</sup>	Kibber total <sup>b</sup>	Tabo (Blue sheep)	Pin (Ibex)	Lossar (Ibex)	Lingti (Blue sheep)	Overall (Blue sheep and Ibex) <sup>c</sup>
<i>C</i>	34	3	37	25	7	1	25	96
<i>S</i> <sub>1</sub>	8	1	9	14	3	1	6	33
<i>S</i> <sub>2</sub>	8	0	8	6	4	1	7	25
$\hat{G}$	51.8	4	55.9	48.2	15.5	3.5	39.6	162.5
Var ( $\hat{G}$ )	2.68	0	2.76	5.89	2.75	0.75	2.42	14.2
$\hat{U}$	13.1	11.3	13.1	10.6	11.9	8.6	15.0	12.6
Var ( $\hat{u}$ )	0.05	2.76	0.01	0.02	0.18	0.07	<0.005	<0.005
<i>N</i>	678	45	735	509	184	30	593	2,049
Var ( <i>N</i> )	593.5	44.1	494.1	706	400.1	52.9	546	2,339.6
±95% confidence interval	48	13	44	53	40	14	46	96
Total area (km <sup>2</sup> )	411	411	411	341	497	219	186	1,654
Density	1.65	0.11	1.79	1.49	0.37	0.14	3.19	1.26
Distance walked per survey (km)	99	99	99	87	91	90	97	464
<i>P</i> <sub>1</sub>	0.8	1	0.82	0.81	0.63	0.5	0.75	0.79
<i>P</i> <sub>2</sub>	0.8	0.75	0.8	0.64	0.7	0.5	0.8	0.74

*C*, Number of groups seen in both surveys; *S*<sub>1</sub>, number of groups seen in first survey only; *S*<sub>2</sub>, number of groups seen in second survey only;  $\hat{G}$ , estimated number of groups; *N* estimated population; *P*<sub>1</sub>, *P*<sub>2</sub>, mean of the estimated detection probability for observer one and two, respectively. Sites Lossar and Pin are occupied exclusively by ibex; sites Tabo and Lingti have only bharal; Kibber has both ibex and bharal

<sup>a</sup> Estimates of bharal and ibex separately for site Kibber

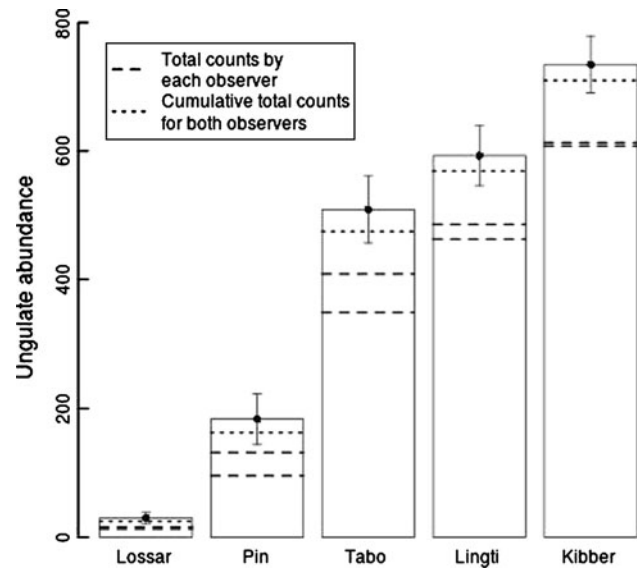
<sup>b</sup> Combined bharal and ibex estimates

<sup>c</sup> Estimates obtained from pooled data from all sites

detection probability was 0.74 and 0.79 for the two observers, respectively. According to site, the detection probability was lowest (0.5 for both observers) at Lossar and highest (0.82 and 0.80, respectively, for each observer) at Kibber. High detection probabilities were also found at Lingti (0.75 and 0.80, respectively, for each observer) and Tabo (0.81 and 0.64, respectively, for each observer). The mountain ungulate (bharal and ibex) abundance estimates ranged from 30 individuals for site Lossar and 735 for Kibber. Mean group size varied from 8.6 at site Lossar to 13.1 at Kibber, with an overall mean of 12.6 (± <0.005) individuals per group.

