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Modeling distribution and habitat suitability for snow leopard (*Panthera uncia*) in the Great Gobi-A Strictly Protected Area of Mongolia

MASTER'S THESIS

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Declaration

I hereby declare that I have done this thesis entitled "*Modeling distribution and habitat suitability for snow leopard (Panthera uncia) in the Great Gobi-A Strictly Protected Area of Mongolia*" independently, all texts in this thesis are original, and all the sources have been quoted and acknowledged by means of complete references and according to Citation rules of the FTA.

In 15/08/2024

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Juno Shimada

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Abstract

Understanding species distribution and habitat suitability is critical for conservation efforts, especially for elusive species like the snow leopard (*Panthera uncia*). Species Distribution Models (SDMs) are effective tools for predicting habitat suitability using species occurrence records and environmental variables, even for elusive animals. This study aimed to provide a prediction of snow leopard habitat suitability in Mongolia and northern China and to compare the effectiveness of different occurrence record collection techniques: camera traps, GPS collars, and their combination. Using Species Distribution Models (SDMs), we analyzed 252 occurrence records from GPS collars and 17 from camera traps, alongside 10 environmental variables including 4 bioclimatic variables, 4 topographic variables, and 2 prey species distribution (Siberian ibex *Capra sibirica* and Argali sheep *Ovis ammon*), through an ensemble model framework which combines the outputs from multiple SDMs. The ensemble models identified 25260 km^2 (Camera traps), 31513 km^2 (GPS collar), and 30220 km^2 (Combined) as very high and high suitable area, which is less than 0.6% of the total study extent across all techniques. Suitable habitats were mainly located in the GGASPA and the Altai Mountain range in western Mongolia, with additional suitable areas near northern Qinghai province, China. These suitable habitats of all techniques were characterized by a prey distribution, particularly Argali sheep. The GPS collar and Combined models outperformed the Camera traps model, with the Camera traps model showing fewer unsuitable areas, while the GPS collar and Combined models were more conservative, indicating highly suitable habitats were confined to specific regions. This study provided a first prediction of suitable habitat for snow leopard in Mongolia and northern China, but also highlighted the need for various improvements. These findings emphasize the need for more comprehensive data collection in broader regions. The results also suggested that to use a combination of both data types: GPS collar and camera traps, while being mindful of potential geographic biases.

Key words: ecological niche modeling, remote sensing, prey abundance, camera trap, GPS collar, China

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List of the abbreviations used in the thesis

AUC:	Area Under the Curve
GBIF:	Global Biodiversity Information Facility
GGASPA:	Great Gobi-A Strictly Protected Area
GPS:	Global Positioning System
HSI:	Habitat Suitability Index
IUCN:	International Union for Conservation of Nature
PA:	Pseudo Absences
QGIS:	Quantum Geographic Information System
SDMs:	Species Distribution Models
TPI:	Topography Position Index
TRI:	Terrain Ruggedness Index
TSS:	True Skill Statistics
UNESCO:	United Nations Educational, Scientific and Cultural Organization
VIF:	Variance Inflation Factor

1. Introduction

Knowledge of species' distribution and habitat suitability is essential for effective management and conservation efforts for threatened species (Lham et al., 2021; Su et al., 2021). This knowledge enables us to identify regions with the highest conservation priorities, allowing us to optimize the designation of regions to where conservation efforts should be focused. This is especially important for rare species, which are susceptible to extinction, and for umbrella species which play crucial roles in their ecosystems. Protection of these species can have cascading benefits for the entire ecosystems. However, determining the distribution of these species is challenging if they have low occupancy, an elusive nature, and inaccessible habitat (Crisfield et al., 2024; Li et al., 2020; Watt et al., 2019). These conditions make it difficult to track them and predict their distributions.

The Species Distribution Models (SDMs) are valuable tools for predicting the spatial distribution and habitat suitability by relating the occurrence of species to environmental variables, such as bioclimate, land cover, and topographic data derived from remote sensing (Ahmad et al., 2020; Elith & Leathwick, 2009; Moudrý et al., 2024; Roy et al., 2022). SDMs for elusive species can be difficult to model appropriately due to the difficulty of obtaining suitable data. However, the presence-only modeling method provides a solution to facilitate SDMs for elusive species when reliable true-absence data are lacking (Swanepoel et al., 2012; Watt et al., 2019).

There are many types of techniques to collect species occurrence records for SDMs, such as from camera trap surveys, signs (footprint, scent marks, scrapes), feces, direct observation, museum specimens, and freely available databases (e.g., the Global Biodiversity Information Facility; GBIF). However, not many studies have been conducted using occurrence records from GPS collars which provide many occurrence records from one individual. In general, SDMs accuracy increases with sample size until an asymptote is reached (Sillero et al., 2021); therefore, GPS collars can have effective potential for SDMs. Most cases of SDMs combine occurrence records from various techniques. However, there are no studies comparing the outcome of using SDMs for each technique individually.

The snow leopard (*Panthera uncia*) is one good target species for predicting distribution using SDMs. Because the presence-only SDMs can facilitate predicting the distribution of species which it is difficult to detect in the wild due to their remote, inaccessible habitat and elusive nature (Ghoshal et al., 2017; Oberosler et al., 2022; Watt et al., 2019). The snow leopard is a globally threatened large carnivore inhabiting mountain regions of Central and South Asia (Oberosler et al., 2022). They are often considered as an umbrella species, a flagship species, and an apex predator which play key roles in regulating their ecosystems (Swanepoel et al., 2012; Watt et al., 2019). They inhabit high mountain regions at elevations up to 5800 m with low density, and especially prefer rugged and steep mountain terrain (Fox & Chundwat, 2016; McCarthy et al., 2005). However, even for this charismatic and threatened species, reliable information on its distribution is insufficient. Only one study has been conducted in Mongolia (Bayandonoi et al., 2021), despite being home to the second-largest population of snow leopards in the world (Munkhtsog et al., 2016). This study implemented modeling across the whole Mongolia, but its prediction did not encompass the surrounding countries. Since snow leopards may move across borders, transboundary prediction is also necessary. Particularly, little is known about the boundary between Mongolia and China, where about 60% of the world's snow leopard population is found (McCarthy & Chapron, 2003).

In this study, I explore the distribution of snow leopards in Mongolia and north of China close to the border with Mongolia and identify suitable habitats. I built an ensemble SDM framework, which combines the outputs from multiple SDMs, to forecast the distribution and understand the impact of the underlying biophysical, bioclimatic, and anthropogenic factors. Additionally, I compared the SDM outcomes based on different occurrence records collection techniques: camera traps, GPS collar, and a combination of both, to assess the effectiveness of using these techniques in SDMs.

2. Literature Review

2.1. Snow leopard (*Panthera uncia*)

2.1.1. Classification, distribution, and population

The snow leopard is an elusive large felid and globally threatened apex predator inhabiting mountain ranges of central Asia (Oberosler et al., 2022). It belongs to the genus *Panthera* of the family *felidae*, so-called big cats. They have been regarded as monotypic species *Uncia*, but recently, three subspecies were described by the genetic analysis: *Panthera uncia irbis* (Northern group: the Altai region), *Panthera uncia uncia* (Western group: Tian Shan, Pamir, trans-Himalaya regions), and *Panthera uncia uncioides* (Central group: core Himalaya and Tibetan Plateau) (Janečka et al., 2017). Because of the geographical boundaries between these groups. The first barrier, the Gobi Desert, separated the Gobi-Altai mountains in southern Mongolia from the Qilian mountains in northern Tibet Plateau, China, leading to the highest genetic differentiation. The second barrier was the low-lying area between the Tien Shan mountains of Kyrgyzstan/China and the western Altai Mountains of Mongolia/Russia, where there was admixture between western Mongolia and Kyrgyzstan/Tajikistan, suggesting more landscape permeability compared to the Gobi. The last barrier was marked by the lack of admixture between the Karakoram and Trans-Himalaya (Pakistan and Ladakh, India) and the core Himalaya populations to the east (Nepal/Bhutan/Tibet) (Janečka et al., 2017; Janečka et al., 2020).

The range of snow leopard spans from southern Siberia in the north across the mountains of Central Asia and the Tibetan Plateau to the Himalayas in the south, which contains 12 countries, including Afghanistan, Bhutan, China (Gansu, Nei Mongol, Qinghai, Sichuan, Tibet, Xinjiang, Yunnan), India (Arunachal Pradesh, Himachal Pradesh, Jammu-Kashmir, Sikkim, Uttaranchal), Kazakhstan, Kyrgyzstan, Mongolia, Nepal, Pakistan, Russia, Tajikistan, and Uzbekistan (McCarthy et al., 2017). They can be found in various mountain ranges such as Sayan, Altai, Tien Shan, Kunlun, Pamir, Hindu Kush, Karakoram, and the Himalayas, encompassing 2.8 million km^2 (McCarthy et al., 2016).

