A multiscale assessment of snow leopard distribution, habitat-use and landscape connectivity in a new national park in China

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Abstract

The newly established Qilian Mountain National Park (QMNP), with and area of 50,200 km^2, was one of the first ten pilot areas of the revised national park system in China. The snow leopard is an important flagship species of the QMNP, although only sporadic field surveys have been conducted since 2011 in the Qilian Mountain region. The lack of data and information has impeded the improvement of conservation and management planning and practice of the national parks. The target of this research was to use data collected from multiple surveys with spatial and temporal variance, with the employment of recent and powerful data analysis algorithms, to explore snow leopard ecology at micro and macro levels in QMNP and provide important contributions for the conservation and management planning of QMNP and surrounding areas.

Firstly, snow leopard density was estimated in Yanchiwan National Nature Reserve (YNNR, an important component nature reserve of QMNP) using Spatially Explicit Capture-Recapture Models (SECR), across a 400 km^2 area with 62 camera traps systematically set up. In total 14 snow leopard individuals were photo captured during the 4,760 camera trapping nights. The overall abundance of snow leopards was estimated to be 26.3 individuals (SE = 5.7, 95% CI 19.2-43.2) over the entire buffered survey area of 1,881.6 km^2. The estimated average snow leopard density for the study was therefore 1.40 (SE=0.30, 95% CI 1.02-2.30) individuals per 100 km^2. Covariates of wild and domestic prey (capture events of blue sheep and domestic livestock), and geography (terrain roughness index) were found had big impact on the model performance.

In YNNR, 249 snow leopard presence locations were acquired from camera traps and genetically-verified fecal samples. Analysis was then conducted on snow leopard distribution, activity and linkage across the extent of YNNR, with an area of 13,600 km^2. A key mountain system (Shulenanshan) in the east of YNNR was identified as the most important area in terms of habitat quality, activity and linkage of snow leopard populations. Based on these analyses, two further areas were identified with high importance for population connectivity, but which were also highly vulnerable from fence and road infrastructure.

Analysis on snow leopard distribution, activity and linkage was then extended to the entire QMNP and areas around, based on a wider dataset of 393 snow leopard presence points. Results indicated 16 high-quality patches and 27 medium-quality patches in QMNP and surrounding areas. The largest high-quality patch located in the mid-east of QMNP, which was consistent with the results from connectivity surface and linkage network analysis about the most important key area. Second largest high-quality patch located at south out of the QMNP, which may play the role of bridge or step stones for the snow leopard population communication between the national park and the main part of Qinghai-Tibet Plateau. Result of least cost path analysis showed that most of the high-quality patch paths went through medium-quality patches, indicating the potential step stone function of the medium-quality patches for snow leopard individuals' dispersal.

Serving as the first case of snow leopard ecological study in national park level landscape in China, this thesis explored population density, distribution, activity and linkage of snow leopard

population in QMNP from micro to macro level scale. The thesis demonstrated how the data with spatial and temporal difference can be used in flagship species with big range and scarce information. This study increased our understanding of snow leopard density in high quality habitat, improved the knowledge of the important impact factors of snow leopard distribution at nature reserve and national park level, and described the scenarios of snow leopard activity and linkage with multiple supposed biologically meaningful thresholds of movement and dispersal abilities. This study increased the knowledge of snow leopard ecology, and the results and suggestions provided in the thesis would be an important reference to the managers when making the conservation and management plan in QMNP and surrounding areas.

Acknowledgement

I would like to express my gratitude to a number of people and institutes who have provided help and support. This project would not have been possible without them.

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And most of all, thank you to my family. My father and mother, you are such understanding parents, the support, as always, from you, is always my greatest source of confidence to continue the snow leopard research. Thank you very much my wife, this would not have been possible without your unconditional, unequivocal, and loving support for years. My son, the “little monkey”, you are the most precious gift I have ever received, thank you for the sunshine you bring when the skies are grey.

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Chapter 1: Introduction

1.1 Snow leopard ecology, distribution and population

1.1.1 Habitat and ecology of snow leopards

The snow leopard (*Panthera uncia*) is the smallest species within the genus *Panthera*, with a body length of 1-1.3 m, tail length 0.8–1.1 m, shoulder height of approximately 60 cm, and a weight of 35-55 kg (Johansson et al., 2013; McCarthy & Mallon, 2016). Most snow leopards live in alpine and subalpine meadows, between an elevation of 2500 to 5800 (McCarthy & Chapron, 2003; McCarthy & Mallon, 2016). Typically, snow leopards occupy rugged mountainous terrain, and can be found on mountain ridges, cliffs, and in valleys (Jackson & Hunter, 1996; McCarthy & Chapron, 2003).

As the top predators, snow leopards mainly prey on wild ungulates, including blue sheep (*Pseudois nayaur*), Siberian ibex (*Capra sibirica*), Himalayan tahr (*Hemitragus jemlahicus*), argali sheep (*Ovis ammon*) and domestic animals such as sheep, goat and yak. Small mammals, such as marmots (*Marmot spp*.) and lagomorphs have also recorded in the diet as a minor food resource (Gobi et al., 2012; Johansson et al., 2015; Shrestha et al., 2018; Lu et al., 2019; Wang et al., 2019).

Snow leopards are commonly known as an umbrella species of the high-altitude ecosystems, and also be recognized as the indicators of healthy ecosystems. The snow leopards and their ecosystems provide essential ecosystem services at local, regional and global levels, in the aspects of culture, water, biodiversity, medicine, agro-pastoralism, carbon sequestration and storage, recreation, and economic opportunities (Snow Leopard Working Secretariat, 2013). Of particular importance are the water services provided by the snow leopard ecosystem, benefiting one-third of the world's total human population (Snow Leopard Working Secretariat, 2013).

1.1.2 Global distribution and population

Snow leopards are distributed across a wide range in the high-altitude areas across Central and South Asia. The distribution starts from the southern Siberia in the north, and goes south though the mountains of Central Asia, and reaches the Himalayas as the southern edge. At present, Snow leopards are known to be present in the Altai, Sajan, Tien Shan, Pamir-Alay, Hindukush, Kunlun, Karakoram, Pamirs, Himalaya and Tibetan Plateau, and the Gobi region in Mongolia (McCarthy & Chapron, 2003; McCarthy et al., 2016). They are found in 12 countries including Afghanistan, Bhutan, China, India, Kazakhstan, Kyrgyzstan, Mongolia, Nepal, Pakistan, Russia, Tajikistan, and Uzbekistan (McCarthy & Chapron, 2003; McCarthy & Mallon, 2016) (Figure 1.1). The presence of snow leopard has not been confirmed yet in Northern Myanmar (a potential location) but the recently estimated snow leopard global range is about 2.8 million km^2 (McCarthy et al., 2016).

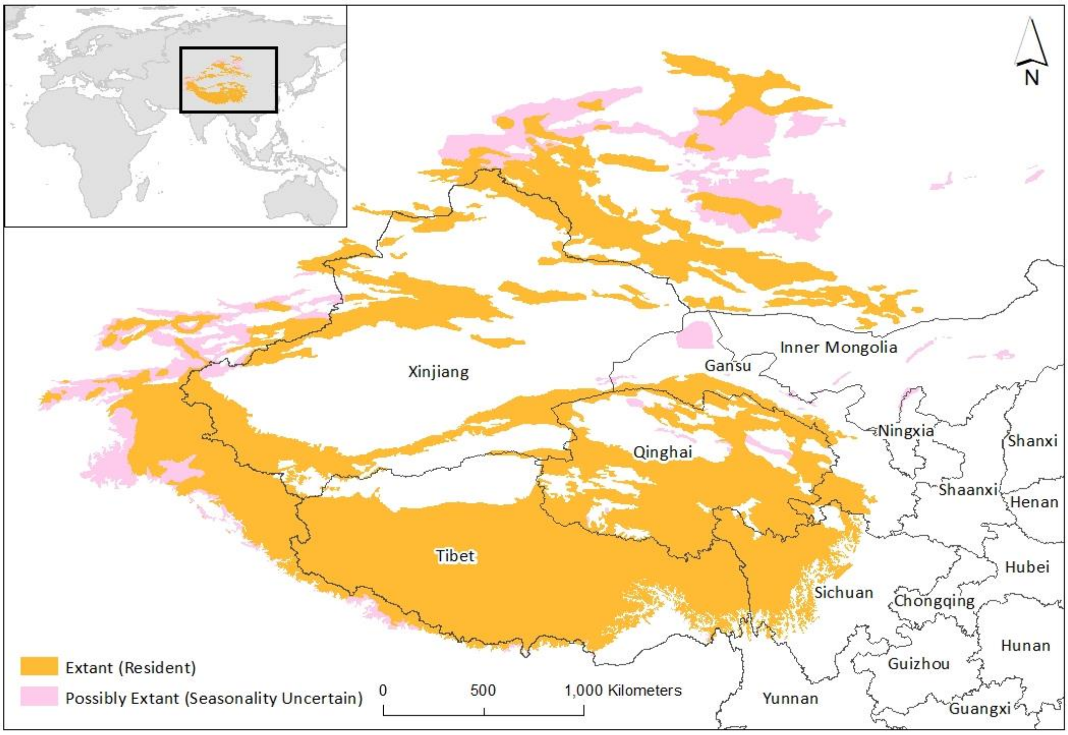

Figure 1.1 Snow leopard extent in the world and in China.

