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Estimating Snow Leopard Population Abundance Using Photography and Capture–Recapture Techniques

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Abstract

*Conservation and management of snow leopards (*Uncia uncia*) has largely relied on anecdotal evidence and presence–absence data due to their cryptic nature and the difficult terrain they inhabit. These methods generally lack the scientific rigor necessary to accurately estimate population size and monitor trends. We evaluated the use of photography in capture–mark–recapture (CMR) techniques for estimating snow leopard population abundance and density within Hemis National Park, Ladakh, India. We placed infrared camera traps along actively used travel paths, scent-sprayed rocks, and scrape sites within 16- to 30-km^2 sampling grids in successive winters during January and March 2003–2004. We used head-on, oblique, and side-view camera configurations to obtain snow leopard photographs at varying body orientations. We calculated snow leopard abundance estimates using the program CAPTURE. We obtained a total of 66 and 49 snow leopard captures resulting in 8.91 and 5.63 individuals per 100 trap-nights during 2003 and 2004, respectively. We identified snow leopards based on the distinct pelage patterns located primarily on the forelimbs, flanks, and dorsal surface of the tail. Capture probabilities ranged from 0.33 to 0.67. Density estimates ranged from 8.49 (SE = 0.22) individuals per 100 km^2 in 2003 to 4.45 (SE = 0.16) in 2004. We believe the density disparity between years is attributable to different trap density and placement rather than to an actual decline in population size. Our results suggest that photographic capture–mark–recapture sampling may be a useful tool for monitoring demographic patterns. However, we believe a larger sample size would be necessary for generating a statistically robust estimate of population density and abundance based on CMR models.*
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Key words

abundance, camera trap, capture–mark–recapture, density estimation, identification, India, photography, snow leopard, Uncia uncia.

Solitary felids like tiger (*Panthera tigris*) and snow leopard (*Uncia uncia*) are notoriously difficult to enumerate (Karanth and Nichols 1998). Indirect pugmark sampling fails to address fundamental questions related to observability and spatial sampling and has not been adequately calibrated to areas of known density (Karanth et al. 2003). Special problems arise from the extensive range, low densities, and cryptic nature of snow leopards (Schaller 1977). They inhabit high mountain ranges usually between 3,000 to >5,000 m, where on-the-ground access taxes even the most determined researcher (Jackson and Fox 1997). In addition, the snow leopard inhabits a relatively prey-poor, high-elevation ecosystem, so surveys are plagued by small sample size and low capture probabilities.

Snow leopards inhabit mountainous regions of Central Asia where they are thinly distributed across a vast area in excess of 1.2 million km^2 (Nowell and Jackson 1996). Total numbers have been crudely estimated at 4,500–7,500 individuals across 12 countries: China, Bhutan, Nepal, India, Pakistan, Afghanistan, Tajikistan, Uzbekistan, Kyrgyzstan, Kazakhstan, Russia, and Mongolia. The status and distribution of snow leopards are poorly defined due to lack of funding, inadequately trained personnel, and logistical difficulties of conducting surveys throughout their range. Population density estimates are limited to a few studies involving radiotelemetry (Jackson and Ahlborn 1989, Oli 1994, McCarthy 2000).

To date, conservationists have depended largely on sign (e.g., scrapes, feces, and pugmarks) left by snow leopards to obtain presence–absence data and indices of relative abundance (Fox et al. 1991, Jackson and Hunter 1996). Sign abundance is tallied along fixed transects and compared with sign frequencies from areas with known snow leopard numbers based on radiotelemetry studies (Jackson 1996, McCarthy 2000). Unfortunately, the relationship between sign frequency and leopard density is poorly understood and difficult to quantify in view of numerous confounding factors (Ahlborn and Jackson 1988). To ensure populations of snow leopard persist, conservationists need to know far more about the species' distributional pattern and population trends over manageable time periods. Repeated and consistent monitoring is needed to detect population or range changes, vital for evaluating the effectiveness of conservation investments targeting snow leopards. To this end, census tools used must be accurate, reliable, cost-effective, and reasonably easy to apply. Karanth et al. (2003) reviewed the efficacy of the tiger "pugmark census method," upon which Indian protected-area managers have relied for over 30 years, concluding it is fundamentally flawed in its underlying assumptions and, therefore, lacking in necessary statistical rigor. Fortunately a new suite of noninvasive techniques (e.g., remote camera trapping and genotyping of DNA contained in hair and scats) offers hopeful prospects for estimating population size with greater accuracy, precision, and scientific rigor, albeit at higher cost. Karanth (1995) demonstrated the feasibility of using photographic captures and recaptures to estimate tiger population size, later refining sampling procedures for assessing population size across representative protected areas

