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Siberian Ibex *Capra sibirica* Respond to Climate Change by Shifting to Higher Latitudes in Eastern Pamir

Yingying Zhuo [1,2,3,4,5], Muyang Wang [1,2,3,4,*], Baolin Zhang [6], Kathreen E. Ruckstuhl [7], António Alves da Silva [8], Weikang Yang [1,2,3,4,*] and Joana Alves [8]

1 State Key Laboratory of Desert and Oasis Ecology, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Urumqi 830011, China
2 Sino-Tajikistan Joint Laboratory for Conservation and Utilization of Biological Resources, Urumqi 830011, China
3 The Specimen Museum of Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Urumqi 830011, China
4 Mori Wildlife Monitoring and Experimentation Station, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Mori 831900, China
5 University of Chinese Academy of Sciences, Beijing 100049, China
6 Kunming Institute of Zoology, Chinese Academy of Sciences, Kunming 650223, China
7 Department of Biological Sciences, University of Calgary, 2500 University Drive Northwest, Calgary, AB T2N 1N4, Canada
8 Centre for Functional Ecology (CFE), TERRA Associate Laboratory, Department of Life Sciences, University of Coimbra, 3000-456 Coimbra, Portugal
* Correspondence: wangmuyang@ms.xjb.ac.cn (M.W.); yangwk@ms.xjb.ac.cn (W.Y.)

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Abstract: Climate change has led to shifts in species distribution and become a crucial factor in the extinction of species. Increasing average temperatures, temperature extremes, and unpredictable weather events have all become a part of a perfect storm that is threatening ecosystems. Higher altitude habitats are disproportionately affected by climate change, and habitats for already threatened specialist species are shrinking. The Siberian ibex, *Capra sibirica*, is distributed across Central Asia and Southern Siberia and is the dominant ungulate in the Pamir plateau. To understand how climate change could affect the habitat of Siberian ibex in the Taxkorgan Nature Reserve (TNR), an ensemble species distribution model was built using 109 occurrence points from a four-year field survey. Fifteen environmental variables were used to simulate suitable habitat distribution under different climate change scenarios. Our results demonstrated that a stable, suitable habitat for Siberian ibex was mostly distributed in the northwest and northeast of the TNR. We found that climate change will further reduce the area of suitable habitat for this species. In the scenarios of RCP2.6 to 2070 and RCP8.5 to 2050, habitat loss would exceed 30%. In addition, suitable habitats for Siberian ibex will shift to higher latitudes under climate change. As a result, timely prediction of the distribution of endangered animals is conducive to the conservation of the biodiversity of mountain ecosystems, particularly in arid areas.

Keywords: ensemble species distribution models; suitable habitat; latitude shift; human distribution; mountain ungulates

1. Introduction

The global ecosystem is being affected by human-induced climate change in unprecedented ways, e.g., phenological change, range shifts, community shifts, and so on [1–3]. For wildlife, climate change will produce a series of terrible outcomes that could further contribute to the sixth mass extinction, such as wildlife population declines and extinction, range distribution shifts, habitat fragmentation, and increased evolutionary pressure for all species [4–6]. According to Thomas, et al. [7], a quarter of terrestrial plants and animals may become extinct by 2050, under the 'middle emission scenario' of climate change. Spooner, Pearson and Freeman [4] predicted that mammal populations would decline by 1.46% to 1.76% annually under the scenario of 'representative concentration pathways 8.5'. In Asia, about 30% of terrestrial species will be at very high risk of extinction under climate change [8].

Habitat shifts and eventual loss caused by climate change are the most pervasive threats to wildlife causing species to migrate towards higher latitudes and/or higher elevations [9–11] and fragmenting suitable habitats [12,13]. For example, Hickling, et al. [14] predicted that 275 of 329 terrestrial species in Europe would move north in response to climate change. Alpine and plateau species are particularly sensitive to climate change as they are typically cold-adapted or cold-tolerant species [15]. In fact, studies have demonstrated that climate change has caused ibex (*Capra ibex*), chamois (*Rupicapra rupicapra*), and red deer (*Cervus elaphus*) in the Alps to move to significantly higher latitudes (i.e., to the north) [16]. Similarly, due to climate change, four antelope species on the Tibetan Plateau (*Procapra przewalskii*, *Gazella subgutturosa*, *P.picticaudata* and *Pantholops hodgsonii*) are predicted to lose up to 53.2% of their habitat and will be forced to move to higher latitudes [17]. In addition, in 90 years' time, the suitable summer range for Alpine ibex will diminish to 26.4% compared with 2011 under the RCP8.5 scenarios, and they will respond to high temperatures by moving to higher altitudes [18], as in the case of chamois who move upslope when it is hotter [19].

The alpine zone of the Pamirs is more sensitive to climate change because the temperature rise is much greater than that in the low-altitude areas [20,21]. Previous studies on ungulates living in the Pamir plateau have shown that climate change will reduce the range of these animals [22–24]. For example, the suitable habitat of Marco Polo sheep (*Ovis ammon polii*) in Eastern Tajikistan may be reduced by more than 60.6% and 63.2% by 2050 and 2070, respectively [22]. Because of climate change, the Chinese population of the same species is losing close to 40% of its suitable habitat, and this is mostly happening at low elevations [24].

