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Climate refugia of snow leopards in High Asia

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ABSTRACT

Rapid warming in High Asia is threatening its unique ecosystem and endemic species, especially the endangered snow leopard (*Panthera uncia*). Snow leopards inhabit the alpine zone between snow line and tree line, which contracts and expands greatly during glacier-interglacial cycles. Here we assess impacts of climate change on global snow leopard habitat from the last glacial maximum (LGM; 21 kyr ago) to the late 21st century. Based on occurrence records of snow leopards collected across all snow leopard range countries from 1983 to 2015, we built a snow leopard habitat model using the maximum entropy algorithm (MaxEnt 3.3.3k). Then we projected this model into LGM, mid-Holocene and 2070. Analysis of snow leopard habitat map from LGM to 2070 indicates that three large patches of stable habitat have persisted from the LGM to present in the Altai, Qilian, and Tian Shan-Pamir-Hindu Kush-Karakoram mountain ranges, and are projected to persist through the late 21st century. These climatically suitable areas account for about 35% of the snow leopard's current extent, are large enough to support viable populations, and should function as refugia for snow leopards to survive through both cold and warm periods. Existence of these refugia is largely due to the unique mountain environment in High Asia, which maintains a relatively constant arid or semi-arid climate. However, habitat loss leading to fragmentation in the Himalaya and Hengduan Mountains, as well as increasing human activities, will present conservation challenges for snow leopards and other sympatric species.

1. Introduction

Accelerated global warming over recent decades is altering ecosystems and threatens biodiversity (Thomas et al., 2004; Walther et al., 2002). Known as the "roof of the world", the Tibetan Plateau and surrounding mountain ranges of Central Asia (henceforth referred to as High Asia (Kuhle, 1990), Fig. 1a) have warmed at more than twice the average warming rate of the Northern Hemisphere (Chen et al., 2009; Liu and Chen, 2000). This high rate of warming places the unique ecosystem of High Asia at risk and threatens many endemic mammals, such as the snow leopard (*Panthera uncia*), chiru (*Pantholops hodgsonii*), blue sheep (*Pseudois nayaur*) and wild yak (*Bos mutus*). Among them, the snow leopard is an apex predator that plays an important role in maintaining stability of the alpine ecosystem (Snow Leopard Network, 2014). Due to its small population size and threats posed by habitat loss, a declining prey base, and poaching, the snow leopard was listed as Endangered by the International Union for Conservation of Nature (IUCN) in 1972 (Jackson et al., 2008). The ongoing climate change characterized by rapid warming could further challenge the persistence of remaining snow leopard populations (Forrest et al., 2012).

Large climate shifts have occurred repeatedly in Earth's history, most recently in the glacial-interglacial cycles of the late Quaternary, which played an important role in the extinction of many megafauna species, such as the wooly mammoth (*Mammuthus primigenius*) and giant deer (*Megaloceros giganteus*) (Cooper et al., 2015; Koch and Barnosky, 2006). During cold periods, many warm-adapted species were locally extirpated, due to the advance of major ice sheets, whereas in warm periods the shift of shrubs and forest drove many cold-adapted tundra-steppe species to localized extinction (Guthrie, 2003; Willerslev et al., 2014). Yet some species survived the late Quaternary because of the