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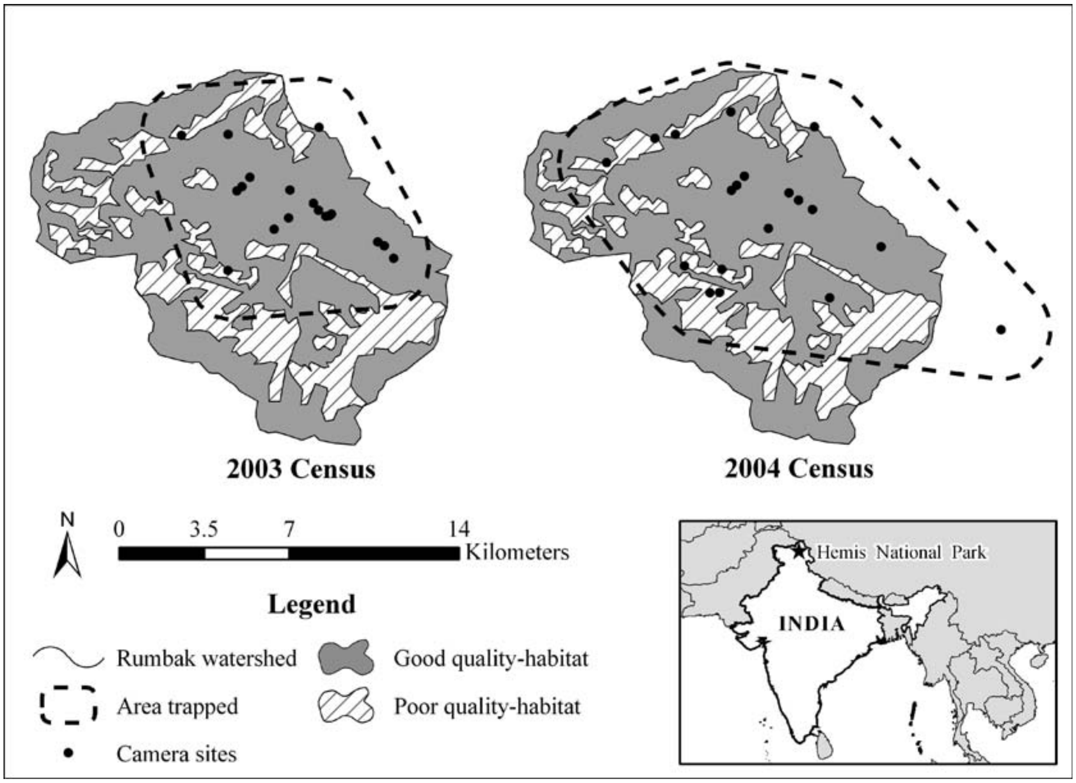

Figure 1. Location of core study area within Hemis National Park, Ladakh, India, showing camera-trap layout for 2003 and 2004 snow leopard censuses.

in India (Karanth and Nichols 1998). We adapted their techniques to estimate abundance of snow leopards in India's Hemis National Park (HNP). Our objectives were to develop a standardized field method and sampling strategy for applying capture–mark–recapture (CMR) closed population models to snow leopards using remotely triggered camera traps, estimate snow leopard density over 2 consecutive (winter) seasons, develop a camera-trapping protocol that could be applied in other parts of snow leopard range within high- and low-density areas to better estimate total numbers, and develop a snow leopard identification protocol based on their distinct pelage patterns. We selected HNP because of its frequent snow leopard sightings, low incidence of poaching, relatively stable ungulate prey populations, and the presence of well-defined travel corridors used by resident and transient snow leopards along which remotely triggered camera traps could be expediently placed for achieving consistent capture probabilities.

Study Area

Established in 1981, HNP covers some 3,350 km^2 in the Trans-Himalayan Range of Ladakh in northwestern India (Fig. 1). Besides offering prime habitat for snow leopards, HNP harbors 4 species of wild sheep and goats, including Ladakh urial (*Ovis orientalis vignei*), common blue sheep (or bharal; *Pseudois nayaur*), and small populations of Tibetan argali (*Ovis ammon hodgsoni*) and ibex (*Capra ibex sibirica*). Other carnivore species include Tibetan wolf (*Canis lupus laniger*), dhole (*Cuon alpinus*), red fox (*Vulpes vulpes*), and Eurasian lynx (*Lynx lynx*). Tibetan wooly hare (*Lepus oiostolus*), pika (*Ochotona roylei*), and Himalayan marmot (*Marmota bobak*) provide an alternative prey base for snow leopards within HNP, along with game birds such as snow cock (*Tetraogallus* sp.) and chukar partridge (*Alectoris chukar*).

The park occupies much of the catchment of the lower Zanskar River, from its confluence with the Markha River to its junction with the Indus River. The study was concentrated in the Rumbak drainage, which was the focus of previous predator–prey studies, and consisted of rolling terrain interspersed with deep narrow valleys (nullahs) and well-broken, boulder-strewn slopes between 3,200 and >6,000 m in elevation. Vegetation was sparse, reflecting the high dry desert conditions with cool to warm summers and cold winters (Fox and Nurbu 1990). Vegetation was predominantly dry alpine steppe consisting of widely spaced shrubs or subshrubs, including peashrub (*Caragana* spp.), wormwood (*Artemisia* spp.), woundwort (*Stachys* spp.), and ephedra (*Ephedra gerardiana*), with buckthorn (*Hippophae salicifolia*), willow (*Salix* spp.), wild rose (*Rosa webbiana*), myricaria (*Myricaria elegans*), poplar (*Populus* spp.), and birch trees (*Betula* spp.) along river courses. The meadows in valley bottoms were dominated by sedges *Carex* spp. and *Kobresia* spp. Plant cover generally was <15%.