The Siberian ibex, *Capra sibirica*, is a typical mountain ungulate, which inhabits the mountains of Southern Siberia, Mongolia, Tianshan, Himalaya, Karakorum, Altai, and Pamir [25,26]. Despite its wide distribution, the species remains poorly studied [27]. Siberian ibex are listed as "near threatened species" by the International Union for Conservation of Nature (IUCN) [25], and as "state second class protection animals" by China [28]. They usually occur at higher elevations from around 1500 m up to 6000 m above sea level. [29].These ibex mostly inhabit mountains, alpine meadows, exposed rock, precipitous terrain interspersed with cliffs, deep valleys, and steep areas with escape terrain [30]. The Siberian ibex mainly feeds on herbs and shrubs in the middle part of the Tianshan Mountains, which is one of seven of the largest mountain systems in the world, located in remote areas of Eurasia [31]. Throughout their distributional range, Siberian ibex show seasonal movement to higher ridgelines in the summer, descending to lower elevations in the winter [32,33]. Such movement can be entirely vertical or reach travel distances of 40 to 100 km [22]. However, Siberian ibex face disturbance from human activities and domestic competition (i.e., hunting and grazing), and climate change, with changes in temperature, wind, and precipitation listed as the main drivers affecting the survival of this species [25,29]. Therefore, it is urgent to study the potential responses of the Siberian ibex to climate change across its distribution range.

In this study, we analyzed the current distribution of Siberian ibex in the Taxkorgan Nature Reserve (TNR), which is located in the southwest of Xinjiang, China, and the factors affecting their distribution by using ensemble species distribution models (eSDMs), which are considered to improve predictive performance compared to individual species models [34,35]. We focused our efforts on determining whether or how the distribution of Siberian ibex will change in response to future global warming. We predict that the suitable habitat for Siberian ibex would decrease in the TNR in the future, and they would be forced to migrate to higher latitudes and/or elevations as a response to climate change. Our study will contribute to understanding the future of ungulates on the Chinese Pamir plateau under climate change. Furthermore, the study provides scientific guidance for the TNR's conservation planning, which needs to take into account potential future changes in the distribution of this species when designing conservation policies and planning the functional zonation of this nature reserve.

2. Methods and Materials

2.1. Study Area

The study area is situated in the Taxkorgan Nature Reserve (TNR) (35.5° to 37.5° N, 74.4 to 77.1° E, Figure 1, an area of ~16,253 km^2) in the eastern part of the Pamir, which is mainly distributed in Taxkorgan County, Xinjiang, China. As part of the Qinghai-Tibetan Plateau, the elevation of the TNR ranges from 2098 m to 8572 m above sea level, with an average elevation above 4000 m. The area has limited precipitation and a dry climate [36]. The average annual precipitation is less than 100 mm, the mean annual temperature is 3 °C, the highest temperature in July reaches 38 °C, and the mean temperature of the coldest quarter is −17 °C. The region is rich in wildlife. Besides Siberian ibex, sympatric ungulates include Marco Polo sheep and blue sheep (*Pseudois nayaur*, AKA bharal). All three species are preyed upon by the snow leopard (*Panthera uncia*). The vegetation is dominated by dwarf shrubs (mainly *Artemisia L.* and *Ceratoides*) and grasses (mainly *Stipa*) [37].

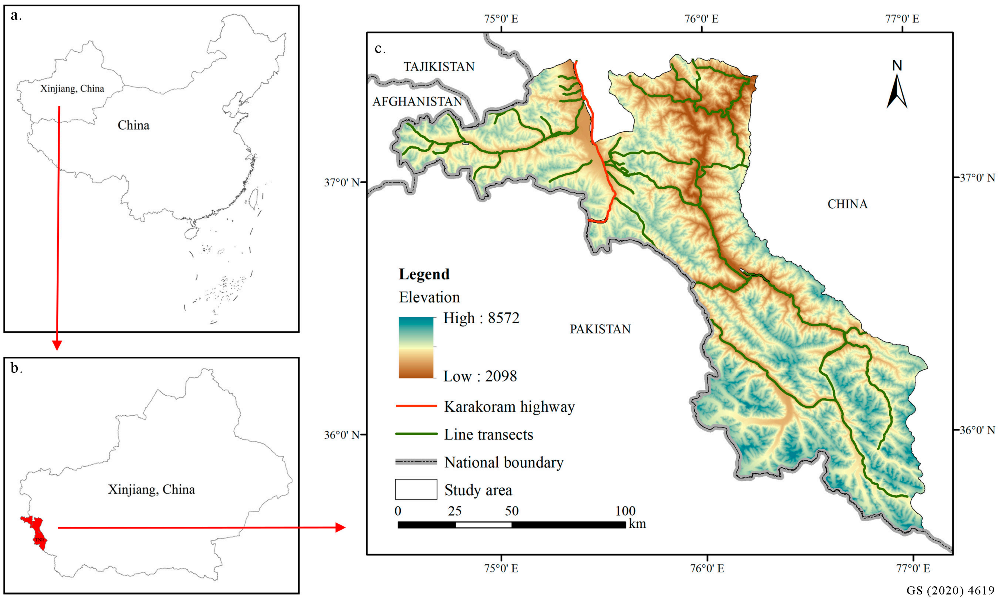

Figure 1. The study area is located in the west of China, which borders Tajikistan, Afghanistan, and Pakistan. (**a**) A map of China. It reflects the location of Xinjiang, a province in China. (**b**) Taxkorgan Nature Reserve (TNR) is located in the southwest of Xinjiang, China. (**c**) The map shows the borders of the Taxkorgan Nature Reserve, with elevation indicated on a green to orange scale. The Karakoram highway is indicated as a red line transect.

