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Conservation and climate change: Assessing the vulnerability of snow leopard habitat to treeline shift in the Himalaya

Jessica L. Forrest [a,*], Eric Wikramanayake [a], Rinjan Shrestha [b,c], Gopala Areendran [d], Kinley Gyeltshen [e], Aishwarya Maheshwari [d], Sraboni Mazumdar [d], Robin Naidoo [a], Gokarna Jung Thapa [b], Kamal Thapa [b]

[a] Conservation Science Program, WWF US, 1250 24th Street NW, Washington, DC 20037-1124, USA
[b] WWF Nepal, Kathmandu, Nepal
[c] Eastern Himalayas Program of WWF US, WWF Canada, 245 Eglinton Ave. East, Suite 410, Toronto, ON M4P 3J1, Canada
[d] WWF India, 172B, Lodhi Estate, New Delhi, India
[e] WWF Bhutan, Kawajangsa, Thimphu, Bhutan

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ABSTRACT

Climate change is likely to affect the persistence of large, space-requiring species through habitat shifts, loss, and fragmentation. Anthropogenic land and resource use changes related to climate change can also impact the survival of wildlife. Thus, climate change has to be integrated into biodiversity conservation plans. We developed a hybrid approach to climate-adaptive conservation landscape planning for snow leopards in the Himalayan Mountains. We first mapped current snow leopard habitat using a mechanistic approach that incorporated field-based data, and then combined it with a climate impact model using a correlative approach. For the latter, we used statistical methods to test hypotheses about climatic drivers of treeline in the Himalaya and its potential response to climate change under three IPCC greenhouse gas emissions scenarios. We then assessed how change in treeline might affect the distribution of snow leopard habitat. Results indicate that about 30% of snow leopard habitat in the Himalaya may be lost due to a shifting treeline and consequent shrinking of the alpine zone, mostly along the southern edge of the range and in river valleys. But, a considerable amount of snow leopard habitat and linkages are likely to remain resilient to climate change, and these should be secured. This is because, as the area of snow leopard habitat fragments and shrinks, threats such as livestock grazing, retaliatory killing, and medicinal plant collection can intensify. We propose this approach for landscape conservation planning for other species with extensive spatial requirements that can also be umbrella species for overall biodiversity.

1. Introduction

Climate change is emerging as an important threat to biodiversity (Beaumont et al., 2011; McCarty, 2001; Thomas et al., 2004). In an era when habitat loss and fragmentation from proximate anthropogenic drivers is rapid, conservationists also have to contend with climate-driven habitat shifts and fragmentation when designing conservation landscapes for large, space-requiring species. While bioclimatic models have been used to predict the persistence of species populations and habitats based on climate change-related threats, they are often impractical for conservation planning due to limitations of scale and reliability (Heikkinen et al., 2006; Lawler et al., 2006). However, individual-species climate models that are more reliable than assemblage or community-based models (Heikkinen et al., 2006) can provide much-needed guidelines for climate-integrated conservation planning (Hannah et al., 2002a; Pearson and Dawson, 2003; Thuiller, 2007).

We developed a hybrid approach that combines a habitat suitability model constructed using field-based ecological data with a correlative bioclimatic model to determine the spatial vulnerability to climate change of a single species: the snow leopard (*Panthera uncia*). A cryptic predator of the alpine and subalpine zones of central and south Asia, snow leopards have a strong affinity for rugged mountain terrain, usually devoid of large forest patches (McCarthy and Chapron, 2003). Despite their wide geographic range, snow leopards are sparsely distributed and occur at low densities (McCarthy and Chapron, 2003). They are often killed in retaliation for livestock depredation by herders and for their pelts by poachers, while their prey species are also widely persecuted and displaced due to over-exploitation of alpine habitat (Fox, 1994). Because of these threats, the snow leopard is listed as an endangered species requiring urgent conservation attention (IUCN, 2010).

Climate change has now emerged as another potential threat to snow leopards (McCarthy and Chapron, 2003). The

* Corresponding author. Tel.: +1 202 495 4171.
E-mail address: Jessica.forrest@wwfus.org (J.L. Forrest).