Methods

Prior to the field study, we compared passive (PIR) and active infrared (AIR) detection systems in 2001 and 2002 to determine which system and camera placement achieved the highest capture rates. We placed CamTrakker™ (PIR; CamTrak South Inc., Watkinsville, Georgia) and TrailMaster™ 1500 or 1550 (AIR; Goodson and Associates, Lenexa, Kansas), and a modified homemade camera trap (AIR) based on the design described by York et al. (2001), side by side at randomly chosen trapping sites

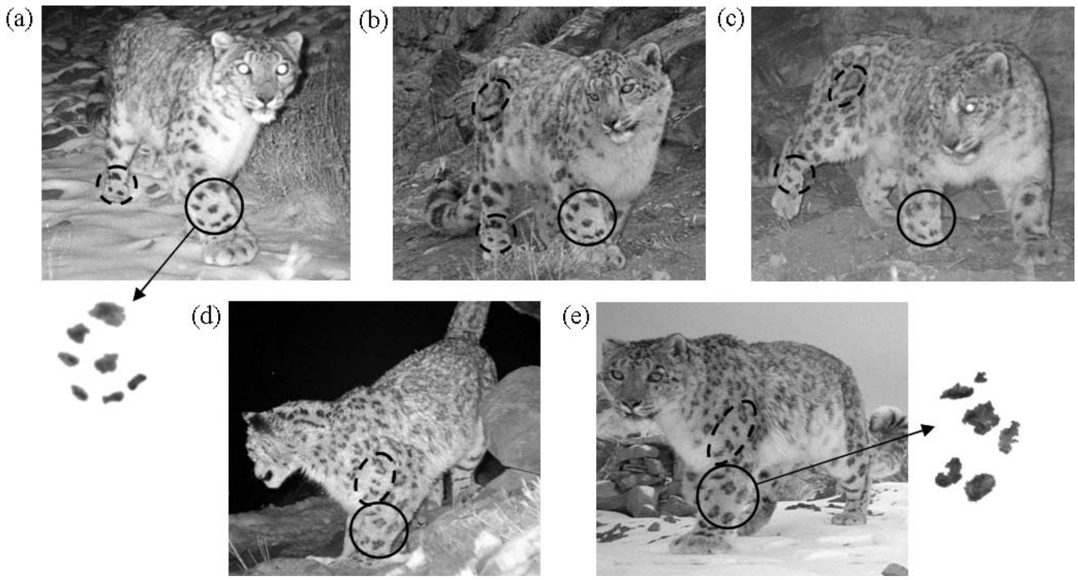

Figure 2. Example of identification of 2 separate snow leopard individuals based on pelage pattern, Hemis National Park (HNP), Ladakh, India. (a, b, c) HNP-1 and (d, e) HNP-3. Solid lines indicate the primary features and the dashed lines indicate the secondary features. Photos a, b, and c indicate the number of secondary features varies with body posture. Spotting patterns can be lifted from the photograph using Adobe Photoshop™ (Adobe Systems, San Jose, California) to assist in individual identification.

to compare the effectiveness of obtaining photos of snow leopards with the least amount of false triggering. We concluded that the TrailMaster 1550 system performed best under the harsh Himalayan environment because of the extended battery life at cold temperature (>3 months) and the ability to set multiple sampling times, link several cameras to a single infrared trigger, and adjust the trigger sensitivity. Consequently, we used TrailMaster 1550s for formal censusing. However, their high cost (>$800 for a single camera trap with 2 cameras), steep learning curve, and occasional false triggering due to heavy rain, snow accumulation, and solar interference were disadvantageous and may be prohibitive for large-scale studies or deployment by insufficiently trained personnel.

Snow leopard travel routes are indicated by the presence and abundance of fresh pugmarks, scrapes, scats, and scent-sprays (Ahlborn and Jackson 1988). We placed camera traps at sites showing high visitation rates, notably narrow ridgelines and valley bottoms at or immediately adjacent to frequently scent-sprayed rocks and scrape sites, or where movement was physically constrained by topography, boulders, and vegetation. Camera-trap density was approximately 2 stations per 16–30 km^2, the estimated minimum home range of an adult female (Jackson 1996), with the area sampled in 2004 nearly twice that surveyed in 2003 (Fig. 1). We deployed 11–18 TrailMaster 1550 monitors, each with 2 Canon™ (Tokyo, Japan) SureShot A-1 35-mm cameras, which were positioned 2–3 m from the infrared beam and synchronized by the TrailMaster Multi-Camera Trigger II. In 2003 the cameras faced directly up or down anticipated travel paths in an effort to obtain close-up photographs of the face for quick identification (Blomqvist and Nyström 1980). Due to the difficulty in obtaining detailed images of the face, we later oriented cameras at either 45° or 90° angles from the snow leopard's anticipated travel path to capture simultaneous photographs of either side of the snow leopard's body, which like other spotted cats has asymmetric pelage patterning. However, placement was often dictated by site-specific conditions and obstacles such as rocks or vegetation. We concealed cameras and infrared sensors within rock cairns and covered them to protect against snow and rain. We used a sensor height of 35–40 cm and a *P* value of 5 (i.e., the sensitivity setting or the time the infrared beam must be broken in order for an event to be triggered). We did not use baits or lures, nor did we move the cameras over the course of the survey due to the labor-intensive nature of sampling the study area. We checked the camera stations every 2–10 days or immediately following sustained snowfall to prevent accumulated snow from blocking sensors and disabling the cameras. We conducted sampling for a period of 65 days between 21 January 2003 through 25 March 2003 and for 70 days between 15 January 2004 through 24 March 2004. We recorded the number of events and frames exposed along with fresh snow leopard sign during each visit. We numbered all film rolls and carefully linked them with each site and monitoring interval.