** Snow leopard range map source: IUCN Red List Panthera uncia (Thomas McCarthy et al., 2017).*

*** Map of China source: Resource and Environment Science and Data Center, Chinese Academy of Sciences. https://www.resdc.cn/data.aspx?DATAID=200*

Despite numerous years of research and surveying, there is controversy about the size of the global snow leopard population. In 2017 the IUCN Red List changed the status of snow leopard from 'Endangered' to 'Vulnerable' (McCarthy et al., 2017). This change followed a long discussion centered on the previous population estimates, which some researchers and conservation organizations thought were either invalid or insufficient (see for example Snow Leopard Trust, 2017). The IUCN took their decision on the basis of a growing body of work on snow leopard population estimation carried out since the previous assessment in 2008, including new technologies and work in areas previous under- or un-surveyed, such as China (Riordan and Shi, 2016). The current global estimate for the snow leopard population is between approximately 7,500 – 8,000 individuals (McCarthy et al., 2017), with approximately 60% of the global population thought to occur in China, making it the single most important country for the species' conservation (Riordan and Shi, 2016).

1.2 Snow leopards in China

1.2.1 Distribution

As the most important snow leopard range country, China contains as much as 60% of the potential habitat (McCarthy & Chapron, 2003), and approximately 60% of the global population of snow leopard (Riordan and Shi, 2016). China also shares over 10,000 km of national borders with 10 out of the remaining eleven snow leopard range countries and one possible range state. Snow leopard are known to present in eight provinces and Autonomous Regions: Tibet, Xinjiang, Qinghai, Gansu, Sichuan, Yunnan, Inner Mongolia and Ningxia (Figure 1.1). Among them, Tibet, Xinjiang, Qinghai, Gansu and Sichuan contain major snow leopard habitat. Snow leopard occurrences have been reported in the region of Hengduan Shan (Forestry and Grassland Administration of Yunnan Province, unpublished data). In Inner Mongolia, over 10 years after the last record, snow leopard individuals were captured and relocated in the high-altitude outcrops in the desert regions in 2011 and 2013 (Shi and Riordan, un-published data), indicating the mountains in the region could be an important linkage between snow leopards' population and landscapes (Riordan et al., 2016; Riordan and Shi, 2016). In Ningxia Hui Autonomous Region, one snow leopard was captured by a camera trap which was set up in August 2020 (Xinhua News Agency, 2021), 66 years after the last record in the region.

1.2.2 Protected areas

Protected areas in China are administered at the national level by the National Forestry and Grassland Administration (NFGA) within the Ministry of Natural Resources of the People's Republic of China (http://www.mnr.gov.cn/). Protected areas are also designated at lower administrative levels, including Autonomous Regions, Provinces and county or municipality (Ministry of Ecology and Environment of the People's Republic of China, 2018). Designations are often complex, particularly but typically include zoning within the PA to limit human activities or define particular management goals across administrative borders. Protected areas can also have multiple designations across administrative levels, representing the importance of sites at different scales (State Council of the People's Republic of China, 1994).

Across the snow leopard range in China, protected areas were highlighted as being important for the species in all provinces and autonomous regions, accounting for approximately 30% of the range area on average (Riordan & Shi, 2016). With the exception of Sanjiangyuan (Three Rivers Source) National Park in Tibet and small overlap with the Giant Panda National Park in Sichuan, all of the PAs reported in the snow leopard range in China were Nature Reserves, at both National or Local levels. In 2017, the National Forestry and Grasslands Administration established a pilot scheme for National Parks in China, which included Qilianshan National Park (details below).

1.2.2.1 Nature reserves

At the end of 2017, China had established 2,750 nature reserves at multiple levels, covering 1,471,700 km^2, representing 14.86% of the total land area; the number of national nature reserve (the top-level nature reserve) was 474, covering a total area of 974,500 km^2 (Ministry of Ecology and Environment of the People's Republic of China, 2018) (Figure 1.2).

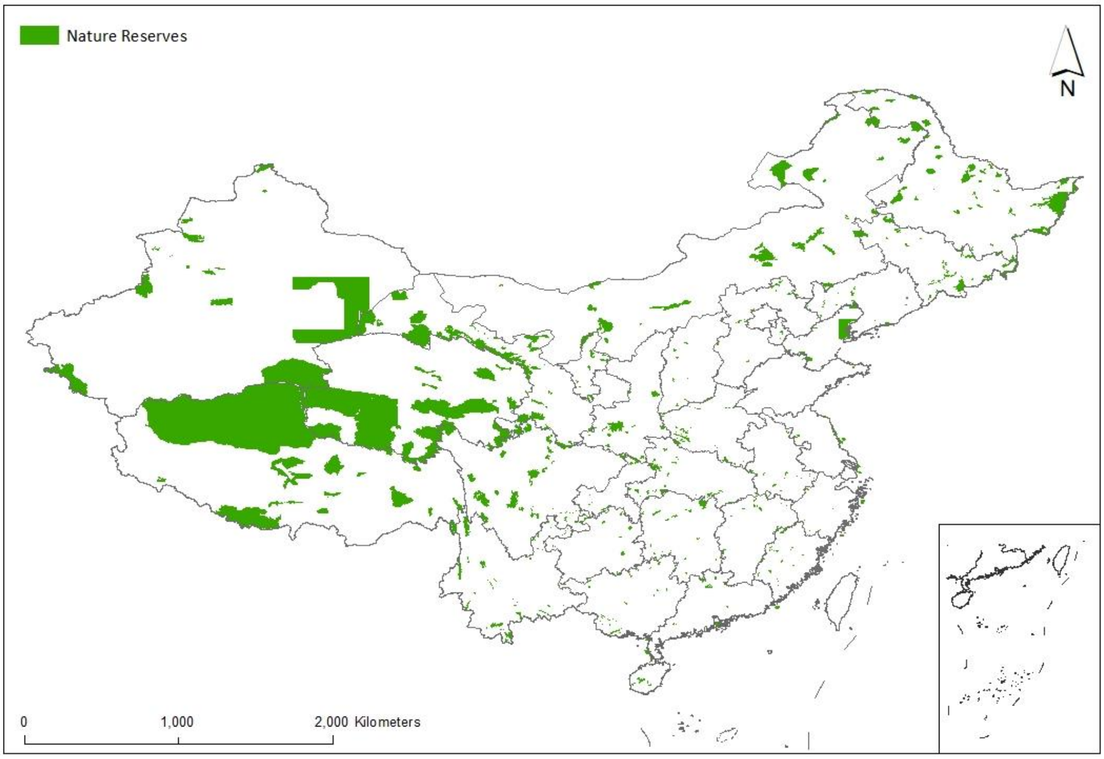

Figure 1.2 Nature reserves in China.

** Map of nature reserves in China source: Resource and Environment Science and Data Center, Chinese Academy of Sciences. https://www.resdc.cn/data.aspx?DATAID=272. The layer collected 477 nature reserves in China up to 2018. Taxkorgan Provincial Nature Reserve in Xinjiang Uygur Autonomous Region was not included in the original layer and added in by author. The layer of Taxkorgan Nature Reserve was provided by the nature reserve administration bureau.*

1.2.2.2 National Parks

In China, establishing protected areas at the nature reserve levels has been the most important way to conserve biodiversity, and the nature reserves have made vital contributions to conservation (Wu et al., 2011; Huang et al., 2019). However, the conservation effectiveness of nature reserves in China has been limited by a variety of problems, including budget and equipment shortage, lack of professional expertise, and ineffective management (Quan et al., 2009; Quan et al., 2011). To address those problems and improve conservation effectiveness, China started to explore and establish national park system. Since 2017, China has established the first 10 pilot areas of the national park system, including Qilian Mountain National Park, Northeast China Tiger and Leopard National Park, Three-River-Source National Park, Giant Panda National Park, Hainan Tropical Rainforest National Park, Wuyishan National Park, Shennongjia National Park, Potatso National Park, Qianjiangyuan National Park, and Nanshan National Park (Figure 1.3), covering over 220,000 km^2, representing 2.3% of the total land area of China (Ministry of Ecology and Environment of the People's Republic of China, 2021) (Table 1.1).

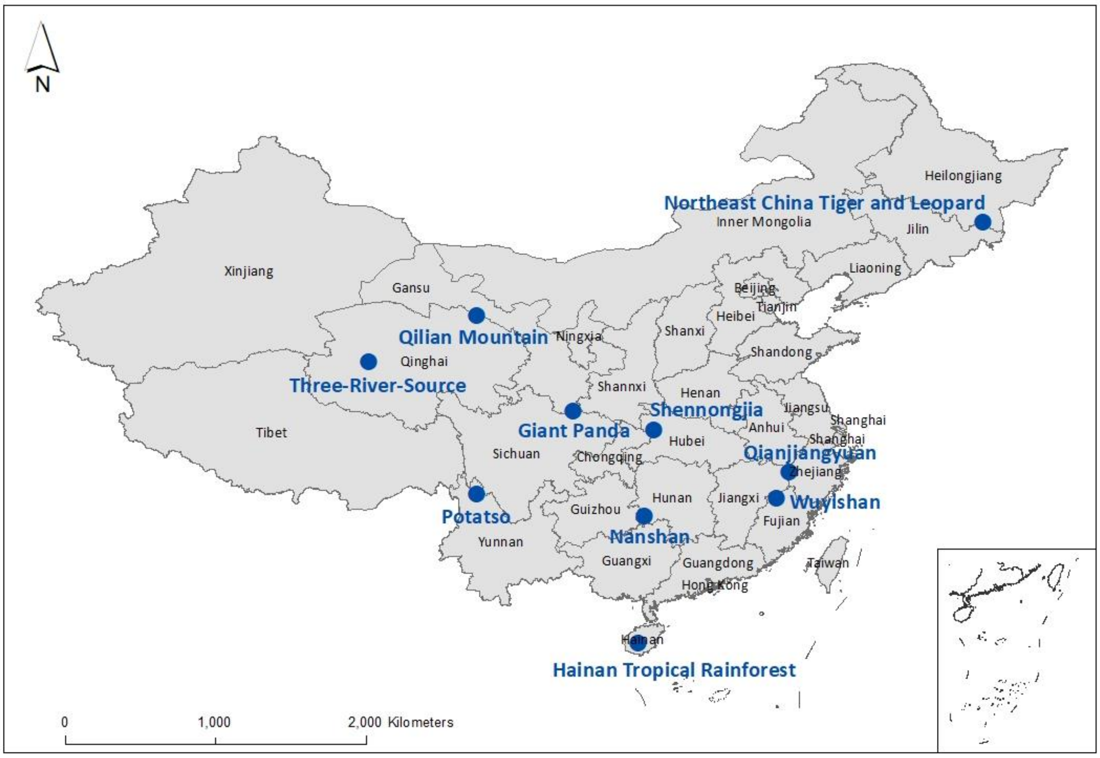

Figure 1.3 The indicative locations of the first 10 pilot areas of the national park system in China, established since 2017.