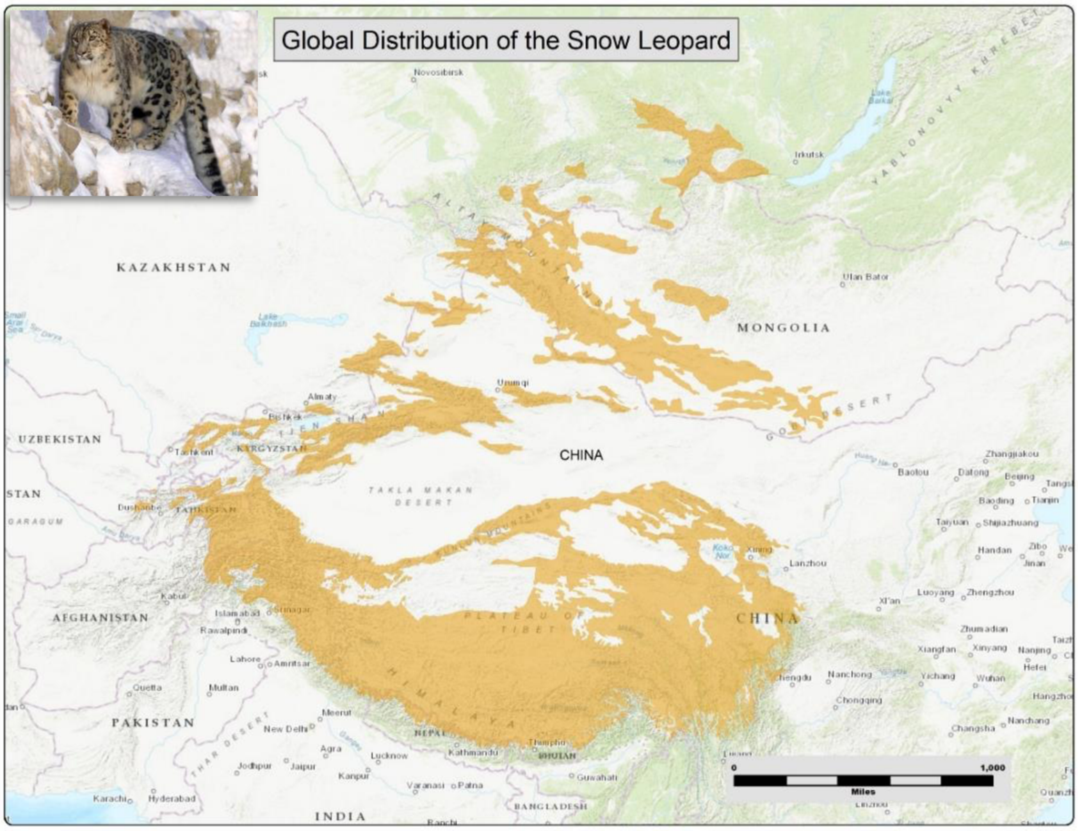

Figure 1. Current distribution of Snow leopard. Source: The Snow Leopard Conservancy.

Due to their secretive nature, generally low density, large home ranges, and remote terrain habitats that are difficult for people to access, the reliable distribution range and population of snow leopards remain uncertain (Oberosler et al., 2022; Suryawanshi et al., 2019). Although robust estimates are not yet available or updated, the global snow leopard population is estimated to be between 2710 and 3386 mature individuals (MacCarthy et al., 2017). Reported snow leopard densities from regional quantitative studies vary by region or country (Table 1). This variation can be partly explained by site-specific differences, such as habitat quality and prey availability. However, a significant portion of the variation is due to differences in survey methodologies (Janečka et al., 2020).

Table 1. Quantitative estimates of snow leopard density.

References	Study sites	Density (/100 km^2)
Alexander et al. (2016)	Qilianshan National Nature Reserve, China	1.4
Guoliang et al. (2016)	Dzungarian Alatau, China	13.2
Jackson et al. (2006)	Hemis National Park, India	8.5
Janečka, et al. (2011)	Tost Uul, Mongolia	1.4
Oberosler et al. (2022)	Suitai Mountain, Mongolia	1.31
Kachel et al. (2017)	Murghab, Pamir mountains, Tajikistan	0.74

2.1.2. Habitat and home ranges

They typically inhabit rugged and steep mountain terrain, at elevations of 600-4000 m in the northern part of their range to 1800-5800 m in the southern part (Fox & Chundwat., 2016; McCarthy et al., 2005). In nearly all parts of their range, snow leopards prefer steep, rugged terrain, well broken by cliffs, ridges, gullies, and rocky outcrops, but they especially prefer irregular slopes exceeding 40° and distinct landform edges, such as ridgelines, bluffs and ravines, provide pathways for movement within their home range (Snow Leopard Network, 2014). Most of their ranges are mainly treeless either due to alpine or desert conditions (Fox & Chundawat, 2016) with arid and semi-arid shrubland, grassland, and steppe vegetation (Kalashnikova et al., 2019). However, some areas have dense forest vegetation, such as the southern slopes of the Himalayas, the western and eastern edges of the Tibetan Plateau, and around the border of southwestern Russia and northern Mongolia (Fox & Chundawat, 2016). These habitat types are characterized by low oxygen and temperature, aridity, low productivity, steep rugged, and harsh climatic conditions. Therefore, snow leopards have evolved adaptations, both morphologically and physiologically, to survive in harsh environments (Kitchener et al., 2016). For example, dense and long pelage protects from cold climates, a large nasal cavity enables efficient countercurrent warming of inhaled air and cooling of exhaled air during breathing, their long tail acts as a balancing organ in the rocky mountain and is used as a muffler to warm their body, and they have mutations in ENGL and EPAS1, which are considered to contribute to physiological adaptation to high altitude (Janečka et al., 2020; Kitchener et al., 2016).

There is considerable variability in the reported home range sizes of snow leopards depending on the locations and countries. A snow leopard estimation study in Nepal using ground-based very high frequency (VHF) tracking reported that their home ranges were between 12 and 39 km^2 (Jackson & Ahlborn, 1989), between 13.9 to 22.3 km^2 (Oli, 1997), between 11 and 37 km^2 (Jackson, 1996). A similar study using VHF tracking in Mongolia in 2005 showed that the home range size of snow leopards ranged between 13 and 141 km^2; however, a satellite-collared adult male in this study showed a much larger range of 1590 km^2 at least (McCarthy et al., 2005). The study using GPS collars for 5 individuals in Mongolia showed that home ranges range between 26.1 and 395 km^2 (Rosenbaum et al., 2023). Not yet enough studies predicting home ranges have been conducted. Thus, information about their home ranges is still limited and biased. Moreover, the home range of snow leopards might be larger than it is suspected in many areas (McCarthy et al., 2005).

2.1.3. Behavior and ecology

Adult snow leopards are normally solitary, but they could form groups of 2-4 individuals during breeding season or with the birth of cubs. Snow leopard cubs stay with their mother for approximately 1-2 years. They apparently try to maintain distance from other individuals by actively avoiding each other, likely facilitated through scent-marking, scraping, and the deposition of other signs (Fox & Chundawat, 2016).

In a study conducted in southwestern Mongolia, year-round data from snow leopards equipped with activity-sensing collars showed that they were more active at night (51% of the time) compared to during the day (35%), with peak activity occurring during dawn and dusk (McCarthy et al., 2005). Another study in Mongolia showed that the peak activity of snow leopards occurs before sunrise and at sunset (Franchini et al., 2023). Snow leopards in Mongolia can make long-distance movements in a short period compared to those in the Himalayas. Snow leopards in Mongolia moved more than 12 km on 14% of the monitored consecutive days. (McCarthy et al., 2005). They use isolated massifs as waypoints when crossing large expanses of open steppe and desert between mountain range (McCarthy et al., 2000).

Snow leopards are known as opportunistic predators that consist of a wide range of prey species (Shehzad et al., 2012). They prey mainly on wild mountain ungulates and domestic livestock. They also prey on medium-sized and small mammals, game birds, and even invertebrates as a supplementary prey, including marmots (*Marmota sibirica, Marmota himakayana, Marmota baibacina, Marmota coudata, Marmot menzbieri*), hares (*Lepus oiostplus, Lepus tibetanus, Lepus timidus, Lepus tolai*), pika (*Ochotoma spp.*), snowcock (*Tetraogallus himalayensis, Tetraogallus tibetanus, Tetraogallus altaicus*), Chukar (*Alectoris chukar*) (McCarthy et al., 2017; Mallon et al., 2016). Sometimes, vegetation occurs in snow leopard scats (Mallon et al., 2016).The main wild mountain ungulates consumed by snow leopard including blue sheep (*Pseudois nayaur*), Siberian ibex (*Capra sibirica*), Himalayan tahr (*Hemitragus jemlahicus*), Argali sheep (*Ovis ammon*), markhor (*Capra falconeri*), Urial (*Ovis orientalis*) (Mallon et al., 2016; McCarthy et al., 2017). In many places, snow leopard distribution essentially overlapped with these mountain ungulates; therefore, the abundance and distribution of wild prey are the key drivers of snow leopard habitat use and density (Ghoshal et al., 2017; Salvatori et al.,2021; Suryawanshi et al., 2017). However, the primary prey varied by country or region: markhor (*Capra falconeri*) was most prevalent in Pakistan, Siberian ibex (*Capra sibirica*) in Mongolia and Kyrgyzstan, and blue sheep (*Pseudois nayaur*) in China (Hacker et al., 2021). In Mongolia, Siberian ibex (*Capra sibirica*) and Argali sheep (*Ovis ammon*) predominate in the snow leopard's diet (McCarthy, 2000; Shehzad et al., 2012). They differ in body size, with adult male Argali averaging around 90 kg and adult male ibex averaging about 75 kg. Both species are strictly diurnal, actively grazing from early morning until late afternoon (Odonjavkhlan et al., 2021). They occur in high-elevation mountain regions up to 5500 m.a.s.l. (Reading et al., 2020a; Reading et al., 2020b). Siberian ibex prefers the rugged terrain, whereas Argali prefers gentler slopes and also occurs in open desert habitats (Odonjavkhlan et al., 2021; Reading et al., 2020a; Zhuo et al., 2022). They are both listed as "near threatened" by the IUCN, and their current population trend is decreasing (Reading et al., 2020a; Reading et al., 2020b). Snow leopards stalk and kill their prey using a nape bite or suffocation through a throat bite. Subadult snow leopards around 20 kg can kill adult blue sheep weighing more than 55 kg (Fox & Chundawat, 2016).