Analytical Methods

We identified individual snow leopards based on their distinct pelage patterns (Figs. 2, 3). We examined each photograph for clarity, subject orientation, and framing to locate unique markings useful for identification based on guidelines modified from Heilbrun et al. (2003):

1. A photograph was considered an initial capture only if it could not be positively matched with a previously photographed individual.
2. A recapture need not have been a photograph of the entire animal, but one that could be positively matched to a previously identified individual.
3. A poor photograph or one that could not be classified as an

Figure 3. Examples of pelage pattern variations on the dorsal surface of the tail of snow leopards, Hemis National Park (HNP), Ladakh, India. (a) HNP-1, (b) HNP-5, and (c) HNP-7.

initial or recaptured individual was classified as a noncapture (Heilbrun et al. 2003).

4. Areas used for identification consisted of uniquely shaped rosettes or spots, or groupings thereof, and their spatial arrangement on the forelimbs, flanks, and dorsal surface of the tail.
5. Distinct areas used for identification were classified as either primary or secondary features. A single primary feature was designated for each photograph and was defined as the most distinct and clearly visible group of markings or individual mark useful for identification. All other useful markings were classified as secondary features.
6. A positive identification was made by comparing the primary feature and at least 1 secondary feature to determine if the animal was an initial capture or recapture.
7. Identification of 1 different feature was considered sufficient to determine that 2 photographs depicted different individuals (Heilbrun et al. 2003:750).

We estimated snow leopard abundance using the software program CAPTURE (Rexstad and Burnham 1991), following procedures described by Otis et al. (1978), White et al. (1982), and Karanth and Nichols (1998). Program CAPTURE tests 7 models, which differ in their assumed sources of variation in capture probability. The simplest, known as the Null Model, assumes no variation between individuals or over time. More complicated models are the heterogeneity model (in which individuals differ due to sex, age, activity, ranging patterns, etc.); the time variation model (with capture probabilities changing over time); the behavior model resulting from differing responses to photographic capture and recapture (e.g., trap-happy or trap-shy animals); and 3 combinations of these models (time and behavior; behavior and heterogeneity; time, behavior, and heterogeneity). The program identifies which model best fits the data set in question and then generates capture statistics for all adequately fitted models, along with computing a test statistic for evaluating the likelihood of population closure. Because this test is not considered statistically robust, we employed the closure test (CloseTest program) provided by Stanley and Burnham (1999) for time-specific data that, in principle, tests the null hypothesis of closed-population time model against the open-population Jolly–Seber model as a specific alternative. The test is most sensitive to permanent emigration and least sensitive to temporary emigration and is of intermediate sensitivity to permanent or temporary immigration. We used 7- and 5-day sampling occasions because these generated sufficient captures, maximized the number of sampling occasions without violating population closure assumptions, and fit the recommendations of capture probabilities ≥ 0.10 (and preferably ≥ 0.20) with a sample of ≥ 5 occasions (Otis et al. 1978). The area sampled was defined by an outer buffer strip equal to the one-half of the mean maximum distance snow leopards traveled between camera-trap stations (Karanth and Nichols 2002). The Snow Leopard Conservancy (Jackson et al. 2005) prepared a detailed handbook for surveying snow leopard populations, available for download (<http://www.snowleopardconservancy.org/handbook.htm>).

Results

Capture Success

In 2003 and 2004 we recorded 66 and 49 captures of snow leopards, representing capture successes of 8.91 and 5.63 individuals/100 trap-nights for these 2 years (Table 1). This equals 1 snow leopard capture for every 11.2 and 17.7 nights of trapping, respectively. Falsely triggered images comprised 63% and 75% of all images in 2003 and 2004, mostly caused by snowfall and errant infrared light, which is most prevalent above 3,500 m in elevation. Domestic stock (primarily sheep and goats) represented 10.3% and 13.7% of nontarget species captured over the 2 years, whereas canids (mostly red fox and wolves) and birds were responsible for most of the remaining nontarget captures (2003 = 5.4%; 2004 = 2.5%). We tallied 112 images of snow

Table 1. Camera-trapping effort and captures of snow leopards in Hemis National Park, India, 2003–2004.

							Snow leopards		
Year	**Sampling period**	**Trap stations**	**Trap-nights[a]**	**Total photos**	**Nontarget species**	**False images**	**Photos**	**Captures**	**Individuals**
2003	21 Jan–25 Mar	18	741	465	86	278	112	66	6
2004	15 Jan–24 Mar	19	871	1,014	174	758	82	49	6

Table 2. Proportion of body parts visible in camera-trap photographs of snow leopards taken in Hemis National Park, India, 2003–2004.