Most human settlements are located below 3500 m above sea level, i.e., along both sides of the Karakoram highway, which runs south from the city of Kashi up to the Taxkorgan Valley, through the Marco Polo sheep distribution area, and over the Khunjerab Pass into Pakistan. The southern part of this route lies in the TNR. The reserve is sparsely populated by nomadic Tajik and Kirgiz herding people and their livestock (about 23,000 in total), who live on both sides of the Karakoram highway and in the main valleys inside of the reserve [38].They move yearly between winter (lower elevation areas) and summer pastures (higher elevation areas with productive vegetation) [39,40]. In some areas of the TNR, Siberian ibex share their habitat with domestic animals, which compete with them for food and space. Since 2018, all of the coal and jade mines have been moved out of the reserve, so the herding people and their livestock are the main human disturbance to wild animals in the TNR.

2.2. Occurrence Data

We conducted a survey of Siberian ibex in the TNR from June to November of 2018 to 2021 (for more details on the line transect survey time please see Supplementary Materials Table S1). After interviewing the reserve staff and herding people, we set up 23 line transects with a total length of 1332.74 km, which covers all the habitats occupied by Siberian ibex in the TNR. Each transect was visited once a year. We followed the transects on foot, by car, and horseback according to the terrain, and scanned the surroundings with binoculars (ZEISS 10 × 42, Oberkochen, Germany) at intervals of 2–3 km to spot Siberian ibex. Upon locating Siberian ibex, we used a telescope (ZEISS 20–60×, Oberkochen, Germany) and laser range finder (ZEISS T*RF 10 × 54, Oberkochen, Germany) to observe and record their location (longitude and latitude), their elevation, and their angle and distance from our observation point. A total of 495 locations were set up along the line transects to search for Siberian ibex, and 123 occurrences of ibex were recorded, i.e., 26, 29, 36 and 32 distribution locations were obtained between 2018 and 2021. To reduce any potential spatial sampling bias (only one occurrence point is retained in each 1 km × 1 km grid), we performed spatial thinning of Siberian ibex occurrence data. The spatial thinning was performed using a randomization approach that maximizes the amount of useful information retained [41–43], while simultaneously reducing the sampling bias by removing as few records as possible using the 'thin' function of the "spThin" package (version 0.2.0) [44] in R (version 4.1.0) [45] with a thinning distance of 1 km. The spatial thinning process kept a total of 109 occurrence data points that were used to build the species distribution models.

2.3. Environmental Variables

We considered different environmental factors that can influence the presence of Siberian ibex, including climate, topography, anthropogenic disturbance, and availability of resources (i.e., Normalized Difference Vegetation Index (NVDI)) (Table 1). Climate data was obtained from the WorldClim version2.1 dataset for 1970–2000 (www.worldclim.org (accessed on 20 September 2020)) [46], with a resolution of around 30 arcseconds (roughly 850 m at the study area latitude). To predict the influence of climate change on Siberian ibex, we selected two projection periods for our model: (1) 2050 (average for 2041–2060) and (2) 2070 (average for 2061–2080) and three greenhouse gas emission scenarios: (1) RCP2.6 (low greenhouse gas emissions [47]), (2) RCP4.5 (medium greenhouse gas emissions [48]), and (3) RCP8.5 (high greenhouse gas emissions [49]) based on the Representative Concentration Pathways (RCPs) of Coupled Model Intercomparison Project Phase 5 (CMIP5). We chose the BCC-CSM1-1 as the General Circulation Model (GCM), which more closely conforms to the climatic conditions of our study area [50]. The 30 m resolution elevation data was derived from the Geospatial Data Cloud site of the Chinese Academy of Sciences (www.gscloud.cn (accessed on 2 September 2021)), from which we also calculated the aspect (the range of 0–360), slope (the range of 0–85), and ruggedness of the area, using ArcGIS 10.6 (ESRI). The latest version (1995–2004) of Human Influence Index, covering population density, human infrastructure, and human access was obtained from the Socioeconomic Data and Applications Center (sedac.ciesin.columbia.edu (accessed on 25 August 2021)) [51]. We derived the global land cover data from GlobeLand30 (www.globeland30.org (accessed on 3 July 2022)) and the NDVI from 2018 to 2021 from the DATABANK Remote Sensing Data Engine (databank.casearth.cn (accessed on 3 July 2022)) [52]. NDVI and HII data used in the future scenarios' models remain unchanged from the current dataset. All factor layers were projected to WGS 1984 UTM Zone 43N and resampled to a resolution of 850 m. To avoid collinearity between the environmental variables, we used the "usdm" package (version 1.1-18) [53] in R (version 4.1.0) [45]. We calculated the variance inflation factor (VIF) between predictor variables for each scenario, and then used a stepwise procedure to eliminate the factors with VIF > 10 [54]. All the variables that entered the ensemble species distribution models of the current and future scenarios were selected by the above processes when modeling the ibex habitat were labeled with an asterisk (Table 1).

Table 1. The environmental variables used in the ensemble species distribution models (eSDMs) of Siberian ibex in Taxkorgan Nature Reserve.