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Intergovernmental Panel on Climate Change (IPCC) projects that the average annual temperature in South Asia and Tibet will increase by 3-4 °C by 2080-2099 based on comparison with historical averages from 1980-1999, while annual precipitation is expected to increase throughout this region as well (Christensen et al., 2007). Previous studies have shown a distinct correlation between treeline and climate (Körner, 1998; Körner and Paulsen, 2004). Therefore, the warmer and wetter conditions consistent with climate change predictions in this region may result in forests ascending into alpine areas, the snow leopards' preferred habitat.

Here we adopt a habitat suitability modeling approach to map snow leopard habitat validated with field data, and use a bioclimatic model to project the effects of treeline shift on this habitat under climate change scenarios. In our approach, we assume that the impacts of climate change will be manifested primarily through changes in the snow leopard's alpine habitat, rather than through direct physiological impacts of temperature and precipitation on snow leopards. We recognize this explicitly in the bioclimatic model by treating the snow leopard's primary habitat as the dependent variable. We also discuss how this approach can be useful to integrate potential effects of climate change into conservation strategies for other high conservation value megaspecies.

2. Methods

2.1. Habitat mapping

We defined snow leopard habitat as: grassland, shrubland, bare areas, and agricultural mosaic in alpine areas (Jackson and Ahlborn, 1989; Jackson, 1996; Oli, 1997; McCarthy and Chapron, 2003; McCarthy et al., 2005; Medias-France, 2008); more rugged relative to the surrounding area (>0.01 in the mountains and >.004 in the Tibetan plateau on a ruggedness scale of 0–0.19) (Sappington et al., 2007; Lehner et al., 2008); and below an upper elevation threshold of 5500 m. These values were based on published literature, expert opinion, and an overlay of snow leopard observations and environmental layers, as elaborated later in Section 2.1 and Appendix A.

To map habitat, we used a habitat suitability scoring approach (Beier et al., 2007; Girvetz and Greco, 2007; USFWS, 1981) in which all suitable classes were provided a score of 1 and all unsuitable classes a score of 0. The layers were weighted equally and summed. Pixels that met all three environmental criteria were retained as snow leopard habitat. We classified all habitat blocks $\geqslant$500 km^2 as good snow leopard habitat, and contiguous blocks $\geqslant$1500 km^2 as "large habitat blocks", containing the best habitat for harboring resident populations of at least 50 snow leopards. This number was based on studies reporting averaged density estimates of 1–2 snow leopards per 100 km^2 in Bhutan to 4–5 per 100 km^2 in Nepal (Fox and Jackson, 2002). We chose a mid-point density estimate of three animals per 100 km^2 for this regional assessment. We validated the result with snow leopard observation points, expert opinion and published literature about snow leopard habitat use (Jackson and Hunter, 1996; Schaller, 1998; Schaller et al., 1988). Because snow leopard observation data that were available to us were not collected in a systematic way with respect to the environmental layers selected for our analysis, we did not use a statistical modeling approach (e.g. generalized linear model of snow leopard presence and absence, maximum entropy model, etc.) to map snow leopard habitat (sensu Pearson and Dawson, 2003).

We assumed that snow leopards use forest habitat very infrequently, which is consistent with published accounts (McCarthy and Chapron, 2003). We confirmed this assumption by overlaying snow leopard observation points with land cover data (Medias-France, 2008). Of 307 snow leopard observations, only 6% overlapped with forest habitat. These points were very close to the ecotone. While the occasional use of forests adjacent to alpine habitat may have implications at the local scale, it is unlikely to be important for regional scale maps of snow leopard habitat. Because the snow leopards' primary prey species, including blue sheep (*Pseudois nayaur*), Asiatic ibex (*Capra sibirica*), Himalayan tahr (*Hemitragus jemlahicus*), argali (*Ovis ammon*), and marmots (*Marmota himalayana*) also live in alpine habitats (McCarthy and Chapron, 2003; Shrestha and Wegge, 2008), we did not model their habitat separately. We assumed that areas above 5500 m do not offer good habitat for snow leopards based on expert knowledge (A. Maheswari and K. Thapa, pers. obs.) and snow leopard observation data. Indeed, 10% of snow leopard observation points fell between 5000 and 5500 m, but only 1% between 5500 m and 6000 m and none above 6000 m (Lehner et al., 2008).