Body position	% sample	
	2003 (n = 112)	2004 (n = 82)
Facial angle		
Not visible or pose not known	19.8	35.8
Sideways to camera (approx. 90°)	9.0	22.6
Looking away from camera (≥90°)	34.2	17.0
Looking toward camera (≤45°)	36.9	24.5
Extent of torso visible		
Not visible	24.3	11.3
Fully visible	9.9	35.8
Approx. 0.75	26.1	24.5
Approx. 0.50	21.6	9.4
Less than 0.25	18.0	18.9
Number of limbs (fore or hind) visible		
None	8.2	18.9
1	9.1	15.1
2	29.1	26.4
3	43.6	30.2
All 4 limbs	10.0	9.4
Extent of tail visible		
Not visible	20.7	15.1
Completely visible (dorsal surface)	37.8	3.8
Mostly visible	12.6	39.6
Approx. 0.50	10.8	26.4
Only slightly visible	18.0	15.1

leopards in 2003, compared with 82 images in 2004. This difference is attributed to the fact that we placed more trap stations within marginal habitat in 2004 and deployed 37 cameras versus the 27 used in 2003. It required 58 days to detect all individuals in 2003, compared with 11 days in 2004. However, we detected 67% of all animals tallied in 2003 within the first 14 days of trapping.

Identification of Snow Leopard Photos

In 2003 cameras were set to photograph snow leopards directly approaching or departing trap sites to primarily document facial features and dorsal tail patterning. Consequently, most snow leopards were photographed looking toward (36.9%) or away from the camera (34.2%; Table 2), which resulted in 26.1% of all images with three-quarters of the animal's torso showing but only 9.9% showing the full torso. In 43.6% of photographs, 3 legs were evident, whereas the dorsal surface of the tail was completely visible in 37.8% of the samples. In 2004 we set one camera to obtain a 45° view and the other a 90° or side view of the passing animal. Consequently, a greater proportion of images (22.6%) captured lateral views of the face, full or three-quarter torsos (60.3%), but with lowered success at photographing the leopard's distinctive dorsal surface of the tail (3.8%). Factors contributing to this high variability in poses and subject angle are the typically narrow travel lane favored by leopards (<2–5 m in width), their tendency to walk immediately adjacent to a rock or cliff base, and individual differences in approach behavior to scented rocks or sites with scrapes.

The best body parts for identification are the lower forelimbs, flanks, and dorsal surface of the tail (Figs. 2, 3). We assigned 96.4% (2003) and 97.6% (2004) of all photographs to 1 of 10 individuals. In 2003 we trapped 6 snow leopards (HNP-1 to HNP-6), judged to be 2 adult males, 2 adult females, 1 subadult male, and a juvenile of unknown gender. In 2004 we recaptured 2 individuals (1 adult female and 1 subadult male), along with 4 new animals (HNP-7 to HNP-10, judged as 2 males, 1 adult female, and 1 juvenile of unknown gender). We documented 2 females with cubs, judged to be about 6 months of age at first capture.

Closure Tests and Model Selection

The 7-day sampling occasion indicated no evidence for a behavioral response after the initial capture in 2003 but did support this conclusion in 2004 (M_o vs. M_b), no time variation in capture probabilities (M_o vs. M_t), and a reasonable fit of the heterogeneity model (M_h; Table 3). There was some evidence of different behavioral responses between newly caught and previously captured individuals that was most pronounced in the 5-day sampling occasion data set in 2003 and the 7-day occasions in 2004, along with a relatively weak fit of the M_h model. Our sample was too small to assess the relative fit of the null model (M_o) versus the heterogeneity model (M_h), the heterogeneity model versus the behavior and heterogeneity model (M_{bh}), or to compute chi-square values for assessing the goodness of fit of the time-based model (M_t). The CAPTURE test for closure supported the assumption of population closure (i.e., no immigration, emigration, births, or deaths) during both surveys, as did the more robust closure test developed by Stanley and Burnham (1999; Table 4). CAPTURE selected the null model for the 7-day sampling occasions in 2003 and the all-effects model in 2004, but we elected to use the null model for population estimation due to the small sample size. In 2003 CAPTURE marginally selected the heterogeneous model (M_h) for the 5-day occasion data set and the null model (M_o) for the 2004 data set.

Estimates of Snow Leopard Capture Probabilities, Population Size, and Density

We recorded relatively high capture probabilities (0.333–0.667) in both years (Table 4). We estimated the sample population at 6

Table 3. Results of tests of assumptions used by CAPTURE for evaluating the fit of 3 capture–mark–recapture models (M_b, M_t, and M_h).

Survey duration (intervals)	Total occasions	M_o vs. M_b			M_o vs. M_t			M_h goodness-of-fit			M_b goodness-of-fit		
		χ^2	df	P	χ^2	df	P	χ^2	df	P	χ^2	df	P
2003													
63 d (7-d)	9	0.470	1	0.493	5.428	8	0.711	9.600	8	0.294	9.215	7	0.238
65 d (5-d)	13	1.798	1	0.179	11.806	12	0.461	21.286	12	0.046	17.552	12	0.129
2004													
70 d (7-d)	10	3.817	1	0.051	9.229	9	0.416	6.733	9	0.665	8.250	7	0.311
60 d (5-d)	12	1.046	1	0.306	15.574	11	0.157	17.407	11	0.096	12.896	9	0.167

Table 4. Results of population closure, estimated abundance, standard error, and capture probabilities of snow leopards sampled in Hemis National Park, India, 2003–2004.