**National park location information source: National Forestry and Grassland Administration of China, National Park Administration of China, http://www.forestry.gov.cn/.*

In terms of the snow leopard ranges, within the 10 Chinese national parks, the Three-River-Source National Park and the Qilian Mountain National Park are particularly important for snow leopard conservation in China. The Three-River-Source National Park is the largest national park, and it secures the water source of the three big rivers: Yangtze River, Yellow River and Lancang River, and as well as protecting the mountain ecosystems. The Qilian Mountain National Park (QMNP) plays the role as an important ecological security barrier in Western China. QMNP is a national key ecological function area for glacier and water conservation, it has important functions of maintaining the ecological balance of the Qinghai-Tibetan Plateau, preventing the southward invasion of the Tengger, Badain Jaran and Kumtagh deserts, maintaining the stability of the oasis in the Hexi Corridor, and guaranteeing the runoff recharge of the Yellow River and inland river. Although the major goals of the two national parks are not same, both of them are highly geographically overlapped with snow leopard range.

Table 1.1 Basic information of the first 10 pilot areas of the national park system in China.
**Data source: National Forestry and Grassland Administration of China, National Park Administration of China, http://www.forestry.gov.cn/.*

National Park	Area (km^2)	Province	Major Ecosystem
Three-River-Source	123,100	Qinghai	Alpine meadow Alpine steppe
Qilian Mountain	50,200	Gansu Qinghai	Temperate mountain coniferous forest Temperate desert steppe Alpine meadow
Giant Panda	27,134	Sichuan Shannxi Gansu	Subtropical evergreen deciduous forest Temperate coniferous forest Cold-temperate coniferous forest Mixed evergreen deciduous broad-leaved forest
Northeast China Tiger and Leopard	14,600	Jilin Heilongjiang	Temperate mixed coniferous broad-leaved forest
Hainan Tropical Rainforest	4,403	Hainan	Tropical rain forests Tropical seasonal rain forests Tropical coniferous forests
Shennongjia	1,170	Hubei	Evergreen deciduous forest Mixed conifer and broad-leaved forest
Wuyishan	1,001	Fujian	Evergreen broadleaf forest
Nanshan	636	Hunan	Subtropical evergreen broad-leaved forest
Potatso	602	Yunnan	Subalpine cold-temperate coniferous forest
Qianjiangyuan	252	Zhejiang	Subtropical evergreen broad-leaved forest

1.2.3 Overlap between Snow leopard range and protected areas in China

The overlap analysis between snow leopard range and protected areas in China was conducted in this study to have a better view of the spatial status of snow leopards in China.

1.2.3.1 Data collection

Three data layers were collected for the analysis:

1) Global snow leopard range. The layer was downloaded from: IUCN Red List *Panthera uncia* (Thomas McCarthy et al., 2017). According to the certainty, the snow leopard range was divided into two types: extant (resident) and possibly extant (seasonality uncertain).

2) Map of China. The layer was downloaded from: Resource and Environment Science and Data Center, Chinese Academy of Sciences. https://www.resdc.cn/data.aspx?DATAID=200

3) Nature reserves in China. The data was from: Resource and Environment Science and Data Center, Chinese Academy of Sciences. https://www.resdc.cn/data.aspx?DATAID=272. The layer included 477 nature reserves in China up to 2018. Taxkorgan Provincial Nature Reserve in Xinjiang Uygur Autonomous Region was not included in the original layer and was added in by author. The layer of Taxkorgan Nature Reserve was provided by the nature reserve administration bureau.

The distribution of global snow leopard extent in China and Chinese protected areas was displayed as Figure 1.4.

1.2.3.2 Data analysis

The data analysis was proceeded using the software ArcGIS Desktop 10.6 (ESRI). Three layers were projected into Krasovsky_1940_Albers coordinate system. The “Intersect” function in ArcToolbox was employed to generate the overlap area between the snow leopard range and layers of China and nature reserves. Area calculation was done by using the “calculate geometry” function in the layer’s attribute table.

1.2.3.3 Results

Based on the IUCN Red List snow leopard range map, the area of global extant and possibly extent were 3 million and 3.5 million square kilometers; 72.2% of the current global snow leopard range and 63.6% (2.22 million km^2） of its possibly extent was located in China. Within the Chinese snow leopard range, about 23% was within the nature reserves, higher than the global average overlap level of 14-19% (Deguignet et al., 2014). The results of the analysis once again emphasis the importance of China, and Chinese protected areas to the global snow leopard survival and conservation.

Table 1.2 Area and percentage of snow leopard range in China and Chinese Nature Reserves (NAs).

Snow Leopard Range*	Area (km^2)	Intersect			
		China (km^2)**	%	NRs (km^2)***	%
Extant	3,006,597	2,171,955	72.2	504,736	23.2
Possibly Extent	3,496,979	2,224,668	63.6	510,888	23.0

** Snow leopard range map source: IUCN Red List Panthera uncia (Thomas McCarthy et al., 2017).*

*** Map of China source: Resource and Environment Science and Data Center, Chinese Academy of Sciences. https://www.resdc.cn/data.aspx?DATAID=200*

**** Map of nature reserves in China source: Resource and Environment Science and Data Center, Chinese Academy of Sciences. https://www.resdc.cn/data.aspx?DATAID=272. The layer collected 477 nature reserves in China up to 2018. Taxkorgan Provincial Nature Reserve in Xinjiang Uygur Autonomous Region was not included in the original layer and was added in by author. The layer of Taxkorgan Nature Reserve was provided by the nature reserve administration bureau.*

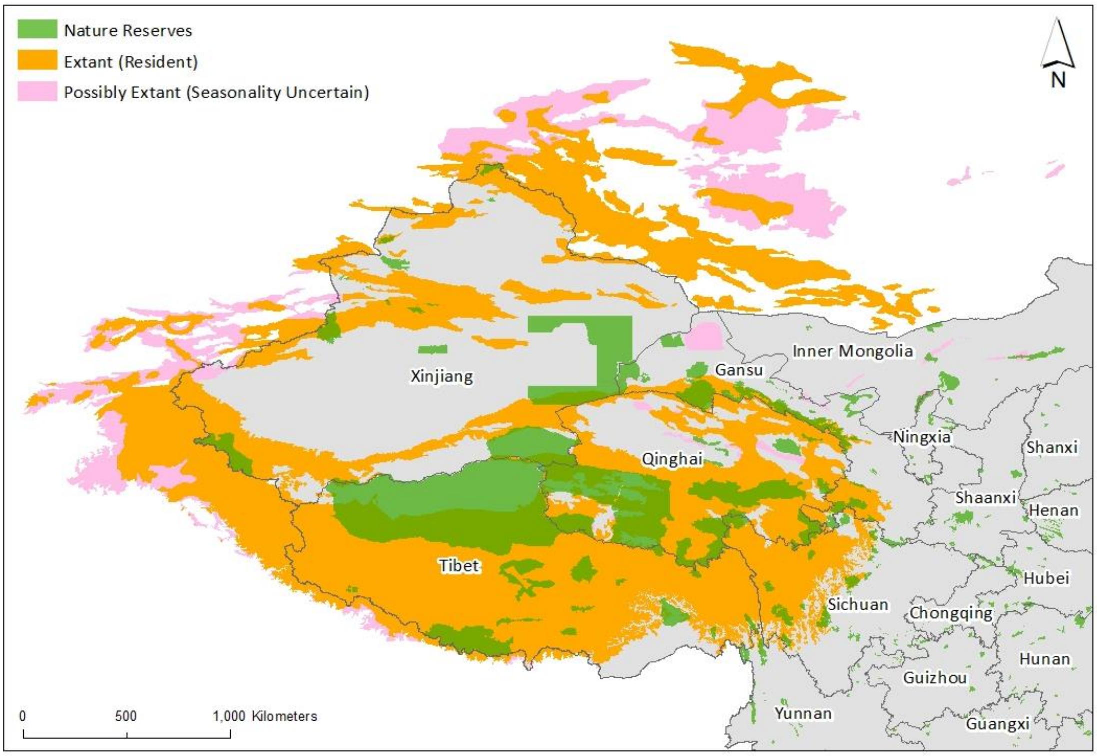

Figure 1.4 Distribution of global snow leopard extent in China and Chinese protected areas.