Snow leopards also prey livestock including goats (*Capra aegagrus hircus*), sheep (*Ovis aries*), bovids (*Bos taurus*, *Bos grunniens*, and potentially hybrids), and horses (*Equus caballus*) (Hacker et al., 2021). The diet of snow leopards in Tost Uul, Mongolia, consisted of 73% wild species and 27% livestock on average throughout the year. However, the composition of livestock varies with the season, being 15% in the summer and 60% in winter (Johansson et al., 2015). Another study showed that livestock made up 31% of the diet in Pakistan and 15% in Mongolia.

There are some potential competitors of snow leopards, such as gray wolf (*Canis lupus*) Eurasian lynx (*Lynx lynx*), wild dog (*Cuon alpinus*), and common leopard (*Panthera pardus*). The gray wolf is similar in size to the snow leopard and shares its range with the snow leopard. However, wolves typically hunt in more open areas and are less adapted to the steep terrain preferred by snow leopards (Mallon et al., 2016). A dietary comparison study in Kyrgyzstan showed that snow leopards hunted argali and ibex in proportion to their availability, whereas wolves targeted argali more frequently and ibex less frequently (Jumabay-Uulu et al., 2014). In regions with livestock but few wild prey, predators may heavily rely on livestock, leading to potential competition (Bocci et al., 2017; Wang et al., 2014). Eurasian lynx also occurs across the snow leopard range, but they are more likely to prey on hares than ungulates (Khorozyan & Heurich, 2023). The common leopard has a distribution that borders the snow leopard's range along the Himalayas and in parts of China, although it primarily inhabits forests, which are not preferred by the snow leopard (Mallon et al., 2016). As these two species are similar in size and dietary habits, competition is likely where they coexist, particularly around the upper forest limit. As climate change causes the tree line to rise, the habitat for common leopards will increase, while that of snow leopards will decrease (Lovari et al., 2013).

2.1.4. Conservation status and Threats

The International Union for the Conservation of Nature (IUCN) Red List of Threatened Species has listed the snow leopard as 'Vulnerable' and currently their population is decreasing (MacCarthy et al., 2017). A large variety of threats affect snow leopards, leading to a global decrease in their abundance (Obrosler et al., 2022). Primary threats include habitat loss and fragmentation, reduction of natural prey, poaching, climate change, and increasing human-wildlife conflict arising from predation of livestock which leads to retailing killing (McCarthy et al., 2017; Snow Leopard Network, 2014). However, the type and extent of threats vary significantly between countries, particularly in large nations like China or Mongolia, where suitable habitats are widespread and divided among different administrative regions (McCarthy et al., 2017).

In recent years, livestock numbers have significantly increased in Central Asia. In contrast, the number of wild ungulates, which are the main natural prey for the snow leopard, has declined mainly due to competition for resource between livestock (Tumursukh et al., 2016). Consequently, the number of wild ungulates in many regions is currently between one and two orders of magnitude lower than that of livestock (Salvatori et al., 2021). Snow leopards occur at low densities in low-productivity and ecologically poor habitats; thus, the reduction of natural prey has a large impact on them. Furthermore, livestock can be prey of snow leopards in some areas; it may consist of 40%-70% of their diet due to lacking natural prey (MacCarthey et al., 2017). Reduction of natural prey potentially increases livestock depredation, and it imposes financial burdens that promote human-wildlife conflict and can result in retaliatory killing (Hussain 2003; Jackson & Wangchuk 2001; Valentová, 2017). Such retaliatory killings remove specific individuals, and herders sometimes try to sell body parts in illegal wildlife markets to recover some of their financial losses (Nowell et al., 2016).

2.1.5. Snow leopard in Mongolia

Snow leopards in Mongolia are typically found at elevations ranging from 600 to 4200 m a.s.l., which is generally lower than where they are commonly found in most of their range (McCarthy & Chapron, 2003). They are distributed across the Mongolian Altai, Gobi Altai, Trans Altai Gobi, Khangai, and Khovsgol mountain ranges containing around 103000 km^2 (McCarthy, 2000; Munkhtsog et al., 2016). The Altai Mountain ranges are recognized as one of the top three crucial and large landscape conservation units for the snow leopard (Tianshan-Pamir-Hindu Kush-Karakorum, Hengduan, Altai); moreover, they are considered an ecological corridor that connects northwestern China to the southern region of Siberia in Russia (Li et al., 2020). They prefer broken mountains with clearly defined ridge lines and cliffs, preferring at the elevation 2500-4000 m with steep slopes between 20 and 60° (Munkhtsog et al., 2016; Rosenbaum et al., 2023).

Mongolia has the second largest population number of snow leopards, estimated at about 1000 adult individuals, and represents the eastern-most population of wild snow leopards (Figure 1) (Mishra et al., 2016; Munkhtsog et al., 2016). They occur at low densities, estimated at 1.31 individuals per 100 km^2 in the Suitai mountain, which is part of the Altai Mountains, stretching from northwest to southwest (Oberosler et al., 2022) and 1.4 individuals per 100 km^2 in the Tost Uul, which is in Gobi Desert (Janečka et al., 2011).

Since the snow leopard is a top predator of the mountain ecosystem of Mongolia, it is considered as an umbrella species for conservation (Munkhtsog et al., 2016). It is protected and listed as a rare species in the Mongolian Wildlife Law and Mongolian Red Book (Bayandnoi et al., 2021). Mongolia plays a crucial role in regional conservation efforts for snow leopards as it borders China in the south, where about 60% of the global snow leopard population is found (Bayandnoi et al., 2021; McCarthy & Chapron, 2003).

In Mongolia, they are faced with many threats, such as loss of natural prey due to competition with livestock for water sources and pasture, loss of habitat due to the development of mining and transportation infrastructure, and poaching (Munkhtsog et al., 2016). Mongolia is the second poached country for snow leopards, following China (Nowell et al., 2016). However, with its climatic conditions and low human population density of 2 persons per km^2 could potentially offer a refugium for the species, if it continues to decline in most parts of its range due to climate change and human activities (Bayandonoi et al., 2021).

2.2. Species Distribution Models (SDMs)

Species Distribution Models (SDMs) are numerical tools that aim to predict and visualize the spatial distribution of a species by relating its occurrence to environmental variables under future, present, or past climatic scenarios (Ahmad et al., 2020; Elith & Leathwick, 2009; Moudrý et al., 2024; Roy et al., 2022). The output of the SDMs is interpreted as the probability of occurrence and the spatial projection of the model is used to forecast the distribution of populations. Additionally, the model output is interpreted as the Habitat Suitability Index (HSI), which is a measure of the ability of a habitat to sustain a species (Watts et al., 2019). It provides predictions of suitable habitats for target species.

A variety of methods are available to construct SDMs depending on the type of species occurrence data used such as presence-absence, presence-background, and presence-only methods (Sillero et al., 2021). The presence-only methods provide a solution for facilitating SDMs when reliable true-absence data are lacking (Swanepoel et al., 2012; Watt et al., 2019). One significant advantage of this method is that it requires only a set of occurrence records and corresponding environmental variables (e.g., bioclimate, land cover, topographic data derived from remote sensing, etc.), both of which are freely accessible in digital format (Arenas-Castro et al., 2022).

With the rise of new powerful statistical techniques, GIS tools, remote sensing, and GPS techniques, SDMs have come to be widely used in ecology and conservation biology (Guisan & Zimmermann, 2000; Melo-Merino et al., 2020). Some of the most common applications include estimating the distribution or suitable habitat for target species (Arenas-Castro et al., 2018; Lham et al., 2021; Su et al., 2021) predicting the impacts of future climate change on species distributions and habitat suitability (Arenas-Castro et al., 2020; Hereford et al., 2017), predicting and assessing the expansion of alien species distributions and the risk of invasion (Jiménez-Valverde et al., 2011; Shrestha & Shrestha, 2019; Thuiller et al., 2005), and conservation planning (Guisan et al., 2013; Regos et al., 2021).

2.2.1. Previous studies of predicting snow leopard distribution using modeling techniques

Some studies have been conducted to predict snow leopard's distribution or habitat suitability using modeling approach such as in Nepal (Aryal et al., 2016; Dominic, 2010; Forrest et al., 2012), India (Islam et al., 2023; Singh et al., 2020; Watts et al., 2019), Pakistan (Hameed et al., 2020; Rashid et al., 2021), Bhutan (Lham et al., 2021), Kazakhstan (Holt et al., 2018), Russia (Kalashnikova et al., 2019), China (Bai et al., 2018; Li et al., 2016; Li et al., 2021; Li et al., 2022: Xiao et al., 2019), and even global scale (Li et al., 2020; Li et al., 2022). Many of these studies focus on the Himalayan region or

Tibetan Plateau, whereas only one study has been conducted in Mongolia (Bayandonoi et al., 2021), despite it being home to the second largest population of snow leopards in the world (Munkhtsog et al., 2016). This study (Bayandonoi et al., 2021) implemented modeling across the whole Mongolia, but its prediction did not encompass the surrounding countries.

3. Aim of the study

The research aimed to investigate the snow leopard distribution in Mongolia and the area of China near the border with Mongolia using ensemble Species Distribution Models (SDMs) approach and the occurrence data from Great Gobi-A Strictly Protected Area of Mongolia.