Variable Type	Variable Name	Description **	Unit
Climate	Bio1	Annual mean temperature	°C
	Bio2	Mean diurnal range	°C
	Bio3 *	Isothermality	-
	Bio4 *	Temperature seasonality	-
	Bio5	Max temperature of warmest month	°C
	Bio6	Min temperature of coldest month	°C
	Bio7	Temperature annual range	°C
	Bio8 *	Mean temperature of wettest quarter	°C
	Bio9 *	Mean temperature of driest quarter	°C
	Bio10	Mean temperature of warmest quarter	°C
	Bio11	Mean temperature of coldest quarter	°C
	Bio12	Annual precipitation	mm
	Bio13 *	Precipitation of wettest month	mm
	Bio14 *	Precipitation of driest month	mm
	Bio15 *	Precipitation seasonality	-
	Bio16	Precipitation of wettest quarter	mm
	Bio17	Precipitation of driest quarter	mm
	Bio18	Precipitation of warmest quarter	mm
	Bio19	Precipitation of coldest quarter	mm
Topographic	Elevation *	The height above sea level	m
	Slope *	The degree of steepness	°
	Aspect *	Orientation of the topographic slope	-
	Ruggedness *	The difference between the highest and lowest elevations in a given area	m
Human distribution	Human Influence Index *	The extent of human activity	-
Food resources	Land cover *	Land cover type	-
	Distance to water *	Distance from the nearest water source	m
	NDVI *	Normalized Difference Vegetation Index	-

Note: The asterisk (*) means this variable entered the ensemble species distribution models. The future environment variables are consistent with the current environment variables, both of which have been tested for collinearity, and they are all labeled variables in this table *. ** For more detailed information about climate variables see www.worldclim.org (accessed on 20 September 2020).

2.4. Species Distribution Model

The ensemble species distribution models (eSDMs) combine predictions across different modeling methods [55]. There have been studies showing that the performance of eSDMs is better than single models [34,35]. We used eight species distribution algorithms (generalized linear models, generalized boosting models, generalized additive models, artificial neural networks, flexible discriminant analysis, multivariate adaptive regression splines, random forest, and MaxEnt) [55] to build the eSDMs for Siberian ibex in the TNR. Firstly, we used a random strategy [56] to create 5000 pseudo-absence points [57]. We then split our occurrence data into two parts: one part with 80% of the data was used to calibrate the models, and the remaining part (20%) was used for model testing. All algorithms were run ten times and to obtain eighty single models. Then, we took the average TSS value of these eighty models as the threshold of whether to enter the eSDMs (above average TSS were entered in the final model) and built the ensemble model with a weighted average to project the habitat suitability map for Siberian ibex. The continuous probability of the presence of the eSDMs was transformed into binary values using a cut-off value that maximized TSS to estimate species vulnerability [58,59]. The AUC value (the area under the receiver operating characteristic curve; a value greater than 0.9 is considered excellent) and TSS value (a value greater than 0.85 is considered excellent; a value between 0.7 and 0.85 is good) were used to evaluate the performance of the eSDMs [60,61]. All eSDM analyses were performed using the "biomod2" package (version 3.5.1) [62] in R, version 4.1.0 [45].

3. Results

3.1. Current Habitat Distribution

The eSDMs for Siberian ibex in the TNR showed excellent performance with a high AUC (0.94) and TSS (0.77) value. Among the potential factors affecting the current distribution of Siberian ibex, precipitation seasonality, precipitation of the wettest month, Human Influence Index (HII), NDVI, elevation, and temperature seasonality were the main determining factors (Supplementary Materials Table S2). The presence probability of Siberian ibex was positively correlated with NDVI, and elevations of 3000 to 4800 m (Supplementary Materials Figure S1).

The current suitable habitat for Siberian ibex in the TNR is mainly distributed in the northwest and a small part of the northeast (Figure 2). The suitable habitat area is around 2702.15 km^2, accounting for 16.6% of the total area of the natural reserve.

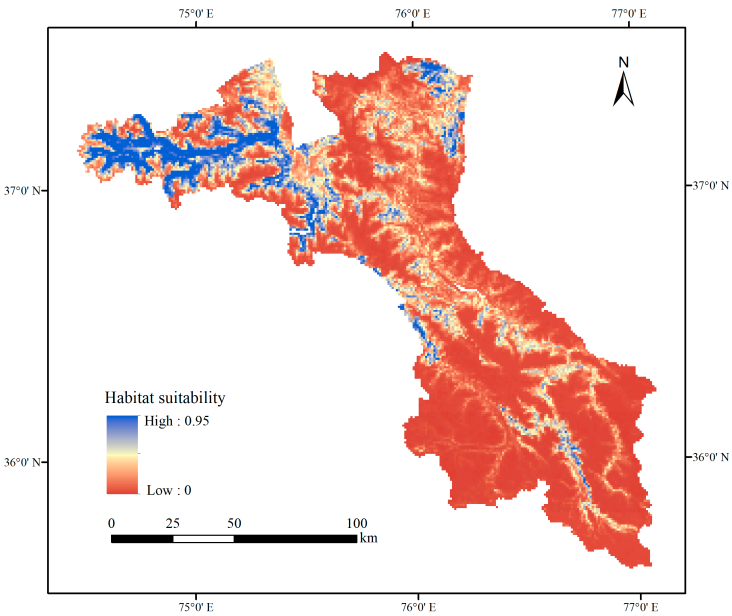

Figure 2. The current habitat suitability of Siberian ibex in Taxkorgan Nature Reserve.