** Snow leopard range map source: IUCN Red List Panthera uncia (Thomas McCarthy et al., 2017).*

*** Map of China source: Resource and Environment Science and Data Center, Chinese Academy of Sciences. https://www.resdc.cn/data.aspx?DATAID=200*

**** Map of nature reserves in China source: Resource and Environment Science and Data Center, Chinese Academy of Sciences. https://www.resdc.cn/data.aspx?DATAID=272. The layer collected 477 nature reserves in China up to 2018. Taxkorgan Provincial Nature Reserve in Xinjiang Uygur Autonomous Region was not included in the original layer and was added in by author. The layer of Taxkorgan Nature Reserve was provided by the nature reserve administration bureau.*

1.3 Yanchiwan National Nature Reserve and the Qilian Mountain National Park

1.3.1 Snow leopard landscapes

Current knowledge indicates that only 14-19% of snow leopard range overlaps with protected areas (Deguignet et al., 2014), and "with 40% of those protected areas being smaller than a single adult's average home range" (Johansson et al., 2016; Sharma & Singh, 2021). In 2013, Snow Leopard Working Secretariat launched a project called "*Global Snow Leopard & Ecosystem Protection Program (GSLEP)*", with the target of to identify and secure at least 20 snow leopard landscapes across the snow leopards' range by 2020 (in shorthand – "Secure 20 by 2020" (Snow Leopard Working Secretariat, 2013). The definition of snow leopard landscape here, is the landscape that contain at least 100 breeding age snow leopard individuals (Snow Leopard Working Secretariat, 2013).

Snow leopard range countries identified 23 snow leopard landscapes under the GSLEP program (Figure 1.6). Some of the snow leopard landscapes are relatively large. For example, the largest is the Pamir from Tajikistan, with the area of 92,000 km^2. As the most important snow leopard range country, China identified three nature reserves: Yanchiwan National Nature Reserve (13,600 km^2), Toumor National Nature Reserve (2,376 km^2), and Taxkorgan Provincial Nature Reserve (15,000 km^2), with a total area of 30,976 km^2.

The Yanchiwan National Nature Reserve (YNNR) was established in 1982 as provincial nature reserve and upgraded to national nature reserve in 2006. Different from the fact that the Toumor and Taxkorgan nature reserves adjoin with other snow leopard landscapes, the YNNR looks like an island in the GSLEP snow leopard landscape map, isolated in the eastern of snow leopard range, with a medium area size (ranked 12th out of 23 landscapes) (Figure 1.5). The characters of isolation and lager area make YNNR has greater significance in snow leopard study and conservation among the three snow leopard landscapes in China.

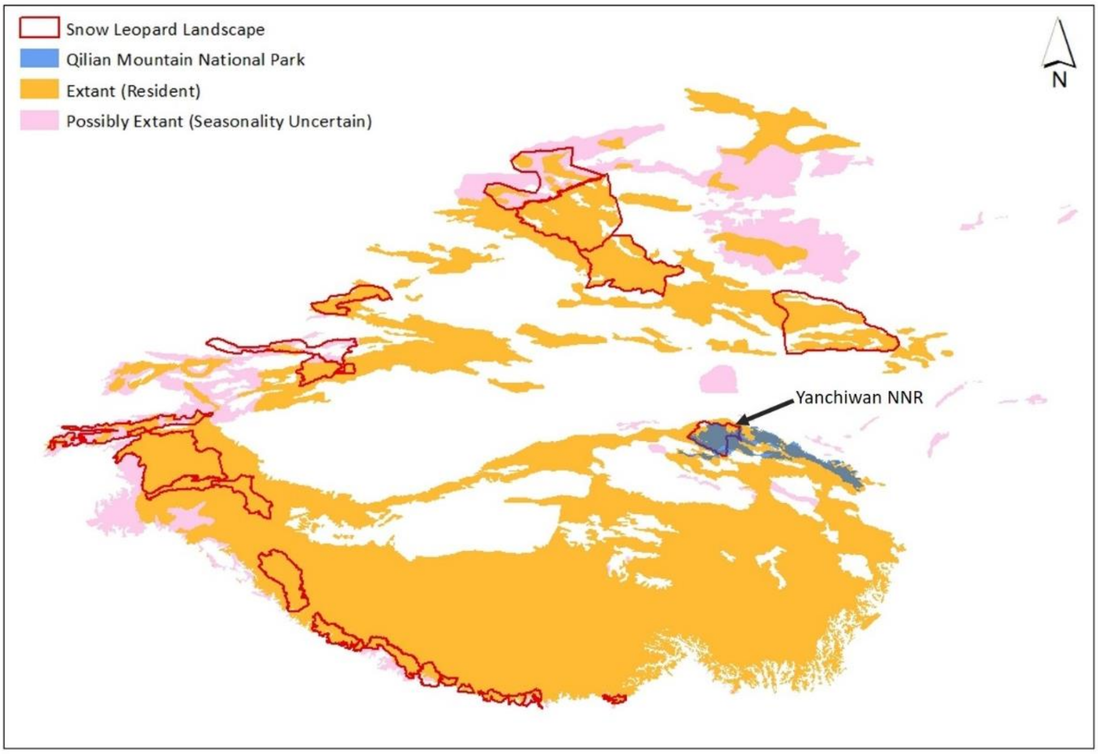

Figure 1.5 The 23 snow leopard landscapes identified to be secured by 2020 under the GSLEP program, with Yanchiwan National Nature Reserve of China be pointed out the east of snow leopard range.

** Map source: data from the Global Snow Leopard and Ecosystems Protection Program: www.globalsnowleopard.org, and modified by Snow Leopard Trust: https://snowleopard.org/*

1.3.2 Qilian Mountain National Park

Established in 2018, the Qilian Mountain National Park (QMNP, N36°29'57'' — 39°43'39'', E97°23'34''—103°45'49'') located in the northeast of Qinghai-Tibet Plateau, across the boundary area of Gansu Province and Qinghai Province (Figure 1.6). The Qilian Mountain has the key ecological functions of maintain the balance of Qinghai-Tibet Plateau, prevent three deserts to invade south, and provide water supply for Yellow River and other inland rivers (National Forestry and Grassland Administration of China (National Park Administration of China), 2019).

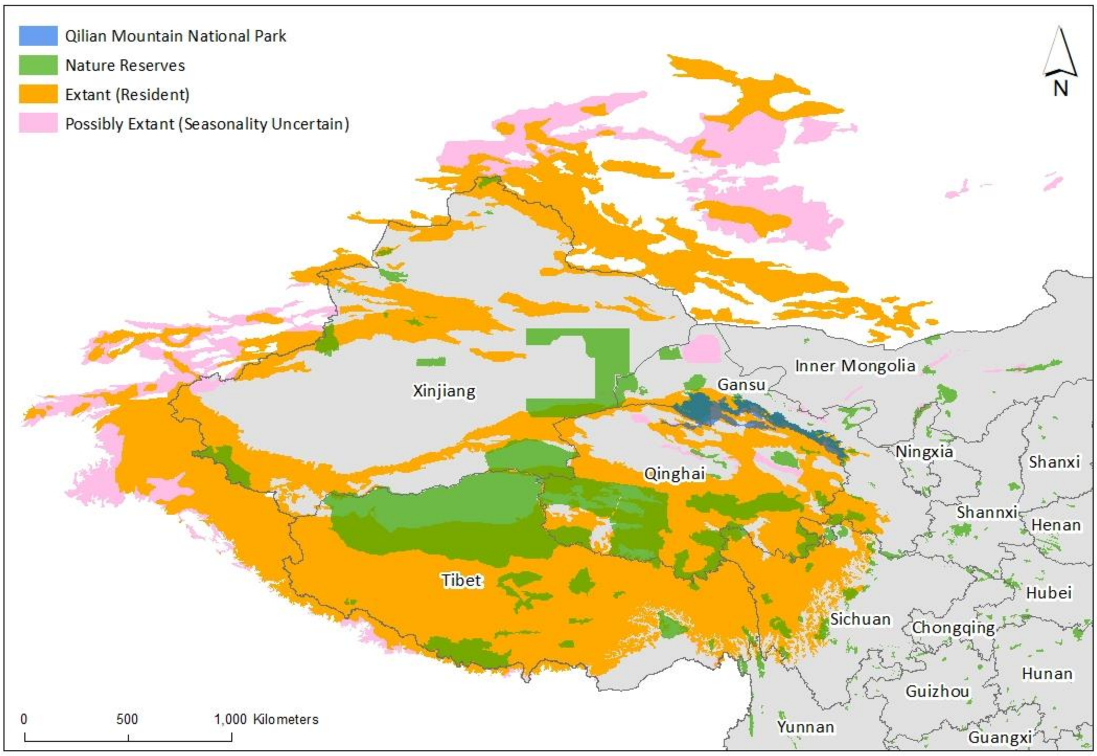

Figure 1.6 Location of Qilian Mountain National Park and nature reserves in Western China.

** Data sources of snow leopard extent, map of China, and nature reserves are same with Figure 1.4.*

*** Qilian Mountain National Park data source: Qilian Mountain National Park Administration.*

QMNP is composed of eight protected areas, including three nature reserves: Qilianshan National Nature Reserve of Gansu Province, Yanchiwan National Nature Reserve of Gansu Province, and Qilianshan Provincial Nature Reserve of Qinghai Province; four forest parks: Gansu Tianzhuxia National Forest Park, Gansu Matisi Provincial Forest Park, Gansu Binggouhe Provincial Forest Park, and Qinghai Xianmi National Forest Park, and one national wetland park: Qinghai Qilian Heiheyuan National Wetland Park.

QMNP has 34,400 km^2 in Gansu Province (68.5%), and 15,800 km^2 in Qinghai Province (31.5%), with a total area of 50,200 km^2. To calculate the extent of overlap between QMNP and the global snow leopard range, the same methods were used as in section 1.2.3.2. The results showed that, within the total area of 50,200 km^2 of the QMNP, the overlap with the snow leopard range was 44,331 km^2, including 44,222 km^2 of the known range and 109 km^2 of the possible range. The overall percentage of overlapped area was 88% (Figure 1.7).