After mapping snow leopard habitat, we identified snow leopard dispersal habitat, or areas that snow leopards can move through, by creating a cost of movement surface and then generating a cost distance model (Appendix B; Beier et al., 2007). We treated all habitat blocks $\geqslant$500 km^2 as source areas, and habitat patches >100 km^2 and <500 km^2 as dispersal stepping stones. We used a threshold of 40 km as the maximum distance between habitat blocks that can be traversed, based on daily movement of radio-collared animals in Mongolia (McCarthy et al., 2005). Connectivity thresholds between core areas were identified by comparing the potential dispersal habitat linkages derived from the cost surface with snow leopard observation data, scientific literature, and field experience (details in Appendix B).

Although our region of interest for this study was the Himalayan mountain range, we first mapped snow leopard habitat and dispersal zones at the extent of the Himalayan mountain range and the adjacent areas of southern China to account for connectivity between our study extent and snow leopard habitat outside our area of interest (see Jackson et al., 2008). We then calculated the total area of each habitat block and clipped the resulting snow leopard habitat and dispersal zone to the Himalayan range (Fig. 1). We defined the Himalayan range as "Himalayan" ecoregions (from Olsen et al., 2001), buffered by 20 km. All analyses were completed in Albers Equal Area Projection for Asia with the WGS 84 datum, using ArcGIS 9.3.1 and Spatial Analyst (ESRI, Redlands, USA).

2.2. Determining the importance of climatic drivers on forest and alpine zones

We used a regression model to predict the effect of current and future climate profiles on the location of the alpine zone. The alpine zone is unsuitable for forest cover due to climatic or other natural environmental conditions (Körner, 2007). We selected a candidate set of climate variables suspected to influence the treeline ecotone (Körner, 1998; Körner and Paulsen, 2004) and 19 bioclimatic variables from Worldclim (Hijmans and Graham, 2006; Hijmans et al., 2005) as independent variables. Candidate variables included mean temperature during the growing season, total precipitation during the growing season, total precipitation as snow (precipitation during months with mean temperature $\leqslant$0 °C), and number of growing season months. We also prepared slope, aspect, and soil type grids at the same resolution and extent as the climate variables. We set the extent of the forest and alpine zone analysis to the Himalayan mountain range and southern China and clipped all environmental layers to this extent. We selected this extent by elevation (<100 m to >8500 m) and latitude (26–40°N) because it includes a wide range of climate zones over which alpine zones may or may not occur.

We classified land cover in the region as either forest, alpine, or unknown, using Globcover 300 m (Medias-France, 2008) and a 15s Void-filled DEM (Lehner et al., 2008). Alpine habitat was defined as