Ability to detect population changes

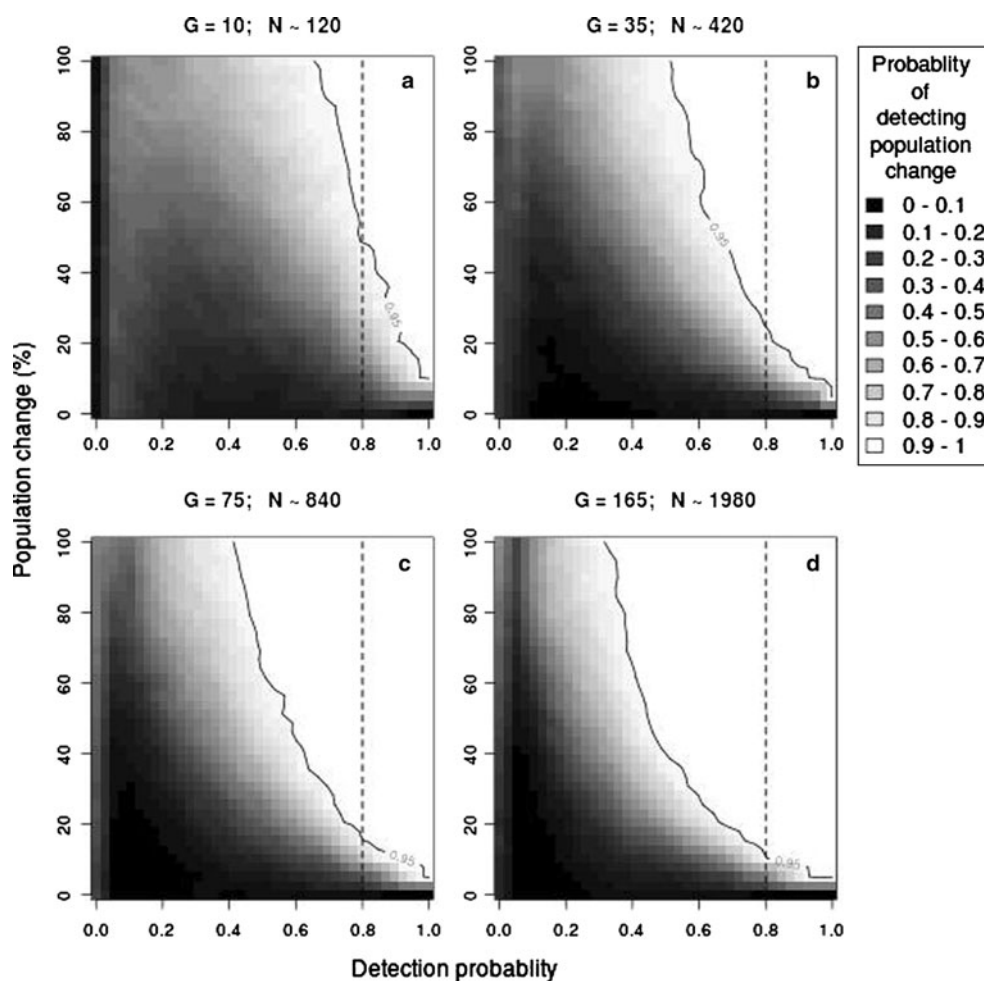
Computer simulations were conducted to assess the ability of the spaced double-observer technique in detecting changes in mountain ungulate populations over time. Our results showed a 95% probability of detecting a 15% change in the population of any size (10, 35, 70 and 165 groups comprising 120, 420, 840, 1,980 individuals, respectively) at an observer detection probability of 0.95. For the smallest population (10 groups comprising 120 individuals), we were able to detect a change of approximately 35–40% (48 individuals) at an observer detection



**Fig. 3** Mountain ungulate abundance estimates obtained using spaced double-observer surveys at five different sites in Spiti Valley. *Dashed lines* Total counts of individual observers, *dotted lines* total counts of both observers combined. *Error bars* represent 95% CI

probability of 0.8 with 95% certainty. An observer detection probability of 0.8 is a more realistic estimate, as was obtained from the field data. At this detection probability, a

**Fig. 4** The probability of detecting different levels of change in mountain ungulate populations using spaced double-observer surveys at various observer detection probabilities. Figure parts represent a gradient of population sizes from **a** 10, **b** 35, **c** 75, and **d** 165 ungulates groups. *Continuous line* 0.95 probability contour, *dashed line* detection probability of 0.80, which represents a realistic observer detection probability, as obtained from field data,  $G$  number of groups,  $N$  number of individuals used in the particular simulation



change of 25% (30 individuals) in the smallest sized population could be detected on 75% of the occasions. The probability of detecting a change in small populations such as this one declined rapidly with a reduction in observer detection probability (Fig. 4). A population decline/increase of 20% was detected with 95% certainty at an observer detection probability of 0.8 for all other population sizes (i.e. 35, 70 and 165 groups comprising 420, 840 and 1,980 individuals). The probability of detecting a change in the population declined with a reduction in the detection probability, but the rate of decline was slower for larger populations than for smaller ones.

## Discussion

The double-observer survey method uses the robust framework of mark–recapture theory to estimate population size (Caughley 1974). We have tested the critical assumptions of this technique, modified and applied it to a problem situation and finally conducted an analysis to estimate the ability of the technique to detect actual population change.