3.2. Future Habitat Distribution

We simulated the potential distribution of Siberian ibex under three greenhouse scenarios for two periods. The performance of the six eSDMs was good (Table 2 and Supplementary Materials Table S3), in which the TSS value range was 0.78–0.81 (average of 0.793), and the AUC value range was 0.94–0.95 (average of 0.947). In these scenarios, temperature seasonality, mean temperature of the wettest quarter, and precipitation of the wettest month were found to be the main climate factors affecting the distribution of Siberian ibex, which will be driving the distribution of the Siberian ibex further in this region. In addition, HII, NDVI, and elevation will also affect the distribution of ibex. Human Influence Index (HII), the indicator of human impact, is also a main factor that will influence the distribution of ibex, since a high HII is not good for the survival of the ibex.

Table 2. Changes in suitable habitat of Siberian ibex in Taxkorgan Nature Reserve under different climate change scenarios.

Period	Future Scenarios	Suitable Habitat (km^2)	The Change of Suitable Habitat (km^2)			The Change of Suitable Habitat (%)	
			Stable	Gain	Loss	Gain	Loss
Current	-	2702.15	-	-	-	-	-
2050	RCP2.6	2290.33	1963.76	326.57	738.40	12.09	27.33
	RCP4.5	2268.65	1911.01	357.64	791.14	13.24	29.28
	RCP8.5	2234.70	1868.39	366.31	833.77	13.56	30.86
2070	RCP2.6	1984.71	1752.79	231.92	948.64	8.58	35.11
	RCP4.5	2577.88	2068.52	509.36	632.91	18.85	23.42
	RCP8.5	2478.90	2015.05	463.85	687.10	17.17	25.43

Our models indicated a tendency for a decrease in the suitable habitat of Siberian ibex in the TNR under the future climate scenarios (RCP2.6, RCP4.5, and RCP8.5 for both 2050 and 2070), while the magnitude of the reduction depends on the emission scenario, although most of the changes do not appear to be spatially substantial (Figure 3). The average decline of suitable habitat predicted in the future is 14.76%, when compared to the present. Under the RCP2.6 for 2070, the suitable habitat decreased the most, reaching 26.55% (717.4 km^2) in some models. Moreover, there was no obvious change in the distribution of Siberian ibex along the altitudinal gradient under climate change (Figure 4). However, we found that the centroid of Siberian ibex distribution tended to move north under different climate scenarios (Figure 5).

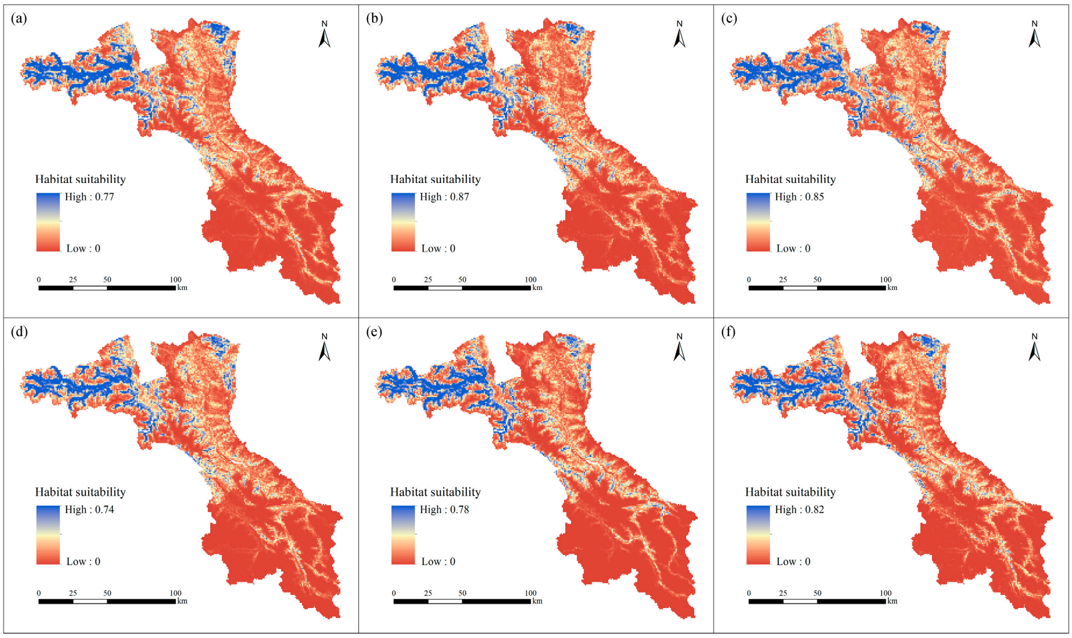

Figure 3. The habitat suitability of Siberian ibex in Taxkorgan Nature Reserve under three greenhouse gas emissions scenarios for two periods; top panel predictions for 2050 and bottom panels for 2070. (**a**) RCP 2.6 for 2050; (**b**) RCP 4.5 for 2050; (**c**) RCP 8.5 for 2050; (**d**) RCP 2.6 for 2070; (**e**) RCP 4.5 for 2070; (**f**) RCP 8.5 for 2070.