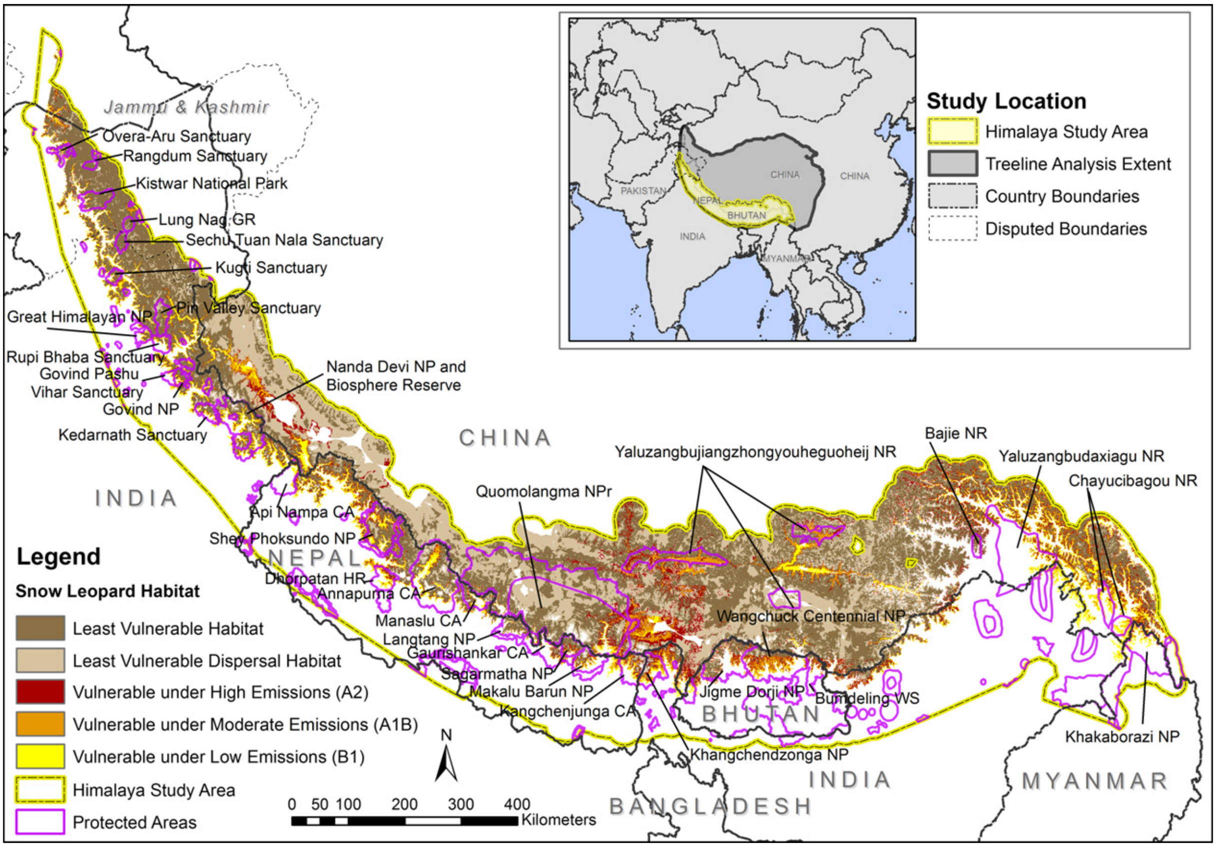

Fig. 1. Vulnerability of snow leopard habitat in the Himalaya to climate-induced habitat change. Data sources: Protected Areas – WDPA 2011, WWF Bhutan, WWF Nepal; Country boundaries: ESRI ArcWorld 2004. Country boundaries do not express official endorsement or acceptance. (CA = Conservation Area, GR = Game Reserve, NP = National Park, NPr = Nature Preserve, NR = Nature Reserve, WS = Wildlife Sanctuary).

grassland, shrubland, agricultural mosaic, and ice cells at elevations greater than 3000 m. All forest classes in the land cover map were defined as forest for our analysis. Other classes, such as agriculture found at <3000 m and water, were classified as 'not applicable,' as they were not relevant to this analysis. We randomly generated 10,000 points across the study area and identified the land cover, climatic, and other abiotic values at each. Points landing in forest or alpine habitat were selected from the 10,000 records and used for our modeling. Since our dependent variable was binary (forest/alpine), we used logistic regression to model the probability that a cell is in the alpine zone.

We removed the independent variables that were highly ($r > 0.7$) correlated to select an independent set of predictors. Consequently, the initial set of variables was reduced to four: (1) mean temperature during the growing season; (2) total precipitation during the growing season; (3) total precipitation as snow; and (4) total precipitation from December to February. We used the "glm" function in R version 2.9.1 (R Development Core Team, 2010) to determine the relationship between these four environmental variables and our dependent variable.