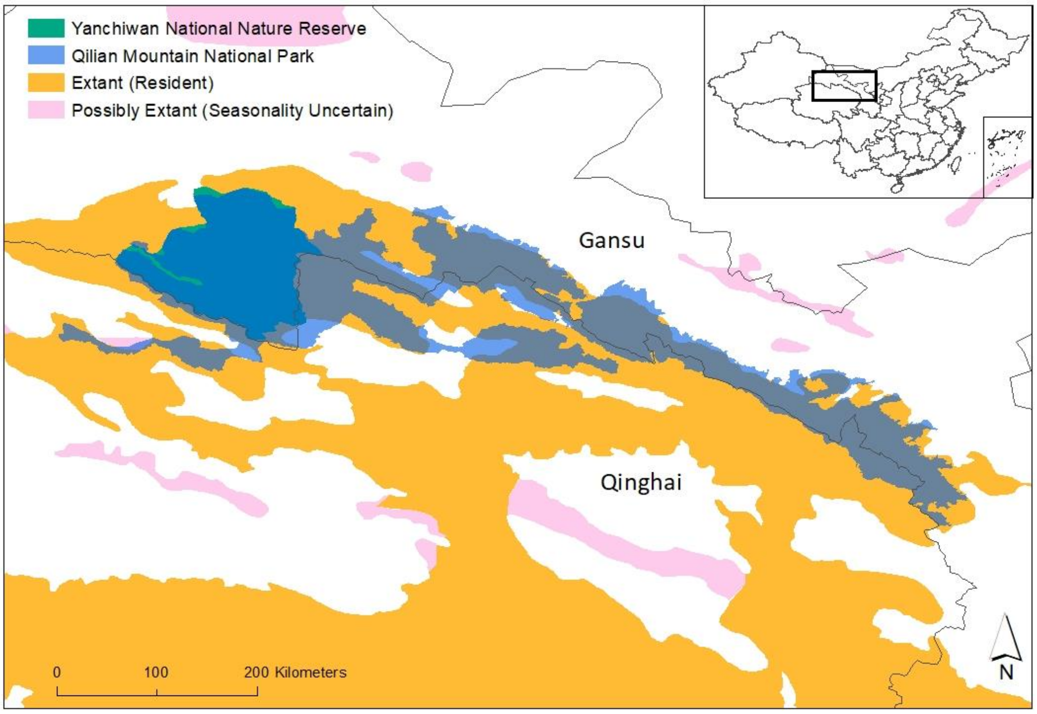

Figure 1.7 Overlap between Yanchiwan National Nature Reserve, Qilian Mountain National Park and snow leopard extent.

** Snow leopard range map source: IUCN Red List Panthera uncia (Thomas McCarthy et al., 2017).*

*** Yanchiwan National Nature Reserve data source: Yanchiwan National Nature Reserve Management Bureau.*

****Qilian Mountain National Park data source: Qilian Mountain National Park Administration.*

The Qilian Mountain National Park has much larger area (if it is listed in the GSLEP snow leopard landscapes, QMNP could be rank at the top 5 largest landscapes), and high rate of overlap with snow leopard range (88%). In a sense, compared with 13,600 km^2 of Yanchiwan National Nature Reserve, the QMNP could be treated as an important major upgrade of snow leopard landscape in Qinghai-Tibet Plateau in China. Its significant importance on snow leopards and their landscape conservation in China should be emphasized.

1.3.3 Snow leopard studies in QMNP

In 1980s, Schaller *et al* (1988) conducted field surveys in Gansu and Qinghai province, confirmed the distribution of snow leopards in Qilian Mountain and explored snow leopard diet. Liu *et al* (2003) analyzed snow leopard diet and based on scat samples. In total 159 snow leopard scats were collected from Qilian Mountain range (Sunan and Subei County), and another 43 scats got from the boundary area between Qilian Mountain and Altun Mountain (Aksai County). Analysis of faecal DNA showed that snow leopard in Qinghai-Tibet Plateau showed some genetic differences to populations in Danghenanshan (located in QMNP) and Qiangtang National Nature Reserve in Tibet (Zhou et al., 2014). From 2015, after comprehensive work in Qilianshan National Nature Reserve, the joint team from Beijing Forestry University and University of Oxford published a series of papers about snow leopards, covering the fields of density estimation (Alexander et al., 2015a; Alexander et al., 2016b), site use (Alexander et al., 2015b), human-wildlife conflict (Alexander et al., 2015b) and inter-species relationship (Alexander et al., 2016a) These studies demonstrated the importance of the national park to the conservation of snow leopards in China.

1.3.4 Research gaps of snow leopards in Qilian Mountain

In 1974, a wildlife survey organized by Gansu Province recorded snow leopard in the Subei County (area of where the present Yanchiwan National Nature Reserve located), confirmed the snow leopard distribution in the area (Liu et al., 2010). From 1984-1987, Schaller et al (1988) conducted surveys in Gansu and Qinghai province, recorded 261 suspected snow leopard signs. No other snow leopard surveys were done since then until our snow leopard survey conducted in 2012.

Although the previous studies in Qilian Mountain have greatly improved our knowledge of snow leopards in the region, several research gaps exist. Firstly, only a small number of studies conducted in the region, covering limited research aspects. Before 2015, only three studies published on journals, with one was about rapid survey (Schaller *et al*., 1988), and two were focusing on diet and genetic diversity based on scat samples (Liu et al., 2003; Zhou et al., 2014). This situation was improved markedly in 2015 and 2016, with several papers published, covering some more basic ecological aspect (Alexander et al., 2015a; Alexander et al., 2015b; Alexander et al., 2016a; Alexander et al., 2016b).

Secondly, only very small areas have been systematically surveyed and studied. The survey conducted in 1980s in Qilian Mountain was mostly road travel, with one 610 km^2 block to survey snow leopard signs and wild ungulates (Schaller et al., 1988). The two scats-based studies on diet and genetic differences only referred the counties of sample source, the sizes of sampling areas were not mentioned (Liu et al., 2003; Zhou et al., 2014). In Qilianshan National Nature Reserve, an area of 480 km^2 was surveyed using camera traps in the unit of 4×4 km grid cells, formed the only known systematic surveyed area from the publications (Alexander et al., 2015a; Alexander et al., 2015b; Alexander et al., 2016a; Alexander et al., 2016b).

Probability due to the limitation of targets, extents, resources and durations of previous projects, the conducted studies in Qilian Mountain range were mostly unsystematic, and at micro level (500 km^2 or so), leaving huge blanks of spatial and ecological studies.

1.4 About this thesis

1.4.1 Background

Since 2012, a research group (based in the Wildlife Institute, Beijing Forestry University, in collaboration with the University of Oxford and Marwell Wildlife), have been working on snow leopard studies in Yanchiwan National Nature Reserve and Qiianshan National Nature Reserve in Qilian Mountain region. Rapid assessments, pilot surveys, and systematic surveys have been carried out and a lot of data and samples collected (unpublished data from Wildlife Institute, Beijing Forestry University). In 2017, the Qilian Mountain National Park was established, and the snow leopard was recognized as the flagship species of QMNP. This generated the need to increase the understanding of the snow leopard population, its distribution and habitat associations across the QMNP. Such information is essential as “Good decision making for conservation planning needs to be founded on rigorous science and reliable information while acknowledging and remedying the uncertainty associated with knowledge” (IUCN – SSC Species Conservation Planning Sub-Committee, 2017; Sharma and Singh, 2021).

The merged Yanchiwan and Qilianshan National Nature Reserves account for a large part (approximately 50%) of the Qilian Mountain National Park, and potentially, the data that had been collected in the two national nature reserves could be used to make important contributions for the study of QMNP snow leopard studies at a landscape scale. Although those data collected from multiple projects were, to an extent, spatially and temporally limited, they could have an important role when employing recent and powerful data analysis algorithms.

1.4.2 Aims and objectives

The overall aim of this research is to explore the snow leopard ecology from micro-level (Yanchiwan National Nature Reserve) to macro-level with the extent of wider range of Qilian Mountain National Park, and contribute to the management and conservation planning and practice of the national park.

The main objectives are:

2 To use systematic camera trapping survey, combined with spatial explicit capture-recapture analysis, to estimate snow leopard density at the study site.

3 To apply multiple algorithms of Species Distribution Models (SDMs), predict the snow leopard habitat at national nature reserve level.

4 To identify the snow leopard habitat patches with good quality in Yanchiwan National Nature Reserve, and analyze the corridors connecting those patches.

5 To upgrade the snow leopard distribution, habitat patches and linkage analysis from nature reserve level to national park level, finish the snow leopard landscape-level ecological analysis for the first time in China.

6 To provide suggestions on management and conservation planning of Yanchiwan National Nature Reserve and Qilian Mountain National Park, based on the results obtained from this research.

1.4.3 Thesis outline

This thesis is structured as follows:

Chapter 2: Estimation of Snow Leopard Density in Yanchiwan National Nature Reserve Using Spatially Explicit Capture-Recapture Models

In this chapter, we estimated snow leopard density in Yanchiwan National Nature Reserve using Spatial Explicit Capture-Recapture based on camera trapping data. A total of 62 camera trap stations (camera trap type: LTL ACORN-5210 & 6210) were set up across 400 km^2 area in November 2015, and 54 cameras were retrieved in June 2016. Data from January to March 2016 was used to estimate the density of snow leopards in the study site. Covariates of geography (elevation, slope position, topographic position index) and prey (number of blue sheep capture events and livestock capture events) were used in the models to explore the impact of different covariates on density (D), encounter rate (lambda0) and half of the radius of the activity ranger (sigma) of snow leopards.