3.1. Research objectives

1. To obtain the predictions of current distribution and identify suitable habitat for snow leopard in Mongolia and the border with China.
2. To determine the effect of biotic and abiotic factors on the snow leopard distribution and habitat suitability.
3. To compare the effectiveness of occurrence records collected from different techniques for setting SDMs (GPS collar vs. Camera traps vs. Combined).

4. Methods

4.1. Study area

The study area is part of the Great Gobi-A Strictly Protected Area (GGASPA), located in southwestern Mongolia bordering China (Figure 2). It occupies 4.419 million ha, with altitudes ranging from 525 to 2683 m.a.s.l. (Nasanbat et al., 2021). The area became a protected area in 1975 and was designated a Biosphere Reserve by UNESCO in 1990. Since then, it has become one of the largest Biosphere Reserves in the world. It has great desert and semi-desert ecosystems, and this extremely harsh environment has given rise to unique flora and fauna (Walzer & Kaczensky, 2005). The large mammal fauna in this area includes globally endangered species such as wild Bactrian camel (*Camelus bactrianus*), Gobi bear (*Urus arctos isabelinus*), Asiatic wild ass or khulan (*Equus hemionus*), Black-tailed gazelle (*Gazella subgutturosa*), Argali sheep (*Ovis ammon*), Siberian ibex (*Capra sibirica*) and snow leopard (*Uncia uncia*) (Batsaikhan et al., 2004).

The GGASPA has a large unvegetated depression surrounded by the mountain ranges, the Atas Bogd, the Tsagaan Bogd, Eej Uul, and Edren. The vegetation in the area is dominated by desert-steppe and semi-desert plant communities which are well-adapted to dry conditions and are shared with drylands of neighboring countries, mainly China (von Wehrden et al., 2006). The climate of the area is highly continental with long cold winters and short hot summers (Kaczensky et al., 2011). The east of the area is influenced by the Monsoon system and west of the area is influenced by western disturbances from the Mediterranean region; however, this area is screened against both circulation systems (von Wehrden et al., 2006) and gets little precipitation in summer and in winter. The precipitation is largely restricted to the summer, especially from July to August, usually in the form of showers with small amounts. In the mountain region, little or no snow falls during winter. Detailed climatic data of the eastern part of the area is only available from the Ekhiin Gol meteorological station at the northern boundary of the study area. Aerial temperatures of the area range from -34 ℃ to +40 ℃, and ground temperatures from -33℃ to +70℃. Annual precipitation is around 60 mm with ranges from 30 to 140 mm concentrated from July to August (Esposito et al., 2024; Nasanbat et al., 2021).

The GGASPA has a minimum anthropogenic effect due to its remoteness and restrictions on access to people. Therefore, GGASPA is ideal for predicting the natural habitat requirements of the species under minimum anthropogenic influence.

The study extent for SDMs (Figure 2) includes the whole Mongolia and the northern area of China near the border with Mongolia. Since snow leopards may move across borders, I included China near the boundary for transboundary prediction.

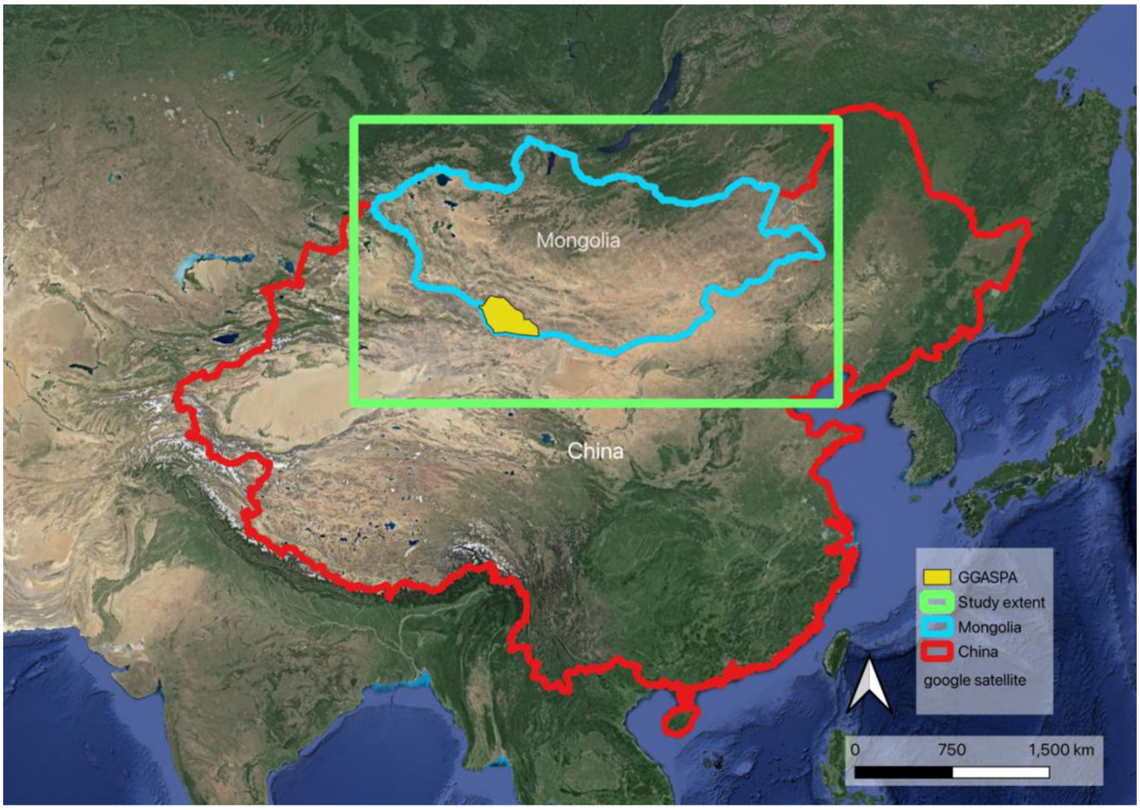

Figure 2. Location of Great Gobi-A Strictly Protected Area and Study extent for Species Distribution Models.

4.2. Data collection

4.2.1. Species occurrence data

4.2.1.1. Snow leopard

(i) GPS collar data

One adult male snow leopard (given name "Uuliin ezen") in Tsagaan Bogd mountain was collared from April 2019 to February 2020. During the survey, a total of 1130 snow leopard occurrence records were obtained from the collar. These occurrence records were spatially filtered to maximally one occurrence per 1×1 km^2 grid. Consequently, 252 snow leopard occurrence records were used in the model.

(ii) Camera traps data

The occurrence data of snow leopards from camera traps were collected through camera trap surveys in Tsagaan Bogd mountain from the 7th of December 2018 to the 28th of February 2019 (83 days), and in Atas, Inges mountain from the 3rd of June 2021 to the 28th of October 2021 (178 days). In the survey in Tsagaan Bogd mountain, 51 camera traps were set, and in Atas, Inges mountain, 36 camera traps were set. They were placed mainly along natural pathways frequently used by both carnivores and mountain ungulates, with a minimum distance of about 3 km between camera traps. The camera traps were positioned using ropes and stones at a height of 30-50 cm above the ground, without the use of baits. The cameras operated 24 hours a day, capturing a sequence of 3 pictures per passage, each with date and time stamps. Consequently, a total of 17 snow leopard occurrence records were obtained from two surveys and used in the model.

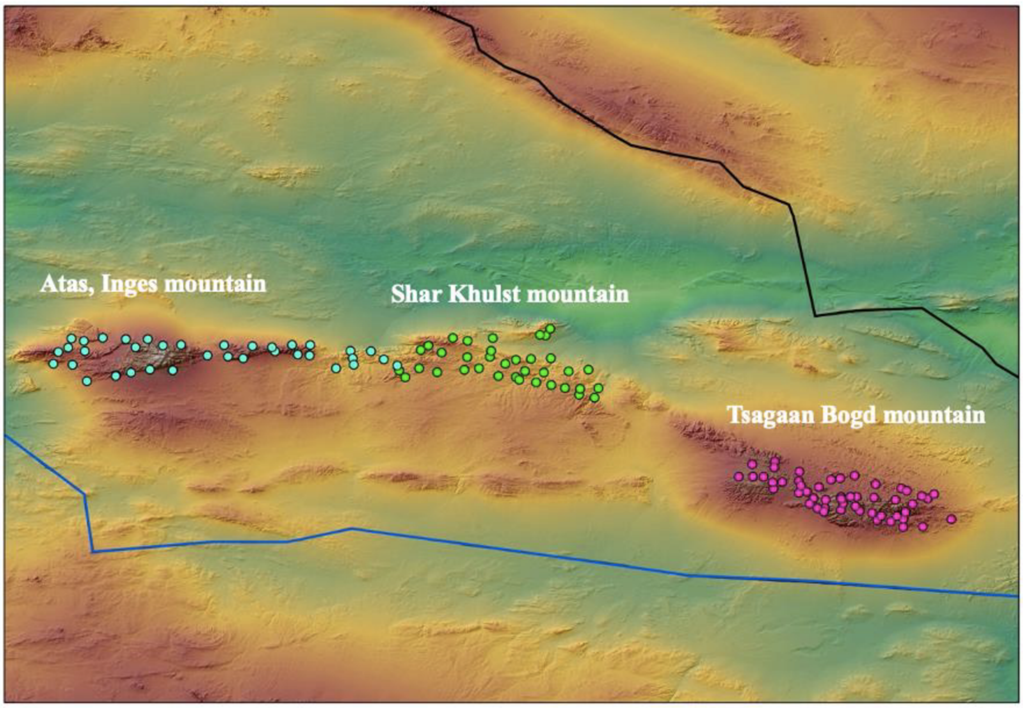

Figure 3. Location of camera traps in Great Gobi-A Strictly Protected Area.