The resulting probabilities from this model were mapped spatially using the standard logistic function. The predicted map of forest and alpine zones was examined against the Globcover 300 m classification and Landsat 7 images (USGS) representing May to September during the 2000s. We selected a threshold probability $f(z)$ of 0.43 to assign cells to predict alpine and forest zones. This threshold appeared to optimize the predictive capacity of both forest and alpine zones (98% of observed alpine habitat was correctly predicted when $f(z) > 0.43$ and 83% of forest correctly predicted when $f(z) \leqslant 0.43$).

To judge the robustness of our 4-variable model, we performed a sensitivity test in which each of the four significant variables were removed one at a time, and the model re-run to look at the effect on AIC. We also assessed the predictive power of the models by using an independent data set of 1000 randomly assigned points within the study area, and compared the predicted probability produced by the model with the actual land cover value. As with the set of points used to train the model, we defined points landing in forest as forest; those landing in grassland, shrubland, agricultural mosaic, and ice at elevations greater than 3000 m as alpine; and all other points as not applicable. This resulted in a total of 803 points identified as forest or alpine for the accuracy assessment. Finally, we tested the same variables using the maximum entropy model, Maxent (Phillipps et al., 2006). All of these supplementary analyses showed that the GLM with the four data variables described above produced the most accurate representation of the current alpine and forest zones.

2.3. Projecting forest and alpine zones under future climate scenarios

We analyzed the potential change in the alpine and forest zones under three IPCC-4 climate scenarios: low emissions (B1), medium–low emissions (A1B), and high emissions (A2) (Meehl et al., 2007a). For each emissions scenario, we selected an ensemble average of monthly precipitation and temperature variables from 16 General Circulation Models (GCMs) projected to 2070–2099, and downscaled to 0.5°. The selection of emissions scenarios and averaged GCMs represent a range of plausible future climates. However, even the highest emissions scenario we selected for this study may underestimate future climate change because global emissions rates from 2000 to 2007 have been shown to exceed predictions of even the highest IPCC scenario (McMullen and Jabbour, 2009; Raupach et al., 2007).

To prepare future climate variables, we began with monthly average temperature departure data for 2070–2099 and monthly total precipitation departure data for the same period (Zganjar et al., 2009). This departure data is the difference between current climate surfaces (from 1951 to 2000; Mitchell et al., 2004) and future downscaled climate surfaces (Meehl et al., 2007b).

We created future climate variables under each of the three emissions scenarios to match the current climate variables using a change factor approach (sensu Diaz-Nieto and Wilby, 2005; Ramirez and Jarvis, 2010; Wiens et al., 2011). The change factor approach maintains the original resolution of the climate change layers, while downscaling the future climate layers to match the resolution of the current climate and environment data used to map snow leopard habitat. This method assumes that future climate will follow current climate patterns (Ramirez and Jarvis, 2010).

We used the logistic regression function described earlier to project the "future" spatial distribution of forest and alpine zones under low, medium, and high emissions scenarios. The future alpine zone was next overlayed on current snow leopard habitat to identify the areas most and least vulnerable to change under climate change projections.

3. Results

3.1. Forest and alpine zone model accuracy

Of the four variables that emerged as significant drivers of the alpine zone, total snow was positively correlated with the probability that a particular point falls in alpine habitat, while the other three variables had inverse correlations (Table 1). These results are consistent with published hypotheses that suggest trees require a minimum growing season temperature and precipitation (Körner, 1998; Körner and Paulsen, 2004). The resulting model of forest and alpine zones had an accuracy of 98% for predicting the current alpine zone and 83% for predicting the forest zone. The latter is likely an underestimate of accuracy because some predicted forest zone points that are actually non-forest represent forests converted to agriculture or other human uses; slopes in the forest zone that are too steep to support trees; or wetlands in areas climactically suitable for forests. Since our objective was to predict the distribution of the alpine zone (where trees cannot grow due to climatic limitations), we deemed the accuracy level acceptable for the study.

3.2. Snow leopard habitat in the Himalaya and southern Tibetan Plateau

When the result was validated with snow leopard observations, we found that 78% of observations overlapped with pixels defined as habitat. We estimated 217,000 km^2 of snow leopard habitat, most of which is in nine large snow leopard habitat blocks (Fig. 1). All large habitat blocks are connected by dispersal habitat to form one potential metapopulation in the Himalayan region.