We first tested whether conducting both surveys simultaneously for mountain ungulates, as allowed by its proponents (Forsyth and Hickling 1997), would actually lead to underestimation of the population size. Our computer simulations confirmed the latter, especially when animal groups were randomly assigned detection probabilities that included lower values starting from 0.10. Computer simulations showed that, in the field, if the detection probability for certain groups was  $<0.50$ , then simultaneous surveys could underestimate the number of groups by approximately 15% and overestimate the observer-specific detection probability by approximately 10%. However, if the detection probability for all groups was likely to be higher ( $c > 0.50$ ), then the estimates from simultaneous surveys were almost equal to spaced surveys and true values. This result suggests that simultaneous surveys might still be useful in areas where observers are familiar with the landscape and the distribution of animals but that in new areas, spacing between the two observers will be necessary. Simulation results were borne out by our field exercise, where the estimation of the ibex population obtained from simultaneous surveys was 20% lower than the estimate obtained



from spaced surveys. Thus, we suggest that the observers be separated in time and or that they use separate survey routes while counting animals in the same area, especially if a significant number of groups are expected to have detection probabilities of  $<0.5$ .

Based on observations made on the bharal and ibex during previous studies in our study area (Suryawanshi et al. 2010; K. R. Suryawanshi, Nature Conservation Foundation, unpublished data), we used a 60-min separation period between the two observers, which was sufficient to capture changes in the activity and location of groups, leading to a change in the probability of detection by each of the two observers. This modification allows a surveyor to avoid violating the critical assumption of mark–recapture (and double-observer) theory that each survey is a simple random sample of the entire population. In the field, this can be achieved by (1) both observers starting the survey from different ends of the survey trail covering the entire area; (2) if surveying a valley, each observer can use different ridge lines to survey the valley, ensuring that both the ridges provide a complete view of the entire valley; (3) both observers can chose two different paths but should ensure that both the paths allow visual coverage of the entire area to be surveyed.

All these three methods also separate the observers in time, leading to a more independent sampling of the population. We also recommend that efforts be put into understanding the behaviour and ecology of the target species as well as the geography of the landscape to decide on how best to separate the observers in either time or space.

Our repeated surveys of the same mountain ungulate population on different days suggest that the method is sufficiently precise for scientific and conservation purposes. While we could not test the method for accuracy in the field (as we did not have sites with known population sizes), our computer simulations suggest that the method is also accurate in estimating the actual population size (Fig. 2a).

As our third objective we employed the double-observer survey methods with observers separated in time and space to estimate ungulate abundance at five different sites. We used this method in areas with an expected gradient of mountain ungulate densities based on previous knowledge. Across these sites, our surveys yielded robust population estimates for comparison in the future. Although in accordance with Forsyth and Hickling (1997) we used the total area surveyed to arrive at the density estimate, we recommend that future work focus on a better estimation of the effective area sampled.

Finally, we used computer simulations to estimate the observer detection probabilities necessary to detect finer level population changes at various population sizes. Our results suggest that a detection probability ranging between

0.7 and 0.8 is sufficient to detect a change of 20% in populations comprising more than 420 individuals. For smaller populations (approx. 100 individuals), we suggest that the investigators channel their efforts towards improving the detection probability to achieve detection probabilities of  $>0.85$  to detect a change of up to 30% of the original population.

#### Management implications

Estimating mountain ungulate abundance and density has remained a challenge in most mountain regions of the world. While current monitoring methods, such as total count and indices of abundance, provide population trends, these methods cannot be used for statistical comparisons over time or across space. We have refined the double-observer method to estimate mountain ungulate abundance with greater precision and accuracy. Our results show that the double-observer method is precise and statistically robust with sufficient power to detect changes in population.

Effective conservation of endangered carnivores, such as the snow leopard, demands efficient conservation of their mountain ungulate prey. Currently, almost no robust estimates of abundance and densities of snow leopard prey species, such as the Himalayan ibex, markhor and bharal, exist. Hunting, habitat modification, increased livestock grazing, disease and development are the major current threats faced by most mountain ungulate species (McCarthy and Chapron 2003). It is important to have robust estimates of mountain ungulate populations in order to be able to estimate the effectiveness of conservation intervention measures. Due to the remoteness and lack of scientific expertise in most mountainous areas of the world, Singh and Milner-Gulland (2011) suggest participatory monitoring of mountain ungulates with local people to complement scientific surveys. The double-observer survey is a simple, cheap and relatively fast method while also being statistically robust and sufficiently precise for ecological studies. We recommend the use of the double-observer method in participatory monitoring efforts as it provides a robust platform to plan long-term mountain ungulate population monitoring as well as scientific studies demanding robust population estimates. Finally, we would like to point out that while we have attempted to evaluate and improve the double-observer technique as a robust field method for enumerating mountain ungulates, we have not addressed the issue of spatial variation in this paper. Depending on the expected pattern of spatial variation and size of the study area, appropriate stratification is recommended to identify the specific survey sites, which can then be sampled using the double-observer technique (Yoccoz et al. 2001).

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