4.2.1.2 Prey data

Siberian ibex (*Capra sibirica*) and Argali sheep (*Ovis ammon*) were chosen as preferential prey of the snow leopard because they predominate in the snow leopard's diet in South Gobi (McCarthy, 2000; Shehzad et al., 2012). The occurrence data of these species in GGASPA was recorded during camera trap surveys in Tsagaan Bogd mountain, in Atas, Inges mountain (same surveys as for the snow leopard), and in Shar Khulst mountain from 31st of March 2020 to 13th of June 2020. For the camera trap survey in Shar Khulst mountain, 37 camera traps (HCO Scout Guard and UOVision) were set across 35 sites, encompassing a total area of 725 km^2. The camera traps were set in the same way as for the other surveys already mentioned above. The Siberian ibexes were observed at 33 sites and Argali sheep were observed at 22 sites in total. In addition, to supplement the occurrence data, I obtained the 108 Siberian ibex occurrence data and 43 Argali sheep occurrence data from the whole Mongolia from the Global Biodiversity Information Facility (GBIF, https://www.gbif.org/), and these occurrence records were combined with camera traps data and spatially filtered to maximally one occurrence per 1×1 km^2 grid. A total of 77 Siberian ibex occurrence data and 61 Argali sheep occurrence data were used in the model.

Table 2. Summary of the presence-only records used in the study.

Species	Code	Source	Number of occurrences	Number of occurrences used for modeling
Snow Leopard *(Panthera uncia)*	Pu	The collar data from one individual	1,130	252
		Camera trap surveys	17	17
Siberian ibex *(Capra sibirica)*	Cs	GBIF	108	77
		Camera trap surveys	33	
Argali sheep *(Ovis ammon)*	Oa	GBIF	43	61
		Camera trap surveys	22	

4.2.2. Predictive variables

To calculate the model for predicting snow leopard distribution and habitat suitability, I obtained predictive variables consisting of bioclimate data, topography data, land cover data and potential prey distribution. Potential prey distribution was selected because wild prey abundance is one of the main influences on the population of snow leopards (Suryawanshi et al., 2013). Before obtaining these variables, I created the shape file of the area of interest which covers the whole of Mongolia and the northern part of

China by QGIS. Bioclimate data were acquired as 19 global bioclimatic variables from the WorldClim database (V2.1) at a resolution of 1 × 1 km^2 and cropped into the area of interest. The 19 bioclimatic variables characterize temperature and precipitations (Table 3). I obtained land cover data (the Dynamic Land Cover map from the Copernicus Global Land Service (CGLS-LC100) and the Digital Elevation Model (ALOS World 3D; AW3D30) from Google Earth Engine (Gorelick et al., 2017) at an original resolution of 100 m and 30 m, respectively. I derived topographic variables including elevation, aspect, slope, topography position index (TPI), terrain ruggedness index (TRI) from the Digital Elevation Model by using spatial analysis tools of QGIS. Since the resolution of topographic (30 m^2) and land cover (100 m^2) differ from the bioclimatic data (1 km^2), I resampled both datasets into the resolution of 1 km^2 using one of the bioclimate data as reference raster using the 'resample' function of the *raster* R package.

A higher correlation between predictive variables could affect model fitting (Sillero et al., 2021); therefore, I applied a multicollinearity analysis by using Spearman correlation coefficient and variance inflation factors (VIF) to remove factors affected by collinearity. According to the multicollinearity analysis results, the 12 variables with Spearman's pairwise correlation coefficient < 0.8 and VIF <10, were retained as predictors which include 6 bioclimatic variables (BIO2, BIO4, BIO5, BIO13, BIO15, BIO19), 5 topographic variables (aspect, elevation, slope, TPI, TRI) and land cover (Appendix 1 & 2). In addition, to narrow down the number of predictors for better modeling performance, I applied the density plot. Firstly, 500 points were randomly selected from predictive variable layers (background records). Secondly, I extracted primary selected predictive variables on prey occurrence records (presence data) and on background records (background data). After this data preparation, presence data were represented against background data by density plots. Based on the density plots, those showing a peak separated from a peak of the background plot were retained (Appendix 3). Thus, the final predictor dataset included 8 variables: elevation, slope, terrain ruggedness index (TRI), land cover, BIO2 (Mean Diurnal Range), BIO5 (Max Temperature of Warmest Month), BIO13 (Precipitation of Wettest Month), BIO15 (Precipitation Seasonality). Although it is recommended to select a set of predictor variables according to the number of occurrences (Sillero et al., 2021), I decided to select this set of variables because I believe that they better describe the environmental conditions and characteristics of the snow leopard's distribution range.

Prey distribution was also modeled using the occurrence records mentioned above and the predictive variables which were selected through multicollinearity analysis and the density plots. For snow leopard models, I included both prey (*Capra sibirica* and *Ovis ammon*) distribution models as additional predictor variables.

Table 3. Predictive variable data sets used in this study.

Predictors	Variable	Description	Units	Resolution	Source	As predictor
Bioclimate	BIO1	Annual Mean Temperature	°C	1 km	WorldClim (https://www.worldclim.org/)	×
	BIO2	Mean Diurnal Range				✓
	BIO3	Isothermality (BIO2/BIO7×100)				×
	BIO4	Temperature seasonality				×
	BIO5	Max Temperature of Warmest Month				✓
	BIO6	Min Temperature of Coldest Month				×
	BIO7	Temperature Annual Range				×
	BIO8	Mean temperature of Wettest Quarter				×
	BIO9	Mean temperature of Coldest Quarter				×
	BIO10	Mean Temperature of Warmest Quarter				×
	BIO11	Mean Temperature of Coldest Quarter				×
	BIO12	Annual Precipitation	mm			×
	BIO13	Precipitation of Wettest Month				✓
	BIO14	Precipitation of Driest Month				×
	BIO15	Precipitation Seasonality				✓
	BIO16	Precipitation of Wettest Quarter				×
	BIO17	Precipitation of Driest Quarter				×
	BIO18	Precipitation of Warmest Quarter				×
	BIO19	Precipitation of Coldest Quarter				×
Topography	elevation		m	30 m	Google Earth Engine (https://earthengine.google.com/)	✓
	slope		Degree			✓
	aspect		Degree			×
	TPI	Topography Position Index	-			×
	TRI	Terrain Ruggedness Index	-			✓
	Land cover		-	100 m		✓

4.3. Species Distribution Modeling

I implemented the SDMs for prey species (Siberan ibex *Capra sibirica* and Argali sheep *Ovis ammon*) to first predict their distribution. Then, I ran the SDMs again to predict snow leopard distribution using the modeled prey species distributions and the selected predictive variables. I calibrated SDMs based on the ensemble forecasting approach using the R package *biomod2* (version 4.2-1), which can run 10 modeling techniques at the same time. The algorithms available in *biomod2* are: (1) generalized linear model (GLM); (2) generalized additive model (GAM); (3) generalized linear boosting model (GBM); (4) classification tree analysis (CTA); (5) artificial neural network (ANN); (6) surface range envelope (SRE); (7) factorial discriminant analysis (FDA); (8) multivariate adaptive regression spline (MARS); (9) random forest (RF); (10) maximum entropy using Phillip's Maxtent software (MAXTENT. Phillips.2).

As only presence data could be obtained, I randomly generated pseudo-absences (PA), the same number of the occurrence (presence) points of species, and this process was repeated ten times in the model calibration. The use of pseudo-absences is necessary to address the lack of "true-absence" data required for model calibration; however, it also offers certain advantages, such as preventing the inclusion of inaccurate or false absence information (Arenas-Castro et al., 2020; Sillero et al., 2021). I used hold-out cross-validation to evaluate the models, with 30 evaluation runs for each PA, and setting 80% of the occurrence records to calibrate the models and 20% to test the model performance.

The effectiveness of each SDM was evaluated through true skill statistics (TSS) and the area under the curve (AUC), which are the most widely used evaluation metrics in SDMs. Finally, to deal with uncertainty in models coming from the single-algorithm techniques, I built ensemble (consensus) models among those satisfying the conditions AUC $\geq$ 0.7, and TSS $\geq$ 0.4. I used the weighted mean of all the partial projections (Marmion et al., 2009), a consensus method that considers the weights proportional to the selected evaluation scores (i.e., the higher the AUC of the model, the greater the importance in the ensemble modeling; Konowalik & Nosol, 2021).

4.4. Spatial projections

The output of ensemble models was interpreted as occurrence probability ranging from 0 to 1 and reclassified in R software into 5 categories: very high probable, high probable, moderately probable, low probable, not probable. These probabilities correspond to the snow leopard habitat suitability index, so they were characterized as very high suitable (values ranging from 1.0 to 0.8), high suitable (0.8-0.4), moderate suitable (0.4-0.1), low suitable (0.1-0.05), unsuitable (0). Then I projected the habitat suitability index to the map and calculated the occupied area by each class per map.