3.3. Snow leopard habitat change under climate change scenarios

The model projected that, under the IPCC's high emission scenario (A2), about 30% of snow leopard habitat will be vulnerable to change along the Himalayas (Table 2). Even if emissions remain relatively low (B1 scenario) and begin to decrease below current levels by 2050, up to 10% of snow leopard habitat could be lost (Table 2). Under the high emissions scenario, the number of large snow leopard habitat blocks will fragment from 9 to 15, and become smaller on average (Table 3). Two snow leopard habitat blocks would lose connectivity completely from the rest of the metapopulation and become isolated (Table 3).

Our results suggest that under the high emissions scenario (A2), Bhutan would lose about 55% of its current snow leopard habitat, while habitat in Nepal could decrease by as much as 40%. India and China would lose about 25% of their existing habitat in the Himalayan mountain range. In terms of absolute extent of habitat loss, however, China and India, which have the most snow leopard habitat, would lose considerably more habitat than Nepal and Bhutan (Table 2). Most habitat loss would be along the southern, peripheral areas of the snow leopard range and in the deep river

Table 1
Logistic regression results indicate that all four variables are very significant drivers of treeline. The AIC of the model was 1315.6, the lowest of all alternative models containing subsets of these variables.

Variable	Coefficient	Standard error	*z*-value	*p*-value
Intercept	12.054315	0.569147	21.180	
Average monthly precipitation during the growing season[a]	−0.079188	0.003245	−24.402	<2e−16
Total precipitation as snow[b]	0.045269	0.003790	11.944	<2e−16
Total precipitation December to February	−0.043399	0.004585	−9.466	<2e−16
Mean temperature during the growing season	−0.087770	0.005956	−14.736	<2e−16

[a] Growing season defined as months where mean monthly temperature >0 °C.
[b] Snow months defined as months where mean monthly temperature ⩽0 °C.

Table 2
The approximate amount of good snow leopard habitat (patch size >500 km^2) that might remain under different climate scenarios as a result of habitat change from alpine to forest cover.

Country	Original area (km^2)	Low emissions (B1) Remaining area (km^2)	Medium emissions (A1B) Remaining area (km^2)	High emissions (A2) Remaining area (km^2)
Bhutan	4900	4600	3200	2200
China	133,300	125,700	113,500	100,200
India	54,200	47,300	43,100	38,200
Myanmar	900	200	0	0
Nepal	20,000	17,500	14,600	11,700
Pakistan	3700	2300	2100	1900
Total	217,000	197,600	176,500	154,200

Table 3
Projected change in the area of large snow leopard habitat blocks ($\geqslant$1500 km^2) and their connectivity in the Himalaya under a high emissions scenario.

	Current	High emissions (A2)	% Change
Total area	216,935 km^2	148,918 km^2	−31
Total Number	9	15	67
Average size	24,104 km^2	9927 km^2	−59
Median size	3880 km^2	5254 km^2	35
Number of isolated habitat blocks*	1	3	

* Refers to number of isolated populations based on connectivity of snow leopard habitat by dispersal habitat.

valleys that incise the mountains (Fig. 1). North–south directed habitat connectivity between the Himalayan Mountains and the trans Himalayan region in Tibet should, however, remain.

4. Discussion

4.1. Sources of uncertainty

The IPCC scenarios lay out different trajectories for emissions, largely dependent on national and global policies, technological advances, and economic development plans (Meehl et al., 2007a). Conservation recommendations must take this uncertainty in greenhouse gas emissions and climate effects into consideration. We looked at three emissions scenarios to include a range of potential change.

A number of GCMs simulate current and future climate, each with their own set of assumptions about global weather patterns and regional manifestations. Most models tend to agree that the Himalayas will become warmer and wetter. Recent weather station data appear to confirm that temperature is increasing at three times the global average, while precipitation trends are more ambiguous (Christensen et al., 2007; Shrestha and Devkota, 2010; Xu et al., 2009). We selected the average of 16 GCMs for each of the three emissions scenarios, each of which represents a warmer and wetter trend in our study area.