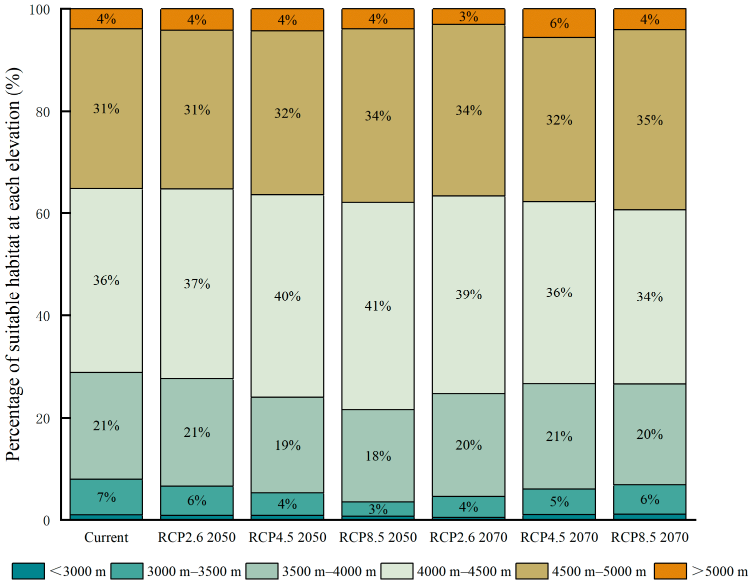

Figure 4. The proportion of suitable habitat area for Siberian ibex at different elevation gradients in Taxkorgan Nature Reserve under current and future climate scenarios.

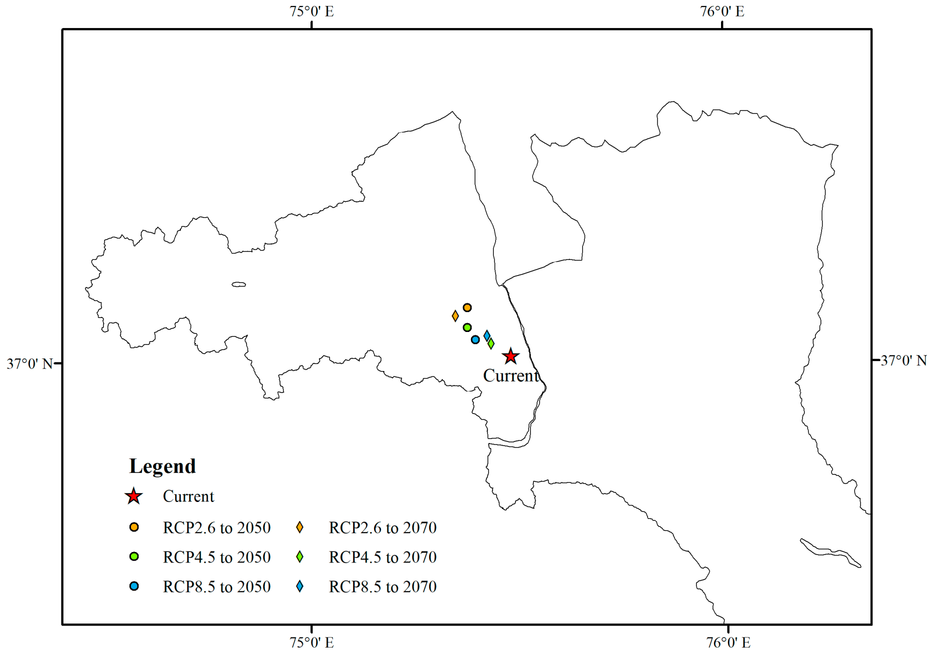

Figure 5. Centroid distribution of suitable habitat for Siberian ibex in Taxkorgan Nature Reserve under current and future climate scenarios. The average shift to the north is 5.81 km when the latitude difference is taken into account, and 10.20 km in the RCP2.6 for 2050.

We found that the northwest of the reserve was the most stable suitable habitat for Siberian ibex under any climate scenario (Figure 6). The area can act as a climate change refuge for Siberian ibex (Supplementary Materials Figure S2), which is the overlapping area of current suitable habitat and future stable suitable habitat. The region with major losses of current suitable habitat was mainly located in the southern part of the reserve, and the area with an increase was mainly located in the central part of the reserve. The loss rate of suitable habitat was highest under the scenarios of RCP2.6 for 2070 and RCP8.5 for 2050, reaching 35.11% and 30.86% loss, respectively. However, we found that the lost suitable habitat and the newly gained suitable habitat were not concentrated in low or high elevations under different climate scenarios. At the same time, we also found that the stable suitable habitats were mainly located in the northwest and a small part of the northeast of the reserve. Under RCP4.5 for 2070, the area of stable suitable habitat was the largest at 2577.88 km^2.