5. Results

5.1. Model evaluation and variable contribution

Except for three models in Camera traps (CTA, FDA, and MARS), all individual SDMs performed very well for both AUC (AUC_{Collar_mean} = 0.99±0.02, $AUC_{Combined\_mean}$ = 0.98±0.01, and AUC_{Camera_mean} = 0.97±0.06) and TSS (TSS_{Collar_mean} = 0.95±0.03, $TSS_{Combined\_mean}$ = 0.94±0.04, and TSS_{Camera_mean} = 0.94±0.17) metrics. Therefore, these three models were not used for ensemble modeling. Compared with overall models for three data sets (GPS collar, Camera trap, and Combined), the GPS collar showed the best model ensemble performance ($AUC_{Collar\_ensemble}$ = 0.99; $TSS_{Collar\_ensemble}$ = 0.98), followed by Combined ($AUC_{Combined\_ensemble}$ = 0.98; $TSS_{Combined\_ensemble}$ = 0.98) and Camera traps ($AUC_{Camera\_ensemble}$ = 0.97; $TSS_{Camera\_ensemble}$ = 0.96). However, some individual models for Combined and Camera traps have better performance than GPS collar, such as ANN and GBM for Combined, and MAXTENT for Camera traps (Figure 4).

In the Camera traps model, Argali sheep distribution contributed most (51%) to snow leopard habitat suitability, followed by Siberian ibex distribution (39%), BIO13, Land cover, elevation, and BIO15 (less than 10%; Figure 5). In the GPS collar model, Argali sheep distribution contributed the most (52%), followed by BIO13 (17%), BIO2 (13%), Siberian ibex distribution (11%), elevation, and BIO5 (less than 10%). In the Combined model, Argali sheep distribution contributed the most (54%), followed by BIO13 (21%), Siberian ibex distribution (13%), BIO2 (10%), elevation, and land cover (less than 10%). Argali sheep distribution contributed the most among all techniques. Siberian ibex distribution, also a prey species, has the second-most contribution in models for Camera traps, but less contribution in GPS collar and Combined. Therefore, in the Camera traps model, prey distribution contribution is more conspicuous. With regards to the climatic variables, BIO13 contributed the most in all techniques but the climatic variables that come next are different with each technique. In the Camera traps model, BIO15 comes next but in the GPS collar model and the Combined model, BIO2 comes next. Among the topographic variables, elevation contributed the most, followed by land cover; however, their contribution was less than 10% in all tchniques. Other topographic variables, such as slope and TRI, contributed very little (Figure 5).

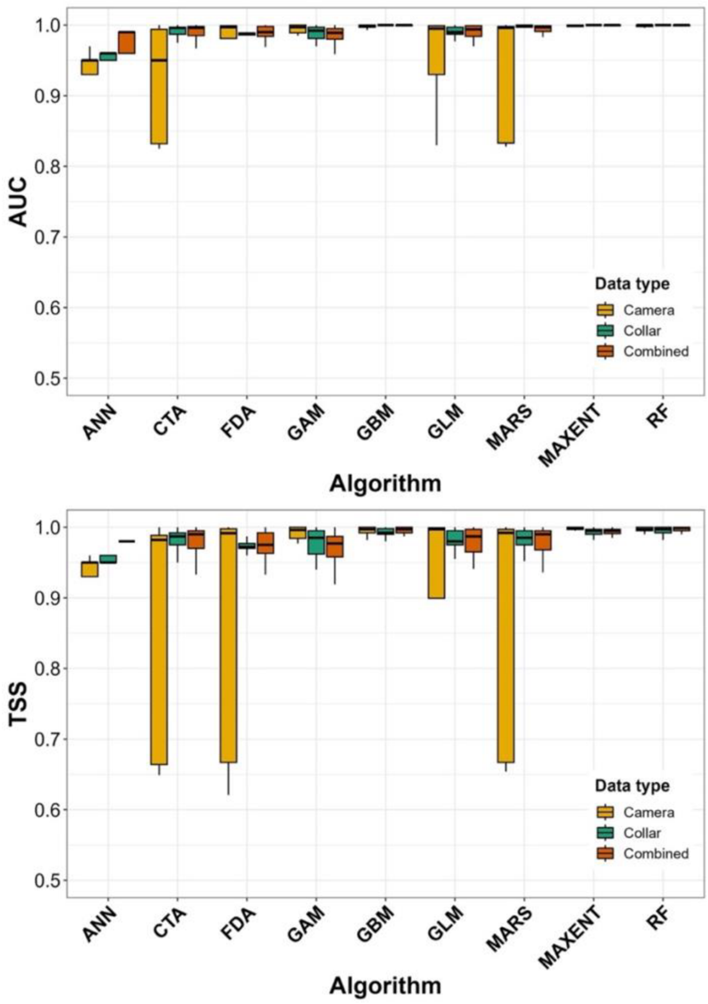

Figure 4. Comparison of model performance by each individual technique based on the AUS and TSS values.

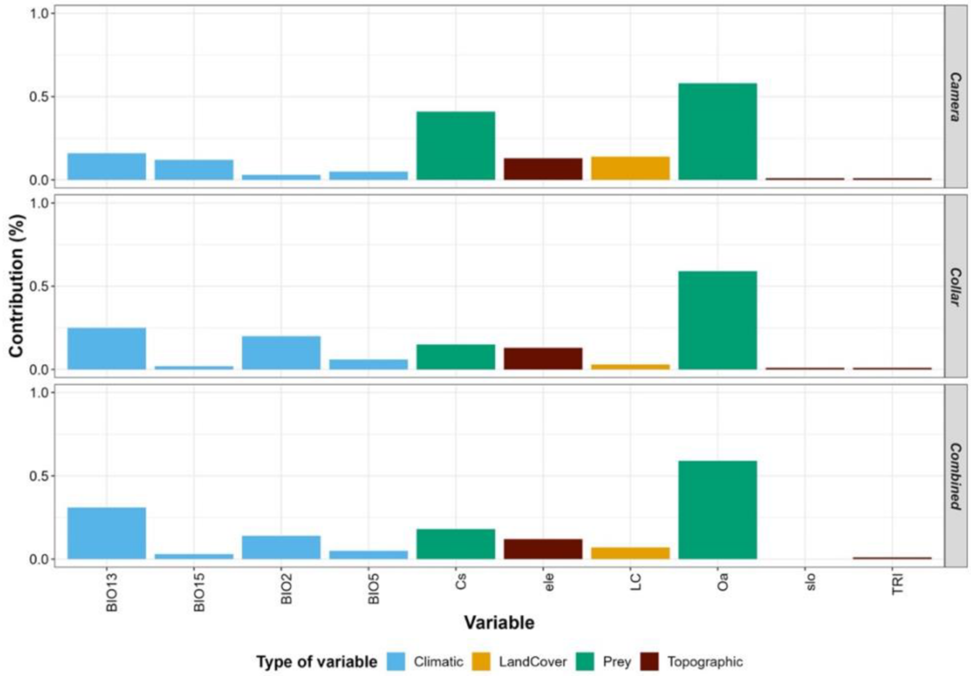

Figure 5. Variable contribution to the Maxent realized niche models for each occurrence data type.

Regarding the response curves, the highest values of probability of finding the snow leopard in the study area were overall related to >60% of suitable areas for both prey, Argali sheep and Siberian ibex, and precipitation of the wettest month (Figure 6).

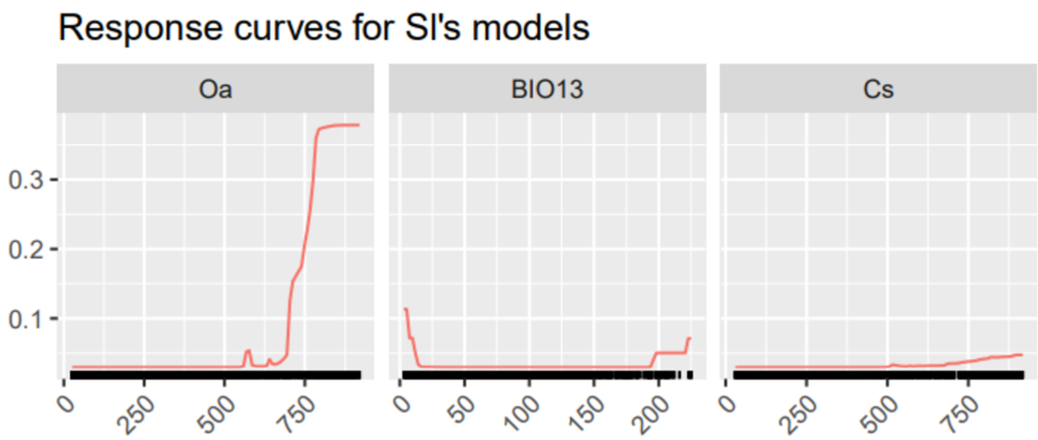

Figure 6. Response curves of predicted habitat suitability for the snow leopard (GPS-based model) to the most important predictors, Argali sheep (Oa), Precipitation of Wettest Month (BIO13) and Siberian ibex (Cs).

5.2. Habitat suitability map of snow leopard

The predicted suitable habitat map for the snow leopard based on ensemble modeling is shown in Figure 7 and the occupied area by habitat suitability classes in Table 4. In terms of occupied area, the low suitable area has the largest percentage in the Camera traps map (86.57%, 4856066 km²), while the unsuitable area has the largest percentage in the GPS collar map (76.39%, 4285290 km²) and in the Combined map (75.81%, 4252405 km²).

The combined area of very high suitability and high suitability only covers 0.44% (25260 km²) of the study extent in the Camera traps map, 0.55% (31513 km²) in the GPS collar map, and 0.52% (30220 km²) in the Combined map. The GPS collar map showed the largest occupied area of very high and high suitability. In the Camera traps map, the low suitable area covers almost the whole area, while in the GPS collar map and in the Combined map, the suitable areas are concentrated in the Gobi area, and the low suitable area encompasses the western regions of Mongolia. Therefore, it can be said that the Camera traps map is more generalist, while the GPS collar map and the Combined map are more conservative.