There is also uncertainty in current climate surfaces. We selected interpolated climate surfaces that rely on global assumptions about weather patterns with respect to elevation, and show more accuracy regarding temperature than precipitation. These climate surfaces do not capture local weather patterns well (Hijmans et al., 2005), which can be highly variable over small distances in the Himalayas due to the complex terrain. But, this is the only current climate surface available at moderate resolution, necessary for a region where ecological niches are highly dependent on extreme changes in altitude.

Different species distribution models can produce different results (Elith et al., 2006; Pearson et al., 2006). We minimized uncertainty by first comparing two models: MAXENT and logistic regression, and selecting the better model of the alpine zone. We also carefully selected input variables to match the hypothetical drivers of forest cover and treeline. Finally, we compared the outputs of the treeline model with qualitative predictions and observations of treeline shifts attributed to climate trends, including recent studies from Nepal, (Vijayprakash and Ansari, 2009), India (Dubey et al., 2003), and the Tibetan Plateau (Ni, 2003). Our climate change-driven model predictions are corroborated by these sources and observations.

We note that natural factors such as topography, substrate, rate of soil formation, and wind can prevent or protract the upslope movement of forests where temperature and precipitation are otherwise suitable (Körner, 2007). Anthropogenic factors such as grazing and forest clearing for crops and pastureland can also influence habitat changes (Bauer, 1990; Nautiyal et al., 2004; Rawat, 1998). These latter areas, when heavily impacted by humans, are unlikely to serve as good snow leopard habitat (Wolf and Ale, 2009), currently or in the future.

The snow leopard habitat maps are also subject to uncertainty. The land cover, elevation, and ruggedness data layers are coarse scale representations of actual conditions, and come with their own inherent error. We calculated ruggedness based on a 500 m DEM (Lehner et al., 2008). The resulting ruggedness grid may mask sub-pixel variations in terrain, which may be important microhabitat for snow leopards. For this regional scale analysis, however, we felt that 500 m resolution was sufficient for identifying relatively rugged terrain compared with the surrounding landscape. The maximum dispersal distance used in our model may overestimate actual dispersal of snow leopards in the Himalaya, due to terrain that is more difficult to traverse in our study area as compared with Mongolia, where the dispersal study took place (McCarthy et al., 2005). We did not include data layers such as livestock grazing, prey availability, or hunting by humans of snow leopards and their prey, all of which have important influences on habitat use. As such, the maps should be interpreted as potential habitat given adequate prey, and where negative human impacts are controlled. While the scores we selected to create the map were based on available literature and expert opinion, the scoring and decision rules are nonetheless subjective. Indeed, all modeling approaches come with their own inherent error and bias (Araújo et al., 2005). Nonetheless, this regional map of potential snow leopard habitat in the Himalayan region can be interpreted as the best available.

4.2. Ecological and physiological factors for climate-integrated landscape design for conservation

Our results indicate that climate change could lead to some loss of snow leopard habitat in the Himalayan mountain range, but that substantial habitat will remain intact. Habitat in Bhutan, Myanmar, and Nepal is likely to be pushed northward toward the China border, while local populations in eastern China and northern India may become completely isolated. Most of the resilient areas occur along the southern boundary of China, emphasizing the need for a regional conservation strategy for snow leopard conservation to protect these areas.

We assumed that snow leopards will have limited capacity to adapt physiologically and ecologically to warming conditions, by using the same habitat preference scores in current and future versions of the snow leopard habitat model. If forests do move upslope under warming conditions as predicted, they will likely be occupied by common leopards (*Panthera pardus*), wild dogs (*Cuon alpinus*), and in Bhutan, tigers (*Panthera tigris*). Snow leopards will then have to contend with resource competition from these species, which are better adapted to forest habitats. The upper altitude limit of snow leopards and their prey will be determined by their physiological tolerance for oxygen deprivation. While high passes above 5500 m could act as dispersal corridors, it is unlikely that snow leopards will be able to live and hunt at these altitudes without the benefits of long term physiological adaptations (Sharma, 2002; Storz, 2007).