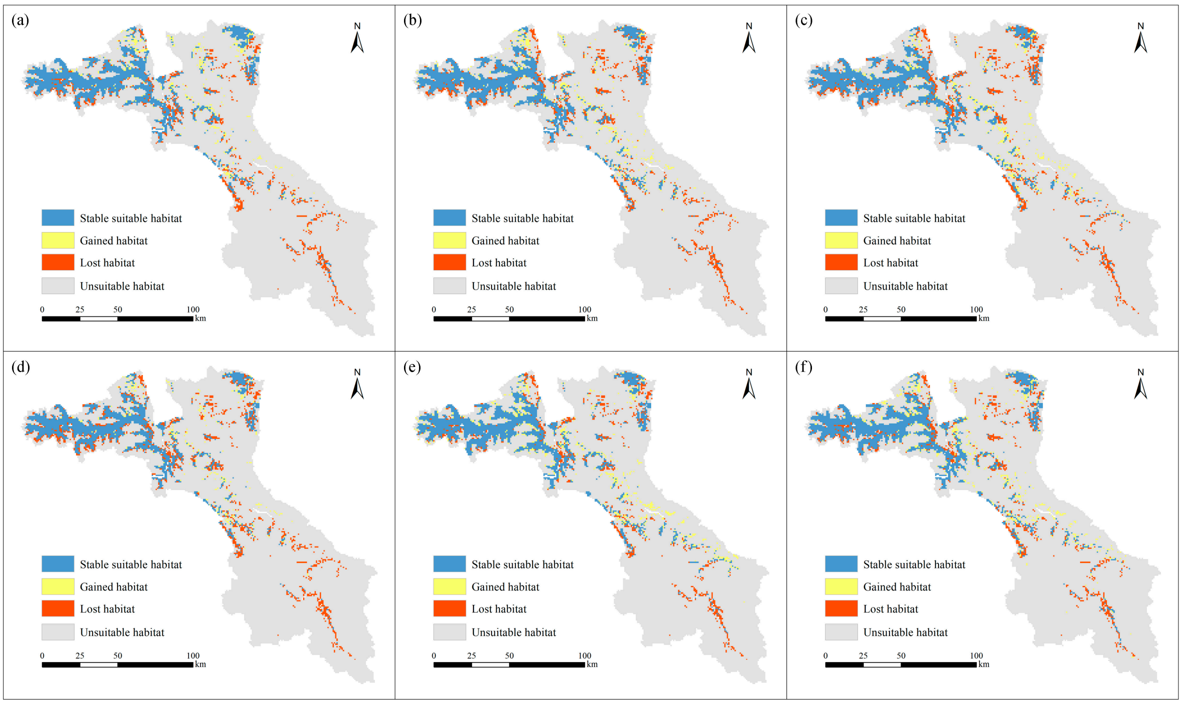

Figure 6. Transfer of suitable habitat for Siberian ibex between current and future climate scenarios in Taxkorgan Nature Reserve. (**a**) RCP 2.6 for 2050; (**b**) RCP 4.5 for 2050; (**c**) RCP 8.5 for 2050; (**d**) RCP 2.6 for 2070; (**e**) RCP 4.5 for 2070; (**f**) RCP 8.5 for 2070.

4. Discussion

Numerous studies have confirmed the profound influence of climate warming on the change in distribution of ungulates [15,63,64]. Such change could be deleterious, leading to a reduction in species abundance or even extinction as habitats deteriorate [65,66]. In the Apennines, Italy, the Apennine chamois may undergo a drastic decline in its historical core range in the next 50 years with a 95% reduction or near-extinction at worst [67]. The Taxkorgan Nature Reserve, located in the Eastern Pamir, is home to several ungulates, including the Siberian ibex. In the present study, we, for the first time, forecast the potential habitat shifts/loss of Siberian ibex in the Eastern Pamir under climate change. We showed that climate change and human disturbance have combined negative impacts on the distribution of Siberian ibex.

Suitable habitat for Siberian ibex currently accounts for only 16.6% of the reserve. Suitable habitat would further contract in the future because any newly gained suitable habitat would be smaller than the habitat being lost. The extent of habitat loss could be up to 29.15% and 27.99% at most by 2050 and 2070, respectively, depending on the climate change scenarios we used in our models. This is partially because the Pamirs are a complex ecosystem that is highly vulnerable to climate change. For example, the glaciers in the Eastern Pamirs that play a crucial role in the water cycle in high elevation areas [68] continue to accelerate their retreat [69] due to a significant upward trend in temperature and precipitation [70]. Meanwhile, reliable water sources remain crucial for the survival of animals [71,72] and the survival and distribution of plant communities. In fact, our models confirmed that the distribution of Siberian ibex in this region is strongly affected by precipitation (precipitation seasonality and the precipitation of the wettest month) and temperature (temperature seasonality). This is consistent with the results for Siberian ibex in Tajikistan [29] and in Pakistan [73]. The rise in temperature will likely cause Siberian ibex and other alpine ungulates to show behavioral and physiological responses, such as heat avoidance and heat stress, leading them to move to higher elevations or seek shade in the short term [16]. Furthermore, the precipitation of the wettest months may affect the distribution of ibex via the change in the phenology and richness of plants [17,74]. In addition, we found that Siberian ibex prefer to inhabit areas with high NDVI, i.e., where there is high vegetation cover allowing species to acquire food without moving too far [29,75]. Ruggedness is also a vital factor that influences the distribution of Siberian ibex in the TNR. The rugged terrain helps ungulates avoid predators [29,76]. In our study, the probability of the presence of ibex decreases accordingly when HII is greater than 15. A higher HII value means more serious human disturbance, which means ibex prefer to inhabit areas with low human disturbance.