In total 14 snow leopard individuals were photo captured during the 4,760 camera trapping nights. The top six models with summed 95% AICc weight were selected and averaged. The overall abundance of snow leopards was estimated to be 26.3 individuals (SE = 5.7, 95% CI 19.2-43.2) over the entire buffered survey area of 1,881.6 km^2. The estimated average snow leopard density for the study was therefore 1.40 (SE=0.30, 95% CI 1.02-2.30) individuals per 100 km^2. The encounter rate at activity centers (lambda0) was 2.28×10^{-2} (SE = 3.22×10^{-3}, 95% CI 1.73×10^{-2}-3.00×10^{-2}), and the estimated half of the radius of the activity ranger of snow leopards (sigma) was 3755 m (SE = 252 m, 95% CI 3294 m-4281 m). Blue sheep capture events (AICcwt = 0.424), terrain roughness index (AICcwt = 0.315) and livestock capture events (AICcwt = 0.124) were the most important determinants of snow leopard density, The encounter rate at activity centers (lambda0) was monopolized by terrain roughness index (tri). The possible future study design improvements were discussed, principally by conduct domestic and wild prey census and density estimation, and increase the geographic heterogeneity of camera trap stations.

Chapter 3: Predicting Snow Leopard Occurrences with Multi-Scale and Multiple Algorithms in Yanchiwan National Nature Reserve

Accurate distribution information of the snow leopard, especially as a flagship species, is required and critical for making conservation policies and management measures. This requirement was particularly important and urgent for the Yanchiwan National Nature Reserve, which acted as a crucial part of Qilian Mountain. Based on a total of 249 (153 camera trap sites and 133 fecal sample locations) confirmed snow leopard presence locations from the field survey between 2014 to 2017, we used three Species Distribution Models (Maximum Entropy (MaxEnt), Random Forest (RF) and Generalized Linear Model (GLM)) with multi-scale predictors optimization (seven scales from 300 m to 14,400 m), to explore the snow leopard distribution in Yanchiwan National Nature Reserve (YNNR). As a result, out of 27 variables, 15, 8 and 15 variables were selected for MaxEnt, RF and GLM respectively. The variable selections of three algorithms were different in terms of the variables, and the scales. Among the variables, road density, slope position, roughness and elevation were common selections of three SDMs, showed the importance of those four predictors in YNNR. Radius of Gyration of fenced area (gyrate_am_Fe) appeared in GLMs at large scale of 9,600 m, suggested the possible impact of fencing on snow leopard distribution. An ensemble habitat suitability map of snow leopard for YNNR was produced based on three suitability maps made from the three SDMs. Shulenanshan Mountain (east) had the largest area with high quality of suitable habitat for snow leopard, meanwhile Yemananshan (middle) Danghenanshan Mountain (west) got less good quality areas with the shape along mountain range distributions.

As the first case using multiple algorithms with multi-scale species distribution models on snow leopard, this chapter presented significant meaning for conservation and management design and practice in YNNR. Key areas for snow leopard distribution have been identified, along with scale-dependent features that influence them, which establishes a scientific basis for the policy makers.

Chapter 4: Snow Leopard Activity: Habitat Patches and Linkages in Yanchiwan National Nature Reserve

Habitat fragmentation across landscapes risks isolating subpopulations of species, reducing breeding opportunities across metapopulations and potentially increasing rates of inbreeding depression. Having good understanding on core habitat patches and important corridors across the landscape, will be crucial for making conservation planning and giving management suggestions on snow leopard in Yanchiwan National Nature Reserve. On the basis of distribution models produced in chapter 3, in this chapter, we further explored the connectivity surfaces, least cost paths, medium and high-quality habitat patches, and linkages between patches of snow leopards in YNNR. We used software FRAGSTATS to reclassify YNNR and surrounding buffer area into medium and high-quality habitat based on percentiles (<70th, 70th~90th, > 90th). Medium and high-quality patches with areas over 50 km^2 were selected. To simulate the high, medium and low level of habitat resistance, an exponential decay was used, with the base value of 10, 100 and 1,000 respectively. The programme UNICOR was then used to produce resistant Kernel connectivity surfaces and Kernel density estimation on least cost paths for each of the three levels of resistance surfaces. Four thresholds of snow leopard movement and dispersal ability with biological meaning were set for the both analyses. The shortest paths between high-quality patches with three levels resistance were identified by using the program CONEFOR. Layer of grazing areas in YNNR was generated by consulting the Director of Yanchiwan Conservation Station at the time, with the unit of 4 × 4 km grid cells.

A total of seven medium quality and 12 high quality patches were identified. The least cost paths between high-quality patches were relatively consistent with high, medium and low level of resistance. Shulenanshan Mountain occupies the largest connectivity surface. Yemananshan Mountain range, in the middle part of YNNR, was identified as potentially important, having the shortest paths at thresholds above 250,000-pixel. High-quality patches were highly overlapped with grazing areas. Two areas with high path densities were identified as key areas for snow leopard linkage, but were most like being adversely impacted by country road, road fences and grazing fences. Based on the results, suggestions on further studies and management were given, such as conducting fecal samples molecular genetic analysis, satellite telemetry on snow leopards, gradually reduce the grazing extent and intensity, and making plans to reconnect the patches if they were proofed being isolated by field data.

Chapter 5: Qilian Mountain National Park-Snow Leopards in Distribution, Habitat Patches and Linkages

To remove the factors that have been limiting the conservation effectiveness of protected areas in China, in 2017, the National Forestry and Grasslands Administration established a pilot scheme for National Parks in China with 10 pilot national parks. Qilian Mountain National Park (QMNP) located in one of the key snow leopard habitats in China—Qilian Mountain range, with an area of 50,200 km^2. It was an urgent requirement also a big challenge to conduct national park level snow leopard study to support conservation, management and resource utilization for the newly established QMNP. In this chapter, we combined the information from field works conducted within the current QMNP extent from 2013 to 2018 for form a dataset. Based on this dataset, we: 1) employed multiple species distribution models (Maximum Entropy, Random Forest and Generalized Linear Model) with multiple predictor scales to predict snow leopard distribution, and produced resistance surface; 2) analyzed connectivity surface and linkage network using UNICOR; 3) identified medium and high-quality patches using CONEFOR; and 4) mapped least cost paths between medium and high-quality patches with “Linkage Mapper”. Based on 393 snow leopard presence locations, we identified 16 high-quality patches and 27 medium-quality patches in QMNP and surrounding areas. The largest high-quality patch located in the mid-east of QMNP, which was consistent with the results from connectivity surface and linkage network analysis about the most important key area. Second largest high-quality patch located at south out of the QMNP, which may play the role of bridge or step stones for the snow leopard population communication between the national park and the main part of Qinghai-Tibet Plateau. Result of least cost path analysis showed that most of the high-quality patch paths went through medium-quality patches, indicating the potential step stone function of the medium-quality patches for snow leopard individuals’ dispersal. Based on results from this study, suggestions on further study, conservation and management planning and practice in QMNP and surrounding areas were provided.

Chapter 6: Discussion

This final chapter summarized the findings of this study in Yanchiwan National Nature Reserve, Qilian Mountain National Park and areas around as the first case of snow leopard ecological study in national park level landscape in China. The discussion then took a wider view on the opportunities and suggestions on the further step studies in the area. The application to conservation and management of this study was discussed.

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Chapter 2: Estimation of Snow Leopard Density in Yanchiwan National Nature Reserve Using Spatially Explicit Capture-Recapture Models

2.1 Introduction

Obtaining reliable and accurate species population estimates has long been considered important for ecological studies (Grubb and Whittaker, 1989) and as a basis for the management and conservation of wildlife (Krebs, 1989; Sinclair et al., 2005). Understanding species population trends, deriving parameters (e.g., growth rates) and developing predictions about changes in species abundance remain critical to evaluating policies and intervention to both increase and decrease (control) populations (Fowler, 1987; Noss et al., 1996; Predavec, 1994). Several methods for estimating population abundance have been developed, including capture-mark-recapture (also called capture-recapture – CR) approaches, which were first documented for the human population census in London in 1667 and later used by early ecologists (Krebs, 1989). CR relies on marking animals caught in an initial capture and then estimating the total population based on the ratio of subsequent recaptures relative to newly encountered individuals. These marks should not be lost between captures. Of importance is the concept of a 'closed' population between capture events, where no animals are added, through birth or immigration, or lost through emigration or mortality. For many species these requirements place significant limits, particularly for long-lived and wide-ranging species, where the scale of capture is substantially shorter than generation lengths and smaller than typical home-ranges. Also important is that individuals do not differ in their probability of being capture (equal likelihood) and that each capture location or device has an equally likelihood of capture (Gopalaswamy, 2013; O'Connell et al., 2011; Otis et al., 1981)

Numerous efforts have been made to address the requirements for CR methods and ensure they are applicable for free-roaming wild species, including allowing parameterization of 'open' populations, and accommodating spatial scale through explicit inclusion of capture locations (Borchers and Efford, 2008; Gopalaswamy, 2013). Many advances in the development of robust spatially-explicit population estimation have come from research on terrestrial [mammalian predators], particularly in conjunction with the increased use of remotely operated camera-traps as a survey methodology (Karanth & Nichols, 1998; Royle et al., 2009; O'Connell et al., 2011).

Camera trapping has become a standard technique for surveying medium and large terrestrial wildlife species (O'Connell et al., 2011). For large carnivore surveys, cameras are typically placed along trails and paths that are determined to be frequently used by the species, often based on sign (e.g., footprints, scats) or other information. Numerous models of camera are now available that include remote detection and triggering in response to animals passing in front, flash units and infra-red for nighttime images. The placement of camera is critically important to ensure that resultant images or video are of sufficient quality to identify species and, where required distinguish individuals from coat patterns or other marks. Cameras might be positioned in pairs, for example if both sides of individuals are required for identification, or singly if face or tail patterns along are used. The cost advantage of using single cameras at trapping stations is clear, although failure of a unit can be problematic. In many situations, cameras are ideally left in the positions for a number of weeks, and therefore should be able to withstand the often-extreme environmental conditions (e.g., humidity; precipitation; cold; heat; flooding…). This also applies to the batteries used to power the cameras, with some being particularly sensitive to temperature changes, for example.