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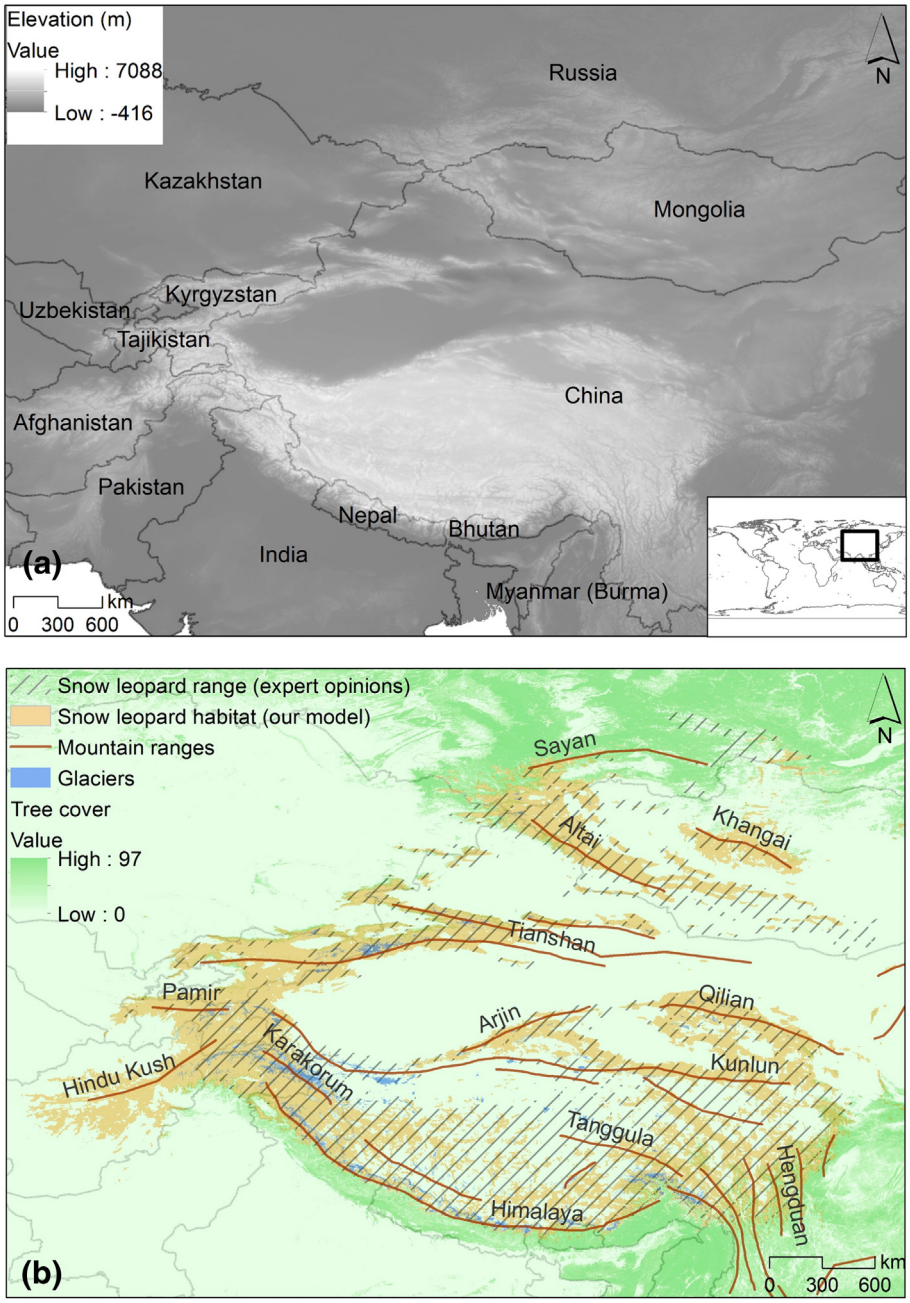

Fig. 1. Distribution of current snow leopard habitat in High Asia. (a), Location of the study region. The study region includes the Tibetan plateau and surrounding mountain ranges (referred to as High Asia). (b), Current snow leopard habitat distribution map. The distribution map predicted by our model (orange) was overlapped with the map derived by expert opinion (McCarthy et al., 2016) (hatched lines). Blue and green colors represent current glaciers (Armstrong et al., 2005) and tree cover (Hansen et al., 2013) ranges, respectively, while brown lines represent the main mountain ranges. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

availability of climate refugia, where they could retreat to, persist in, and expand from under rapid and severe climate changes (Ashcroft, 2010; Keppel et al., 2012). Refugia usually have a relatively stable climate and complex landscape topography, and thus offer the best chance for survival of many taxa when climate changes (Ashcroft, 2010; Morelli et al., 2016). The snow leopard, which originated on the Tibetan Plateau about seven million years ago (Tseng et al., 2014), currently inhabits the alpine zone that lies between the snow line and tree line throughout the mountains of High Asia (Fig. 1) (Snow Leopard Network, 2014). Such alpine zones contracted and expanded greatly during periods of glacier-interglacial cycling (DeChaine and Martin, 2004). Nonetheless, the snow leopard not only survived, but is thought to have had a relatively stable population throughout the late Quaternary (Cho et al., 2013). Analysis of how snow leopards survived the past glacial-interglacial cycles may shed light on understanding the impacts of 21st century climate changes on snow leopards and other species endemic to High Asia.

Here we build a snow leopard distribution model based on contemporary snow leopard occurrences throughout its range and associated bioclimatic variables. Using this model, we assess the impacts of climate change on global snow leopard habitat from the Last Glacial Maximum (LGM) to the late 21st century. We identify climate refugia for snow leopards in High Asia, and analyze the climatic factors and geographical features that promote the existence of refugia. Then we discuss climatic stability of the unique mountain environment in High Asia, which is favorable to snow leopard and other alpine species, and conclude by discussing the challenges to snow leopard conservation.