Much wildlife has shifted its geographic distribution toward higher elevations or latitudes [5,67,77–79], and Chen et al.'s (2011) meta-analysis showed that the distribution of many species has recently shifted to higher elevations at a median rate of 11.0 m per decade [9]. Interestingly, we have not found such a shift to higher elevations, i.e., the distribution of Siberian ibex at different elevations remained unchanged under future climate scenarios. Similarly, no change in elevation was found for most ungulates in the Tibetan plateau [63]. Non-elevational shifts in those ungulates may be the result of physiological temperature thresholds and precipitation tolerance on the one hand. On the other hand, due to the high elevation in the plateau, there are very few areas available at high elevation for most ungulate species to colonize near their range boundaries and upward migration is thus limited [63,80,81]. As part of the Tibetan Plateau, the Pamir plateau may put the same stressors on wildlife, meaning that Siberian ibex may not have any additional room to climb to higher elevations. Furthermore, another study on ungulates, including Tibetan antelope *Pantholops hodgsoni*, Kiang *Equus kiang*, and wild yak *Bos mutus* living on the Tibetan Plateau, revealed that the distribution of the main forage plants will be reduced by more than 50% in response to climate change [64]. Indeed, research by Walther, et al. [82] showed that there has been an upward shift in alpine plants. Meanwhile, the reduction in mountain surface area with rising elevation [83] may not provide Siberian ibex with contiguous patches of habitat. Therefore, the Siberian ibex may simply run out of space to move to.

In our study, human disturbance may further contribute to the non-elevational shift of Siberian ibex. In the TNR, the lower elevation region experiences strong human disturbances, including settlements and infrastructure (HII in our model) [36], where Tajik herding people graze their livestock [38]. Meanwhile, there is strong food competition between Siberian ibex and domestic sheep, and Siberian ibex show strong avoidance behavior towards domestic sheep, which reduces their range of activity [84]. Thus, a series of human disturbances forces Siberian ibex to abandon potential suitable habitats at lower elevations leading to a reduction in the vertical distribution range of ungulates [85], which is similar to the effects found in primates and Walia ibex (*Capra walie*) [85–87].

In addition to responding to climate change by moving to higher elevations, species may also move to higher latitudes to acquire new habitats [14,88]. Global species distribution shifts under climate change are estimated to move toward higher latitudes at a rate of 16.9 km/decade [5,9,14]. By analyzing the centroid of suitable habitat for Siberian ibex at present and the centroid under different climate scenarios, we found that Siberian ibex in our study area showed a trend of moving northward under future climate scenarios. This is consistent with the study of Marco Polo sheep [22] and ibex [29] on the Pamir plateau in Tajikistan, which have the same shift trend in response to climate change. Similarly, research on Britain's mammals has shown that they have shifted 22 km north in the past 25 years [14]. In addition, previous studies have found that birds in different temperature zones have different distribution mechanisms in response to climate change [89]. Birds from the northern temperate regions migrate to higher latitudes [90–92], while those from the tropics migrate to higher elevations [89,93]. In China, Tibetan antelope and goitered gazelle (*Gazella subgutturosa*), both located in the northern temperate zone, also showed a trend of moving northward under climate change [17]. Although we have no evidence that all animals living in the north temperate zone exhibit poleward migration in response to climate change, our results suggest that this could be one of the strategies of Siberian ibex in response to climate change.

It is a crucial step from theory to practice to put forward conservation management opinions based on study results. According to our study, the northwest part of the reserve may be a refuge which will promote Siberian ibex survival under increasingly adverse climatic conditions. This area should therefore be protected in the future. The key conservation issue in this area is finding an effective way for Siberian ibex to survive under climate change. Meanwhile, reducing human activity and grazing in and around the current suitable habitat will help the Siberian ibex obtain more habitat. In addition, the Siberian ibex is an ungulate widely distributed in Central Asia [25]. Identifying and conserving the ecological corridor linking suitable habitat in the reserve and outside the reserve (including domestic and overseas) will help support gene exchange in the population and promote genetic diversity.

Our study revealed that climate change has a strong effect on the distribution of Siberian ibex in the Eastern Pamir, China. One of the expected effects of recent warming is that it may force animals to move to higher, cooler elevations [94]. Siberian ibex generally show seasonal movement along an elevational gradient, i.e., they migrate to higher elevations in summer and to lower elevations in winter due to phenological changes and variable temperatures at high and low elevations. However, intensive human interference at lower elevations may prevent Siberian ibex from migrating to lower elevations, further limiting their distribution and making the range of their distribution along elevation even narrower [95]. Such distribution patterns may reduce the resistance of Siberian ibex to environmental changes. Although we are incapable of further analyzing whether and how interspecific interactions will alter the distribution of the species due to the lack of data on natural predators (such as snow leopards), domestic animals, and the feeding habits of the species in the region, our research is nevertheless conducive to the conservation of ungulates in the plateau ecosystem. Future studies should focus on the effects of intra- and interspecific interactions on species distribution, and the construction of ecological corridors should be considered to better protect species.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/d14090750/s1, Figure S1: Response curves of the current ensemble species distribution models for Siberian ibex in Taxkorgan Nature Reserve to each variable, Figure S2: Stable suitable habitat for Siberian ibex in Taxkorgan Nature Reserve under climate change; Table S1: The number of line transects per month for each year (2018–2021) during the survey, Table S2: Ranking of variables' importance affecting the distribution of Siberian ibex in Taxkorgan Nature Reserve, Table S3: The evaluation of ensemble species distribution models (eSDMs, including AUC and TSS) of Siberian ibex in Taxkorgan Nature Reserve under current and different climate change scenarios.

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