Despite these challenges, the use of camera trapping has fundamentally changed the way in which carnivores are studied and has led to new insights about their ecology, conservation and interactions with people (Karanth et al., 1998; Ripple et al., 2014; Sollmann et al., 2011).

Information on density and distribution is the most basic but arguably the most important factor in supporting the conservation of species at risk (Gese, 2001). However, due to the large home range, low density, and their often-cryptic nature, collecting that information on large carnivores has always been challenging (Karanth, 1995). Snow leopards certainly fall into the 'challenging' category: their home range size is large (Johansson et al., 2016), the environment is harsh, logistics are difficult and the costs of surveys are high, making it extremely challenging to conduct surveys to obtain reliable density estimates. Despite numerous years of research and surveying, there is controversy about the size of the global snow leopard population. In 2017 the IUCN Red List changed the status of snow leopard from 'Endangered' to 'Vulnerable' (Thomas McCarthy et al., 2017). This change followed a long discussion centered on the population estimates previously, which some researcher and conservationist organizations thought were either invalid or insufficient (see for example, Snow Leopard Trust, 2017). The IUCN took their decision on the basis of a growing body of work on snow leopard population estimation carried out since the previous assessment in 2008, including new technologies and work in areas previous under- or un-surveyed, such as China (Riordan and Shi, 2016). The current global estimate for the snow leopard population is estimated between approximately 7,500 – 8,000 individuals (McCarthy et al., 2017), with approximately 60% of the global population thought to occur in China, making it the single most important country for the species' conservation (Riordan and Shi, 2016).

Several methods have previously been used to estimate snow leopard density. Sign surveys were used to verify presence and relative abundance or density across study sites by Fox et al. (1991), Jackson (1996) and McCarthy et al. (2008). Camera traps are now widely used as the standard method of studying large carnivores, and it is particularly suitable for density estimation of large felids with uniquely identifiable coat patterns, such as snow leopard (e.g., Alexander et al., 2015). Recently, another non-invasive method, using a scats-based genetic algorithm, has also showed promise with the potential for wide application (Atzeni et al., 2020).

Early population density assessments from this region, based on sign surveys, estimated snow leopards to occur between 1 – 3 animals per 100 km^2 (Koshkarev, 1984; Schaller et al., 1988). Elsewhere in the snow leopard range, such as the Himalayan region of Nepal and India, density estimates have been as high as 5-6 animals per 100 km^2 (Jackson and Ahlborn, 1989; Chundawat, 1992).

More recently, several studies have applied basic Capture-Recapture (CR) methods to assess snow leopard abundance and/or density (Jackson et al., 2006; Janečka et al., 2011; McCarthy et al., 2008; Sharma et al., 2014), and these have typically produced population density estimates between 2 – 4 animals per 100 km^2. However, the original CR method largely relied upon a subjective estimation of the area sampled (Otis et al., 1978; Amstrup et al., 2005) and this has concerns for the accuracy and reliability of the estimates (Jackson et al., 2006; Soisalo & Cavalcanti, 2006; McCarthy et al., 2008; Royle et al., 2013).

Spatially Explicit Capture Recapture (SECR) models potentially achieve more reliable density estimates by incorporating spatial locations of captures (Borchers & Efford, 2008; Royle, Nichols, et al., 2009; Efford & Fewster, 2013; Gopalaswamy, 2013), and also can provide quantified spatial distribution information. The SECR method has been used on different large felids such as tigers *Panthera tigris* (J. Andrew Royle et al., 2009) and jaguars *Panthera onca* (Sollmann et al., 2011). SECR also has been used applied in snow leopard density estimation in China (Alexander et al., 2015a) and India (Sharma et al., 2021), giving population density estimates in the range of 2-4 animals per 100 km^2.

Building on the use of SECR modelling approaches deployed previously in Qilianshan (Alexander et al., 2015a), this chapter uses data from camera trapping to provide densities of snow leopards in in Yanchiwan National Nature Reserve, Gansu Province, China. The aims of this chapter are:

1. to estimate snow leopard population density using the robust SECR method;
2. to assess the influence of geographic and prey covariates on snow leopard density and distribution,
3. to explore recommendations for further survey design improvements in Yanchiwan and the wider mountain ecosystem in which it is placed.

2.2 Materials and Methods

2.2.1 Study area

Yanchiwan National Nature Reserve (YNNR, Figure 2.1) is located in Subei Mongolian Autonomous Count, Gansu Province, China (N38°33′ – 39°10′, E95°19′ – 97°13′). YNNR lies to the west of the Qilian Mountain range (Qilianshan) at the north-eastern margin of the Qinghai-Tibet Plateau. YNNR is about 13,600 km^2 in extent, with mean elevation of 3,800 m and is listed as a global snow leopard landscape by Global Snow Leopard & Ecosystem Protection Program (GSLEP, https://globalsnowleopard.org/).

The reserve elevation declines from east to west and from south to north towards the Gobi Desert in both directions. Four main mountain ranges occur within YNNR: Daxueshan; Shulenanshan; Yemananshan; and Danghenanshan. Livestock husbandry is the main source of income for local residents, with grazing permitted within the reserve. Grazing mainly occurs in the open, flat basins between mountain ranges, and in lower elevation mountainous areas to a lesser degree. Fences are common throughout the reserve, having been the principle means of dividing pastures and seasonal grazing rotations. The majority of these fences are multi-strand wire or wire-mesh, with concrete, metal and wooden posts. New fencing has been banned since 2014. Active efforts are being undertaken to make policies of removing fencing from the reserve, although no official policies have been issued yet.

The study area was located in the Shulenanshan Mountains, which lies in the east of the nature reserve (Figure 1). It is one of the most remote areas of the nature reserve, with fewer than 10 permanent residents and between 150-200 sheep and goats, fewer than 100 yaks, and occasional horses and camels.

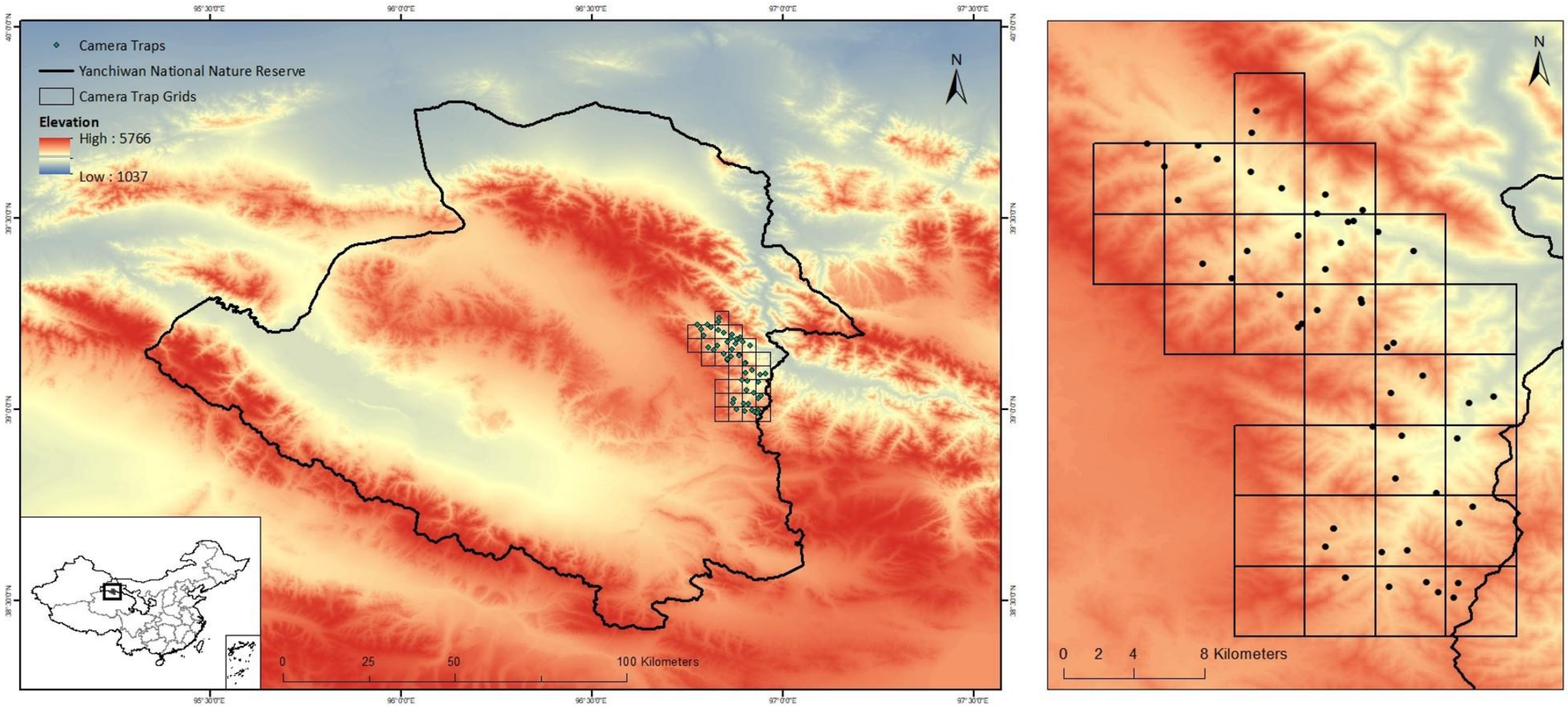


Figure 2.1. The locations of camera traps and survey grids in Yanchiwan National Nature Reserve, Gansu Province, China.