	Test for closure		Null model (M_o)		Heterogeneity model (M_h)		Trap response model (M_b)	
Occasion	CAPTURE[a]	Stanley[b]	Capture probability	Abundance (SE) 95% CI[c]	Capture probability	Abundance (SE) 95% CI[c]	Capture probability	Abundance (SE) 95% CI[c]
2003								
7-d	$z = 0.843$ $P = 0.800$	$\chi^2 = 1.584$ $P = 0.954$ df = 6	0.389	6 ± 0.28 (6–6)	0.333	7 ± 1.36 (7–13)	Capture = 0.316 Recapture = 0.429	6 ± 0.59 (6–6)
5-d	$z = -0.075$ $P = 0.470$	$\chi^2 = 2.496$ $P = 0.981$ df = 9	0.346	6 ± 0.16 (6–6)	0.346	6 ± 5.51 (6–6)	Capture = 0.231 Recapture = 0.404	6 ± 0.59 (6–6)
2004								
7-d	$z = 0.423$ $P = 0.664$	$\chi^2 = 4.601$ $P = 0.799$ df = 8	0.383	6 ± 0.22 (6–6)	0.383	6 ± 0.19 (6–6)	Capture = 0.667 Recapture = 0.333	6 ± 0.01 (6–6)
5-d	$z = 0.539$ $P = 0.705$	$\chi^2 = 8.659$ $P = 0.372$ df = 8	0.333	6 ± 0.22 (6–6)	0.333	6 ± 0.20 (6–6)	Capture = 0.461 Recapture = 0.305	6 ± 0.06 (6–6)

[a] Calculated by program CAPTURE (Otis et al. 1978).
[b] Calculated from Stanley and Burnham 1999.
[c] Approximate 95% CI, to the nearest integer, calculated by CAPTURE (in brackets).

snow leopards (SE = 0.16–0.28, 95% CI = 6–6 individuals) for 2003. In 2004 the population was estimated at 6 (SE = 0.22; CI = 6–6) for both the 7- and 5-day occasion data sets. When computing the 95% confidence interval, CAPTURE converts the values to the nearest integer rather than printing decimals. The heterogeneity model (M_h) produced an ill-conditioned population estimate in the 2003 data set and a very comparable estimate to the null model for the following year. Population estimates for the trap response model (M_b) also were comparable across each year's data set. All individuals were captured within the first 2 weeks in 2004, but it took nearly 2 months to detect all snow leopards in 2003.

The mean maximum distances moved by individual snow leopards between successive captures were 3.15 km and 4.03 km, providing an outer buffer-strip width of 1.58 and 2.02 km in 2003 and 2004, respectively (Table 5). Thus, we effectively sampled areas of 71 km^2 and 135 km^2, of which approximately 60–70% is considered good snow leopard habitat (Fig. 1). The 2003 survey yielded an estimated snow leopard density of 8.49 (SE = 0.22) individuals per 100 km^2 (excluding cubs), compared to 4.45 (SE = 0.16) in 2004.

Discussion

Applicability of Camera-Trap Surveys

Our study suggests that photographic CMR sampling can be a useful tool for estimating snow leopard population size, provided surveys are carefully designed and executed. The higher-quality sensor devices and cameras we used performed well under the harsh conditions prevailing at high elevation in the Himalayas, especially low nighttime winter temperatures, extreme diurnal temperature fluctuations, and high levels of infrared radiation. We successfully identified snow leopards from their pelage patterns; however, subject orientation proved to be the most variable factor. We explored various camera setup scenarios and the most reliable proved to be 2 cameras oriented at 45° on either side of the path of travel. This resulted in more consistent subject orientation and reproducible images of the lower limbs and dorsal surface of the tail, which offered the most dependable means of identification in the absence of crisp side-view pictures. Furthermore, setting up camera stations near the approach to rock scents or scrape sites resulted in more consistent subject orientation, although camera trapping was most productive where a sufficient funnel point existed.

Tigers are readily identified by the striping on their flanks (Karanth and Nichols 1998), while common leopards (*Panthera pardus*), cheetahs (*Acinonyx jubatus*), and jaguars (*Panthera onca*) have clearly distinct spot patterning. Individual identification of snow leopards is more difficult due to their long, soft fur (in excess of 50 mm in winter) and numerous low-contrast, smoky gray–black rosettes and spots that change shape, and, to some degree, orientation with respect to body movement and posture. Small

Table 5. Snow leopard density (individuals/100 km^2) estimates for study area, Hemis National Park, India, 2003–2004.