Anthropogenic threats to snow leopards may be exacerbated under climate change. For example, the switch from traditional, nomadic to sedentary livestock grazing systems (Yangzong, 2006) and increasing herd sizes (Mishra et al., 2003) is causing extensive degradation of alpine grasslands (Rawat, 1998). Collection of medicinal and aromatic plants from alpine areas is also intensifying to meet an increasing demand (Rai et al., 2000; Rawat, 1998). If the extent of alpine habitat shrinks and become fragmented under climate change scenarios, as indicated by our model, livestock grazing and plant collection could become confined and intensified in these smaller spaces, placing greater stress on habitats. Snow leopard prey species, which are now displaced by livestock and persecuted by herders as competitors for forage (Mishra et al., 2004) could then become locally depleted, causing snow leopards to prey on livestock (Wegge et al., 2012), and resulting in increased rates of retaliatory killing (Oli, 1994). Thus, the cascading consequences of climate change can place snow leopards in greater peril than from habitat loss alone. It is therefore important that current non-climate threats be addressed (Wegge et al., 2012) to reduce the potential impact of climate change (Thomas et al., 2004).

Climate change-integrated conservation strategies (sensu Hannah et al., 2002b) require incorporation of climate change, ecological, and anthropogenic impacts into the design, location, and management of protected areas systems (Hannah et al., 2002a,b; McCarty, 2001). Most of the general principles of landscape conservation, such as securing large core areas and maintaining connectivity through corridor and matrix management, remain relevant for climate change-integrated conservation strategies (Hannah et al., 2002b; Moritz et al., 2008). But, they also require that we are able to predict the trajectories of range shifts in species and habitats under climate scenarios with some degree of reliability (Lawler et al., 2006). In order to harness the power of climate projections while taking into consideration their inherent limitations (Hannah et al., 2002a; Heikkinen et al., 2006), we propose that we prioritize conservation efforts in the places where snow leopards already exist and are identified as being potentially less vulnerable to climate change. In this manner, we should positively influence snow leopard survival in this region, even if climate scenarios fail to play out.

4.3. Applicability of approach to conservation planning for other species and geographies

There are several salient aspects of our approach that have applicability to other species and regions. We developed and tested a hybrid approach to predict the effects of climate change on the habitat of an endangered species involving both mechanistic and correlative models. This type of approach has been recommended as a way to produce more reliable analyses of climate change impacts (Heikkinen et al., 2006; Vos et al., 2011). As part of this, we developed a treeline model that is based on global hypothesis about climatic constraints on tree growth at high altitudes. This model, which is highly accurate for predicting current treeline in the Himalaya, could be tested in other montane regions to anticipate the potential extent of treeline shift elsewhere in the world.

Umbrella species have been used in the past to prioritize areas for conserving the selected species and others sharing the same habitat (Branton and Richardson, 2010; Caro, 2003). While climate change is likely to affect individual species in unique ways (Parmesan, 2006), application of this model to umbrella species for which relevant ecological information is available can enable conservationists to develop reasonably accurate climate-integrated landscape conservation plans.

As near-term actions, we recommend that: (a) current non-climate related anthropogenic threats be addressed because, if unchecked, they could exacerbate the future impacts of climate change; (b) habitat less vulnerable to climate change be secured for conservation in the context of the landscape structure; and (c) that programs be implemented to better enable ecologically appropriate land use and management. While we acknowledge the uncertainties inherent in climate projections, we recognize the value of spatial models to guide and refine climate-adaptive conservation strategies. Indeed, as noted by Conroy et al. (2011), we cannot wait for all uncertainties to be resolved by prolonged hypothesis testing, especially given the urgent threats to biodiversity across the globe. Instead, we should proceed with climate-adaptive approaches that include monitoring of changes in habitat and in human communities, while implementing adaptive management measures that respond to evolving outcomes.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.biocon.2012.03.001.

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