High or moderate suitable areas can also be found in China, the southwestern part of the study extent, across all techniques. Among the suitable areas in China, the highly suitable area on the Combined map is larger than on the Camera traps map and the GPS collar map.

Table 4. Summary of the occupied area (km^2) by habitat suitability classes.

	Data type		
Habitat class	Camera traps	GPS collar	Combined
Unsuitable	578396 (10.31%)	4285290 (76.39%)	4252405 (75.81%)
Low suitable	4856066 (86.57%)	1183810 (21.10%)	1155832 (20.61%)
Moderate suitable	149631 (2.66%)	108740 (1.93%)	170896 (3.04%)
High suitable	23647 (0.42%)	26861 (0.47%)	24642 (0.43%)
Very high suitable	1613 (0.02%)	4652 (0.08%)	5578 (0.09%)
Total		5609353	

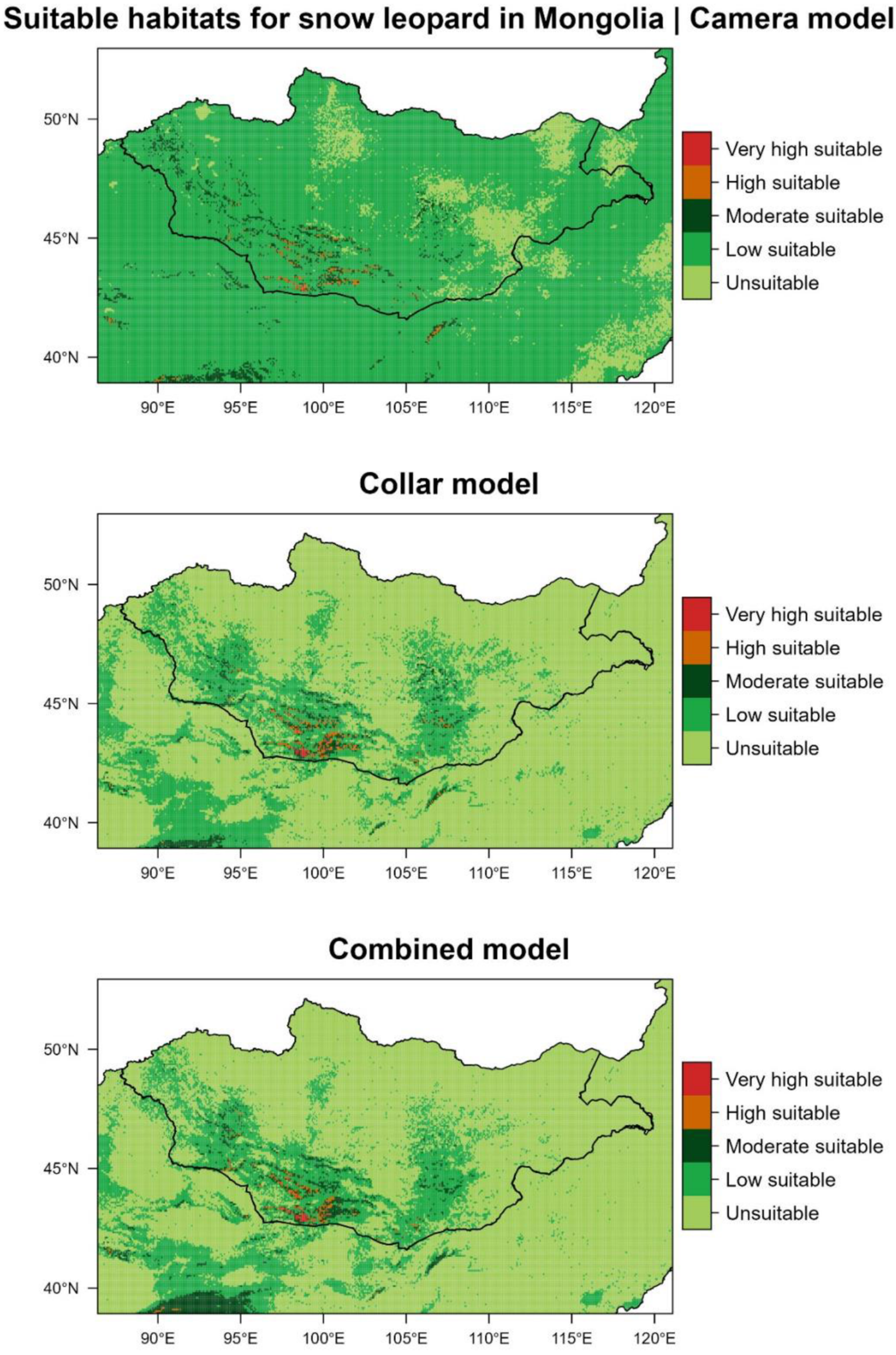

Figure 7. Habitat suitability maps of snow leopard for all techniques.

6. Discussion

In this study, I modeled and mapped the habitat suitability of the snow leopard under current climatic and environmental conditions using three types of occurrence records obtained from three different data collection techniques: GPS collar, camera traps, and a combination of both techniques. The very high and high suitable habitats accounted for less than 0.6% of the total study extent among all techniques. The results revealed that suitable habitats were primarily located in the GGASPA and the Altai Mountain range in western Mongolia. Additionally, areas with high and moderate suitability were found close to the northern Qinghai province in China.

Prey distribution was identified as a crucial factor in predicting suitable habitats for snow leopards. Specifically, Argali sheep (*Ovis ammon*) contributed more significantly to the suitability of habitats for snow leopards compared to the Siberian ibex (*Capra sibirica*).

Compared between the three techniques, the GPS collar and the Combined models demonstrated better performance compared to the Camera trap model. Furthermore, the habitat suitability map produced by the Camera trap model depicted a smaller extent of unsuitable areas, whereas the GPS collar and the Combined models were more conservative, showing a larger extent of unsuitable areas and indicating that highly suitable habitats were more restricted to specific regions.

6.1. Suitable habitat for snow leopards

This study predicted the habitat suitability for snow leopard throughout Mongolia and northern China using ensemble models. Overall, very high and high suitable areas encompass 25260 km^2 (Camera traps), 31513 km^2 (GPS collar), and 30220 km^2 (Combined), which are 0.42% (Camera traps), 0.55% (GPS collar), 0.52% (Combined) of the studied area. A previous similar study showed that <12% of Mongolia is used by snow leopards with a probability of over 50% (Bayandonoi et al., 2021). This discrepancy in suitable habitat size may be due to the size of the sampling area and variables used in the models. This previous study collected the occurrence records across 1017 grid-cells covering 406800 km^2 (40.68 million ha) of potential snow leopard range of Mongolia.

This is 10- fold larger than the GGASPA. They used only topographic and land cover variables such as ruggedness, elevation, NDVI (Normalized Differential Vegetation Index), and forest cover, while missing climatic variables and prey distribution. I assume that these differences affect the results, given that both temperature and precipitation (Mean Diurnal Range - BIO2 and Precipitation of Wettest Month – BIO13) were selected as two of the predictor variables that contributed the most to the models.

Regarding the location of the highly suitable areas, they were concentrated within the GGASPA, where the occurrence data were collected. In other regions, low to moderately suitable areas were found across the Altai Mountain range in western Mongolia. A global habitat suitability study indicated that the central region of the Altai, mostly encompassing western Mongolia, is one of the highest suitable habitats globally (Li et al., 2020). Bayandonoi et al. (2021) demonstrated a higher occupancy probability of snow leopards in the Altai Mountain range in western Mongolia compared to the results from our models. There are two possible reasons to explain these differences. First, the further away from occurrence data collection sites, the more challenging it becomes to accurately predict distribution or habitat suitability (Acevedo et al., 2012), leading to the assumption that our models may underestimate the suitable areas. Second, the two studies showed that terrain ruggedness significantly contributed to the distribution of snow leopards, while the GGASPA is less rugged compared to the Altai Mountain range in western Mongolia. However, this difference in the contribution of the terrain ruggedness might be attributable to the type and source of the data utilized. In two previous studies, the topographic data were obtained from the Shuttle Radar Topography Mission (SRTM), whereas in this study, the high-resolution digital surface model data from satellite remote sensing, which has a higher spatial resolution than that of the previous studies, were used. This gives a point of novelty to this study compared to other studies. Consequently, our models did not indicate highly suitable areas in the Altai Mountain range in western Mongolia.

I also identified a high and moderate suitable area in China, located in the northern part of Qinghai province (the northern corner of the Qinghai-Tibetan Plateau). Qinghai province contains some of the largest contiguous stretches of suitable snow leopard habitat and is a crucial distribution area in China (Liu et al., 2016). Li et al. (2021)

identified suitable habitat for snow leopards in Qinghai province, but their finding showed that suitable habitat was extend to the east or south of the area, with no suitable habitat found around the moderately suitable area identified by our models. However, they mostly collected the occurrence data from high elevation mountain areas, which are not located in the northern part of Qinghai province. Our models indicate that moderately suitable areas exist in the northern part of Qinghai province, suggesting that focusing data collection in this region might be valuable for further investigation.