			Buffer			Density–null model (M_o)	
Year	Area surveyed	Effective area sampled	Mean maximum distance moved	Standard error	Buffer width	Estimated density	Standard error
2003	28.46	70.70	3.15	0.38	1.58	8.49	0.22
2004	60.71	134.87	4.03	0.42	2.02	4.45	0.16

Snow leopard HNP-1, photographed on a camera-trap on a ridge 13,500 feet above Rumbak Village, Hemis Naitonal Park (HNP), Ladakh, Jammu and Kashmir, India, 3 Feb 2003. This individual, also known as Mikmar, is the dominant snow leopard of the area and was featured extensively in a public television nature film entitled, "Silent Roar: searching for the snow leopard."

spots on the snow leopard's forehead, commonly used for identification by zookeepers (Blomqvist and Nyström 1980), often were too faint or grainy when enlarged from photographs to permit individual recognition. Consequently, we relied upon those areas with shorter fur that were less prone to distortion (forelimbs) and better-defined, easily recognizable rosette shapes (flanks and tail). Obtaining good-quality side-profile photographs of snow leopards proved surprisingly difficult because most travel paths were less than several meters wide in this rugged terrain, with snow leopards typically walking close to physical objects like boulders or the base of a cliff, making it difficult to capture simultaneous images of both sides for positive identification at first capture. Furthermore, the more diffuse pelage patterns on the sides proved to be less useful for individual identification than sharply defined spots and rosettes on the lower forelimbs or dorsal tail surface. Photographs taken along travel lanes tended to produce blurry images even with fast film. We, therefore, recommend setting cameras near rock-scents or scrape sites where animals tend to linger, although cameras set to view activity at the rock-scent or scrape site will result in highly variable body poses. Potential sampling bias related to marking at rock-scents and scrapes can be reduced by placing cameras within 3–5 m from such sites.

Our capture-history data fit best with the closed capture–recapture null model (M_o) and only marginally fit the alternative model M_h, which incorporates individual heterogeneity into capture probabilities and represents the model of choice for tigers (Karanth and Nichols 1998, O'Brien et al. 2003). Small sample size undoubtedly is the primary reason for our inability to select a more sophisticated model than the overgeneralized null model, in turn an inevitable consequence of working with a shy species occurring at low densities over extensive mountainous terrain. Nonetheless, we concluded that a 5-day sampling occasion provided sufficient time for detecting and capturing resident snow leopards, with 10–12 consecutive sampling occasions generating sufficient captures and recaptures without violating the population closure assumption.

We recorded higher capture probabilities than reported for tigers in good habitat (0.11–0.26; Karanth and Nichols 1998), dry forest (0.039; Karanth et al. 2004), or for the Sumatran subspecies (0.027; O'Brien et al. 2003). Presumably, this reflects the snow leopards' predilection for using common travel lanes, revisiting the same site to mark frequently (particularly during the winter mating season), and its apparently limited trap-shyness. Capture probability is readily maximized by placing traps at or near communal scenting sites along narrow points where topography constrains and funnels their movements (e.g., stream or valley confluences and intersecting travel routes on ridgelines), especially if these happen to be located within core-use areas (Jackson 1996). Most importantly, there should be no gap large enough for a snow leopard to escape detection entirely or to have too low a probability of detection (Karanth and Nichols 2002). Other considerations include camouflaging traps well, avoiding (whether intentionally or unintentionally) incorporating features that may cue target animals to the nearby presence of a trap, and allowing sufficient trapping nights (total and per occasion) for accruing adequate detection probabilities (Wegge et al. 2004). Our trap sites were not associated with any obvious visual cues and were well concealed within natural rock structures. The probability of detection remained high even during the 5-day sampling protocol, exceeding those for tigers monitored along road corridors within India's best reserves. But like tigers, snow leopard cubs and juveniles are not as easily detected as resident adults, tending to avoid capture by trailing behind their mother (Karanth and Nichols 1998). This cohort is best estimated during winter when cub pugmarks can be more readily detected in snow.

Estimates of snow leopard density almost halved from 8.49 individuals/100 km^2 (excluding cubs) in 2003 to 4.45 in 2004. Given similar mean distances moved and the same minimum number of individuals (6) captured during each CMR survey, we believe these very different estimates reflect differences in camera spacing, coverage, and the type of habitat surveyed. In 2003 we concentrated camera traps within a small core area of prime habitat, whereas in 2004 they covered a larger area that included marginal habitat (Fig. 1), indicating the importance of sampling relatively large areas with proportionate habitat representation. According to Wegge et al. (2004), abundance estimates of tigers may be greatly influenced by trap spacing and trapping duration, in addition to behavioral factors such as trap-shyness. They recommended deriving total counts based on intensive trapping effort per unit area with a small intertrap distance ($\pm$1 km), but this approach rules out a statistically bounded population estimate. Our density estimate using the 2004 CMR data set closely matches Chundawat and Rawat's (1994) estimate of 4 snow leopards based on the availability of blue sheep within the Rumbak watershed. Assuming a density of approximately 6 snow leopards/100 km^2 in areas of good habitat and no more than 4/100 km^2 in marginal habitat, Hemis National Park may contain up to 175 snow leopards. This is substantially more than Fox and Nurbu's (1990) estimate of 50–75 individuals, but comparable to the estimate of Mallon and Bacha (1989) of 75–120 cats within a 1,200-km^2 section. The difference may partially reflect recent conservation initiatives aimed at protecting the snow leopard and its prey by reducing livestock loss, poaching, and retributive killing (Jackson and Wangchuk 2001).