6.2. Variable determining suitable habitat for snow leopards

The prey distribution contributed most significantly to the snow leopard habitat suitability in all the techniques. As previous studies in Bhutan (Lham et al., 2021), India (Ghoshal et al., 2017; Singh et al., 2020), and Mongolia (Salvatori et al., 2021) have indicated, prey distribution is the primary limiting factor for snow leopard distribution. In this study, among the two prey species considered, Argali sheep (*Ovis ammon*) contributed more than Siberian ibex (*Capra sibirica*). However, the diet composition of snow leopard in Tost Mountain in southern Gobi, Mongolia, revealed that Siberian ibex was the most frequently observed prey, constituting 70.4% of the feces, whereas Argali sheep constituted only 8.6% (Shehzad et al., 2012). Other studies have demonstrated a clear mutual co-occurrence of snow leopards and Siberian ibex, with their distribution being closely linked (McCarthy et al., 2005; Salvatori et al., 2021). Therefore, according to previous studies, the Siberian ibex should be the primary contributor to snow leopard distribution, but our results differed. However, some regions have indicated that Argali sheep can be predominant prey for snow leopards. A dietary study in Kyrgyzstan indicated that Argali sheep was the predominant prey, with over 50% frequency of occurrence in snow leopard feces (Jumabay-Uulu et al., 2014). Holt et al. (2018) demonstrated that snow leopards and Argali sheep shared a niche at low elevations in Kazakhstan. Argali sheep prefer more open habitats with gentle slopes and tend to avoid cliffs (Namgail et al., 2004; Odonjavkhlan et al., 2021; Reading et al., 2020a; Zhuo et al., 2022). Given that this model showed a low contribution of elevation, slope and ruggedness to snow leopard distribution, it is possible that Argali sheep and snow leopards share a niche in GGASPA. To confirm this result, the diet composition of snow leopards in GGASPA needs to be examined.

The second contributing variable was precipitation of the wettest month (BIO13). In other countries, temperature contributed more than precipitation (Aryal et al., 2016; Islam et al., 2023; Li et al., 2021; Rashid et al., 2021). These regions are located in the Himalayan Mountain ranges, where snow leopards inhabit elevations up to 7885 m, with elevation serving as a surrogate for temperature. Compared to these regions, the GGASPA has a lower elevation and a drier climate, making precipitation more crucial here than in other regions. Moreover, snow leopards in Mongolia tend to prey on wild ungulates rather than livestock during the summer (Johansson et al., 2015). The wettest months in Mongolia are July and August (Nasanbat et al., 2021; Esposito et al., 2024), and Iwasaki (2006) has found a positive correlation between precipitation and vegetation activity, which is important for wild ungulates. These facts suggest that precipitation could indirectly influence the availability of prey, which is a primary factor in snow leopard distribution according to the results of this study.

6.3. Comparing between three data collection techniques

Comparing the model performance between the Camera trap models and the GPS collar models, the GPS collar models showed significant better performance than the Camera traps models. Generally, model accuracy increases with increasing sample size until it reaches a plateau (Morgan, 2003; Somarathna, 2017). The number of occurrence points from camera traps was 17, while the GPS collar provided 252 occurrence points. Thus, the number of the GPS collar occurrence points was approximately 15 times greater than that of the camera traps. Differences in model performance might be due to differences in the number of occurrence points. Although all Camera traps models did not perform better compared with the GPS collar models, all models satisfied the conditions (AUC $\geq$ 0.7, and TSS $\geq$ 0.4) and even higher than the required conditions (AUC: minimum over 0.8 and maximum 1.0 TSS: minimum over 0.6 and maximum nearly 1.0). Therefore, it can be said that the Camera traps models performed well. In the the Combined models, it was anticipated that the all over models performance would surpass that of the GPS collar due to the increased number of occurrence points. However, while the Combined models performed better than the Camera traps models, most of the Conmibed models did not exceed the performance of the GPS collar models. I assume that this is caused by the geographic bias of the occurrence points. The camera trap points are scattered across the Atas, Inges mountain and the Tsagaan Bogd mountain, while the 252 points of the GPS collar are concentrated on Tsgaan Bogd mountain. Therefore, it can be said that the Combined data has a more scattered distribution of the occurrence points compared to the GPS collar data. If certain areas are disproportionately represented due to intensive local sampling efforts, the performance of the model can be strongly affected or even provide weak results (Barbet-Massin et al., 2010; Fourcade et al., 2014).

Regarding the model outcomes, the Camera traps model showed a different suitable habitat map compared to the GPS collar and the Combined model. The Camera traps model indicated a map with fewer unsuitable areas with large low suitable area, whereas the GPS collar and the Combined model were more conservative, showing suitable areas as being more restricted to certain regions. As I mentioned before, the camera traps occurrence points located in two areas while the GPS collar occurrence data is located in only one area and a large number of points are concentrated there. I assume that the concentration of occurrence points in a specific area leads to a more restricted selection of suitable habitats. Conversely, having fewer occurrence points spread over a wider range allows for a less restricted selection of suitable habitats.

6.4. Suggestions for improvement and future study

We can get a lot of occurrence points from a GPS collar. However, if it is only from a single individual, it can only provide the occurrence data for its home range. This led to geographical bias, which can cause the model to overrepresent the area, and spatial autocorrelation (Fourcade et al., 2014). Therefore, it would be a good idea to collect GPS collar data from several individuals in different areas.

In this study, I conducted SDMs for entirely of Mongolia and northern China using the occurrence data from GGASPA. The study extent covered approximately 412 million ha, while the GGASPA encompassed 4419 million ha. This represents a nearly 100-fold difference in size. The size of the study extent relative to the sampling area affects model calibration capacity, which measures how accurately it predicts the gradual occurrence probability, decreases as the study extent size increases. This is because larger areas often include regions far away from presence locations, making it difficult to infer the relationship between the species and its environment (Acevedo et al., 2012; Amaro et al., 2023; Lapez-Collado et al., 2024; Rousseau & Betts, 2022). This has led to the underestimation of areas that are actually suitable for snow leopards. However, habitat suitability does not always imply the actual presence or absence of a species. Therefore, it is essential to validate the modeling results by assessing how frequently the species actually inhabit the area, either through *in situ* observations or by using independent datasets, both from previously published studies and this study.

Human-snow leopard conflict and human disturbances pose significant threats to snow leopards globally (McCarthy et al., 2017; Snow Leopard Network, 2014; Valentová, 2017). Although Mongolia has low human population density, certain factors impact wildlife. Notably, human-wildlife conflicts arise from livestock depredation (Augugliaro et al., 2020; Mijiddorj et al., 2018) and the indirect effects of competition between livestock and wild ungulates (Rovero et al., 2020). Approximately half of Mongolia's population maintains a traditional lifestyle, with the majority being nomadic pastoralists (National Statistics Office of Mongolia, 2018). Consequently, livestock-related impacts on snow leopards have become a significant concern. Since the GGASPA is a Strictly Protected Area, human access is restricted and livestock grazing is not allowed, so that it can be said that there are almost no anthropogenic influences. Therefore, anthropogenic influence was not included as a predictive variable. However, if the study extent encompasses the entire Mongolia, it includes the area where human, livestock and snow leopard co-occur. In such cases, anthropogenic influences, such as human pressure and the distribution of livestock are better to be considered. On the other hand, only focusing on the natural environment in our models allows for the prediction of potential habitats in the absence of anthropogenic influence.

7. Conclusion

This study provided a first prediction of snow leopard habitat suitability across Mongolia and northern China and the evidence that different occurrence record collection techniques effect the results of models. The analysis revealed that highly suitable habitats are limited and are primarily located within the GGASPA and parts of the Altai Mountain range in western Mongolia. Additionally, the models identified potential suitable habitat in the northern part of Qinghai province, China, where detailed research has not yet been conducted. Since occurrence records were not collected from this area in this study, further analysis from this region is needed. There were discrepancies between these results and previous studies, indicating the influence of different sampling area sizes and type and sources of predictor variables used in the models. This finding emphasizes the need for more comprehensive data collection in diverse locations and consideration of various ecological variables.

Regarding variable contributions to suitable habitat, the results highlighted the importance of prey distribution on snow leopard distribution, especially Argali sheep. However, this finding contrasts with other regions where Siberian ibex is more frequently observed as prey. The differences between this study and previous research underscore the variability in factors affecting snow leopard habitats across different regions, emphasizing the need for region-specific conservation strategies. Further investigation into the diet composition of snow leopards in GGASPA is necessary to confirm if Argali sheep is the dominant prey over Siberian ibex in GGASPA. Additionally, a broader examination of environmental variables across various regions is recommended to enhance SDMs and support effective conservation efforts. While prey distribution and climatic variables are crucial determinants of snow leopard habitat, anthropogenic influences cannot be overlooked. Anthropogenic influences were not included in this study because human access and livestock grazing are restricted in GGASPA. However, for broader conservation efforts across Mongolia, it is imperative to consider anthropogenic influences on snow leopard habitats. Including anthropogenic influences in models for areas where humans, livestock, and snow leopards coexist would provide a more comprehensive understanding of snow leopard's distribution and habitat suitability and help in devising effective conservation strategies.

Comparing the three techniques of data collection, the GPS collar models demonstrated significantly better performance than the Camera trap models, likely due to the larger number of occurrence records. While the GPS collar data provides robust models due to a higher number of points, camera traps data offers broader geographic insights. Therefore, for comprehensive habitat suitability modeling, it is beneficial to use a combination of both data types, while being mindful of potential geographic biases. It is also suggested to collect GPS collar data from several individuals in different areas.

Overall, this study underscores the need for more comprehensive data collection in broader regions and consideration of various ecological and anthropogenic variables to improve predictions of habitat suitability.

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