Sample size is, and will be, a major constraint in any snow leopard camera-trap survey. The species' low numbers and sparse distribution severely limits computation of population estimates and associated confidence intervals. Karanth and Nichols (1998) noted that CAPTURE performs poorly with populations of 20 or fewer individuals. Unfortunately, small populations are characteristic for snow leopards, even in areas with optimal habitat. The only remedy is to sample very large areas (200–400 km^2) concurrently or within an 8-week (or shorter) period to meet the requirement of population closure and to aim for capture probabilities $\geq$0.20 and preferably $\geq$0.30. Cameras should be set to operate 24 hours/day, unless the presence of livestock or other nontarget species could lead to rapid depletion of film. In such circumstances the data must be analyzed to include only captures from time intervals in which all traps are simultaneously in data collection mode. Cumulative capture curves indicate that camera-trap surveys need to be $\geq$35 days in duration to detect sufficient individuals, but $\geq$45–50 days may be necessary for ensuring adequate recaptures. In both years we recorded several occasions during which no snow leopards were trapped.

The ability to trap large areas is severely hampered by rugged terrain and the lack of ready access. Moving traps from one site to another is very time consuming, so that even having a full complement of traps active each and every night of trapping may not be achievable. The only alternative to purchasing and simultaneously deploying more cameras involves dividing the survey area into a number of contiguous blocks ($\geq$3–5) and to move cameras from one location to another within the same block every sixth day or so. Assuming a survey has 20 units available, using a minimum density of about 1.5 cameras/16–30 km^2 and deploying each camera at the same site for $\geq$5 nights to ensure adequate capture probability, it will not be feasible to cover areas larger than 400–500 km^2 during each survey. Furthermore, assuming that only 2 camera stations can be moved to another location within a single day, a minimum of 10 days would be required to move all camera traps to new sites. Therefore, the only alternative is to synchronize movement of traps on a block-by-block basis so that each has a similar trapping effort during each sampling occasion (see Karanth and Nichols 2002). One likely consequence is that some trap sites would be covered for longer periods than others, possibly introducing a trapping bias in favor of those individuals spending more time in such areas.

Implications for Snow Leopard Ecology and Conservation

Given the sparse populations and significant logistical constraints associated with deploying cameras over a wide area, well-conditioned population estimates and confidence limits may be nearly impossible to achieve. However, we believe that camera trapping is a viable tool for estimating snow leopard population size, at least in areas exceeding 2–3 individuals/100 km^2. At a minimum, camera-trap surveys can yield the minimum number of snow leopards present and trapping effort (expressed as the number of animal photographs per trap night) can be viewed as an index of relative abundance provided capture probabilities remain constant between sites and years (Carbone et al. 2001, Jennelle et al. 2002).

Snow leopard HNP-3, photographed on a camera-trap on a ridge 13,500 feet above Rumbak Village, Hemis Naitonal Park (HNP), Ladakh, Jammu and Kashmir, India, 19 Feb 2003.

Our results suggest a tendency to underestimate population size when using sign or sightings as the primary source of information. It also highlights the need for deriving more robust estimates of detection probabilities and population size with noninvasive techniques such as CMR, if necessary using jackknife techniques. We recommend that camera-trap estimates should be supported by ungulate prey abundance surveys and calibrated data from standardized snow leopard sign transects. We detected a change in population composition between 2003 and 2004. The dominant male snow leopard, HNP-1, which was photographed more than any other snow leopard within the study area, was last detected on 23 December 2003. We believe the resulting home-range vacancy played a major role in the addition of 4 new individuals detected during the 2004 camera-trap survey. Several video cameras deployed since February 2001 indicated the presence of HNP-1 and female HNP-2 with 2 cubs, the latter filmed without their mother at some 14–16 months of age (although they may not have yet been independent of her). Snow leopard HNP-1 was captured at least a dozen times on video between early 2001 and his last capture. Between 2001 and 2004, we detected 2 litters, one in February 2001 and the second in February 2004, each comprising 2 cubs born to female HNP-2. She was filmed and photo-trapped consorting with HNP-1 in mid-February 2003. A second breeding female (HNP-9) was photographed with her single cub during the 2004 survey at the far edge of the study area. These observations suggest the study area harbors a healthy cohort of breeding females and possibly also a stable population. The deployment of remote cameras offers a helpful means of obtaining baseline population demographic information, data vital to assessing the long-term effectiveness of conservation measures. However, more research is needed to establish these parameters for snow leopards under varying habitat conditions.

Clearly, obtaining a statistically bounded estimate of population size will be expensive, time consuming, and not feasible in all situations, due in large part to the time constraints associated with monitoring and deploying sufficient camera traps in the species' rugged habitat. The use of less-expensive passive infrared-sensing cameras deployed over longer time spans at frequently visited rock-scents by suitably trained wildlife guards or local villagers, although not as reliable as active infrared sensors in detecting snow leopards, could help facilitate population and demographic monitoring. The identification of individuals from their pelage patterns and the ongoing cataloging of all images accrued over time would provide information on the minimum number of individuals present and the duration of their "residency" within the area surveyed. Capture histories could be used to identify known or probable residents versus transients and dispersing or dying individuals if sample size permitted and camera coverage was sufficiently extensive. Knowing the individual snow leopards that inhabit a particular area might promote stewardship of the species among interested households in the local community, thus aiding in the conservation of this rarely seen carnivore.

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