2.2.2 Camera trap survey

The study area was divided into 20 4 km × 4 km grid cells. In each grid cell, a walking transect survey was conducted of at least 3 km in length to record snow leopard sign (scrapes, footprints, putative scats) (Jackson and Hunter, 1996). Based on these preliminary surveys, two or three sites within each grid cell were selected to set up camera trap stations, with one camera placed per station. Cameras were placed at approximately 50 cm above the ground, and positioned to avoid direct sunlight onto the infrared sensors. The sensitivity of cameras were set as "Low", and the interval between two triggers was set as zero second. Cameras were set to take 3 consecutive photographs when triggered, and operated continuously. The minimum spacing between any two cameras was greater than one kilometer to maximize detection independence, but also balance the need for individual animals to be encountered on more than one camera (Borchers and Efford, 2008; J Andrew Royle et al., 2009). A total of 62 camera trap stations (camera trap type: LTL ACORN-5210 & 6210) were set up across 400 km^2 area in November 2015. In June 2016, 54 out of 62 cameras were retrieved, with the remainder having been lost due to either flooding or landslides. The average distance between the 54 continuously active camera stations was 1,143 m.

2.2.3 Data analysis

Camera trap data processing
A capture event was defined as: 1) for each separate species, all the photos with 30 minutes from the first photo are defined as the same event; 2) for different species appearing separately, there was no time duration definition; 3) for different species appearing at the same time in a single capture (for example, a Himalayan marmot (*Marmota himalayana*) and a blue sheep (*Pseudois nayaur*), we count one capture event for each species. Livestock were categorized as "sheep/goat", "yak", "horse" and "camel". We counted the number of individuals for each category of livestock and also wild species, such as blue sheep.

Snow leopard capture events were reviewed independently by three separate experienced observers (Wang Jun, Zhang Chengcheng and Sydney Greenfield) to identify snow leopard individuals according to the unique coat patterns of each animal. The observers then jointly reviewed the events to reach a final agreement on individuals for which there was potential confusion. Each identified and verified individual was given a unique ID number. Capture photographs that were not of sufficient quality to determine an individual ID were discarded from population analyses, but were maintained for occupancy analyses. To meet the assumption of a closed population in the SECR analysis, we used the data from January to March 2016, which totalled 90 days. For the purposes of the SECR analysis, each day was defined as one occasion.

Covariates
An elevation raster layer was used from NASA'S SRTM (Shuttle Radar Topography Mission, version 4) 3 arc-seconds resolution digital elevation model (Jarvis, et al., 2008). Slope position (slp) and terrain roughness index (tri) were selected as geographic covariates. Slope position (also known as Topographic Position Index (TPI) is used to express the amount of difference in elevation between central and adjacent cells (De Reu et al., 2013; Weiss, 2001). Positive slp value indicates that the central unit is located higher than the average of surrounding units, and vice versa for the negative values. The Topographic Ruggedness Index (TRI) was developed by Riley et al., (1999) to indicate the ruggedness. It is calculated by averaging the squares of elevation differences between eight surrounding cells with the central cell, and taking the square root of this average (Riley et al., 1999). Slope Position and Topographic Ruggedness Index were calculated using the Geomorphometric and Gradient Metrics Toolbox 2.0 (Evans et al., 2014) in ArcGIS v.10.5. The Focal Statistics tool in ArcGIS was used to produce focal mean raster layers of elevation, slope position and roughness with 500 m radius circular neighborhood setting.

Density of prey could be a key covariate in the models of snow leopard density estimation (Sharma et al., 2020). In the study area, neither density estimation survey for wild prey nor livestock population census has been done before. Camera trapping data has been used to estimate ungulate density (Zero et al., 2013). In this case, given the systematic distribution of cameras, we assume that the capture events of blue sheep and livestock can indicate the spatial distribution and relative abundance of prey. Multiple interpolation methods have been used in studies, mainly include inverse-distance weighting (IDW) and the empirical Bayesian kriging (EBK). Inverse-distance weighting calculates cell values by averaging the values of sample data points in the surrounding cells of each processing cell (Donald Shepard, 1968). Empirical Bayesian kriging (Gribov and Krivoruchko, 2020) is a kind of regression that takes least squares estimate of data. Differ from IDW, EBK interpolation is based on the observed sample data points, rather than on a pre-assumed model. EBK has been used in the researches on climate change (Kutuzov et al., 2019; Nocco et al., 2019), spatial variation in phylogenetic diversity of spider communities (Nogueira et al., 2019) and agriculture (Samsonova et al., 2017). A study showed that the performance differed from EBK and IDW, although EBK was the best performed interpolation method (Mirzaei and Sakizadeh, 2016). Therefore, we used EBK interpolation in this study. The Empirical Bayesian Kriging method was implemented using the Geostatistical Analysis tool in ArcGIS to make raster layers of blue sheep events and livestock events. The settings are provided in Appendix 2.1.

SECR modelling

The package “secr 4.3.1” (Efford, 2020) in R was used to estimate snow leopard density using maximum likelihood based SECR Models. Given the sampling design, data were assumed to meet the assumptions that: 1) the snow leopard population was closed during the 90 days sampling period; 2) detection probability was constant during the sampling period; 3) the average density across the period was represented by the overall density; and 4) the average ranging parameter (σ) was consistent across the snow leopards and the study area.

The SECR approach involves a state model and an observation model, the state model describes the animal home range distribution in the landscape, and the observation model relates the risk of detecting an animal at a particular detector to the distance between that detection and a central point of each individual’s home range (Efford, 2020). The integration area (also known as the habitat mask) represents the region potentially inhabited by the species. The habitat mask is constructed by extending the buffer width around the survey area, defined by the outermost camera stations. Based on the extent of camera placements and their capture rates, the “suggest.buffer” function within the SECR package was calculated a buffer width of 14,784m around the survey area with a total area of 1,881.6 km^2.

The effect of topography (elevation, slope position and roughness) and prey (blue sheep and livestock event numbers) on the estimated snow leopard density and encounter rate were then tested. The impact of interactive combinations of covariates on both the density parameters and detection probabilities were assessed. A set of 49 candidate models with all parameter combinations were run (Table 1). Akaike’s Information Criteria (AIC) was used for model selection (Burnham and Anderson, 2002), along with model-averaging to estimate snow leopard density based on models with summed 95% AICc weight.

2.3 Results

During the 90-day sampling period, 49 out of 54 camera traps were functional throughout, with five cameras working for 49, 70, 71,78 and 82, days respectively, with either memory cards or battery capacity being exceeded. In total, there were 4,760 camera trapping days. On average each camera station was operational for 88.1 days. Over the sampling period, 37 out of 54 cameras stations yielded 137 snow leopard capture events, with 14 individual snow leopards identified (Figure 2.2). A total of 250 blue sheep capture events was recorded at 43 sites, with the mean of

4.63 (SD=5.07) captures per camera. The number of capture events of livestock was 253, including 213 yak events, 23 sheep/goat events, 14 horse events and 3 camel events, distributed at 27 stations, the mean was 4.69 times per station (Figure 2.2).

The elevation of cameras stations ranged from 3,269 to 4,111m, with the mean and standard deviation of 3,719.8 and 208.3m, respectively. The slope position of camera stations ranged from -271.3 to 64.3, with only two cameras had slope position above zero (64.3 and 14.7). The mean of slope position was -109.4, and the standard deviation was 58.2. The range of terrain roughness index (tri) was between 5.2 and 11.0, with the average of 8.1 and standard deviation of 1.3 (Figure 2.3).

Spatially-explicit capture-recapture (SECR) modelling produced six top-ranked models that had a cumulative AICc weight of 95% (Table 2.1). In addition to the snow leopard encounter rate (lambda0), linear and non-linear terrain ruggedness index was consistent determinants of snow leopard density. The top rank model highlighted the importance of blue sheep capture events (bse), with an AICc weight of 0.424, followed by terrain roughness index (tri and tri^2) with 0.315 of accumulated AICc weight. Livestock capture events were also an important determinant of snow leopard density in models, although the model weighting (AICcwt = 0.124) was less than that for the blue sheep model (AICcwt = 0.424). When the prey categories were combined (blue sheep + livestock) their joint AIC weighting accounted for more than half of all top ranked models (AICcwt = 0.548). The topographical variables (slope and roughness) had a combined weight of 0.442. The encounter rate at activity centers (lambda0) was monopolized by terrain roughness index (tri).

The snow leopard density surfaces produced from the top six models showed variability in the complexity with which each model defined snow leopard density (fig 2.4a – f). In those maps, the red coloured regions correspond to areas of higher snow leopard density, and regions highlighted in blue colouration correspond to areas of lower density. The top-ranked model (d.bse.lambda.tri), determined by blue sheep encounters (bse) was spatially relatively simple (Figure 2.4a), with an apparent north-south split in snow leopard density. Similarly, the density surface produced by the model driven by livestock encounters (lse) appeared to show a localized effect on snow leopard density (Figure 2.4c). Density surfaces from models driven by topographic features, including terrain ruggedness (Figure 2.4d), appeared to be more complex, reflecting the intricate network of ravines and ridgelines. The ensembled density surface, calculated as the weighted sum of the snow leopard densities from the six top-ranked models across the study area, according to the AICc weight of each model, accounted for the relative influence of each covariate as a determinant of snow leopard density (Figure 2.4g).

From the SECR modelling, the overall abundance of snow leopards was estimated to be 26.3 individuals (SE = 5.7, 95% CI 19.2-43.2) over the entire buffered survey area of 1,881.6 km^2. The estimated average snow leopard density for the study was therefore 1.40 (SE=0.30, 95% CI 1.02-2.30) individuals per 100 km^2. The encounter rate at activity centers (lambda0) was 2.28×10^{-2} (SE = 3.22×10^{-3}, 95% CI 1.73×10^{-2}-3.00×10^{-2}), and the estimated half of the radius of the activity ranger of snow leopards (sigma) was 3,755 m (SE = 252 m, 95% CI 3294 m-4281 m).

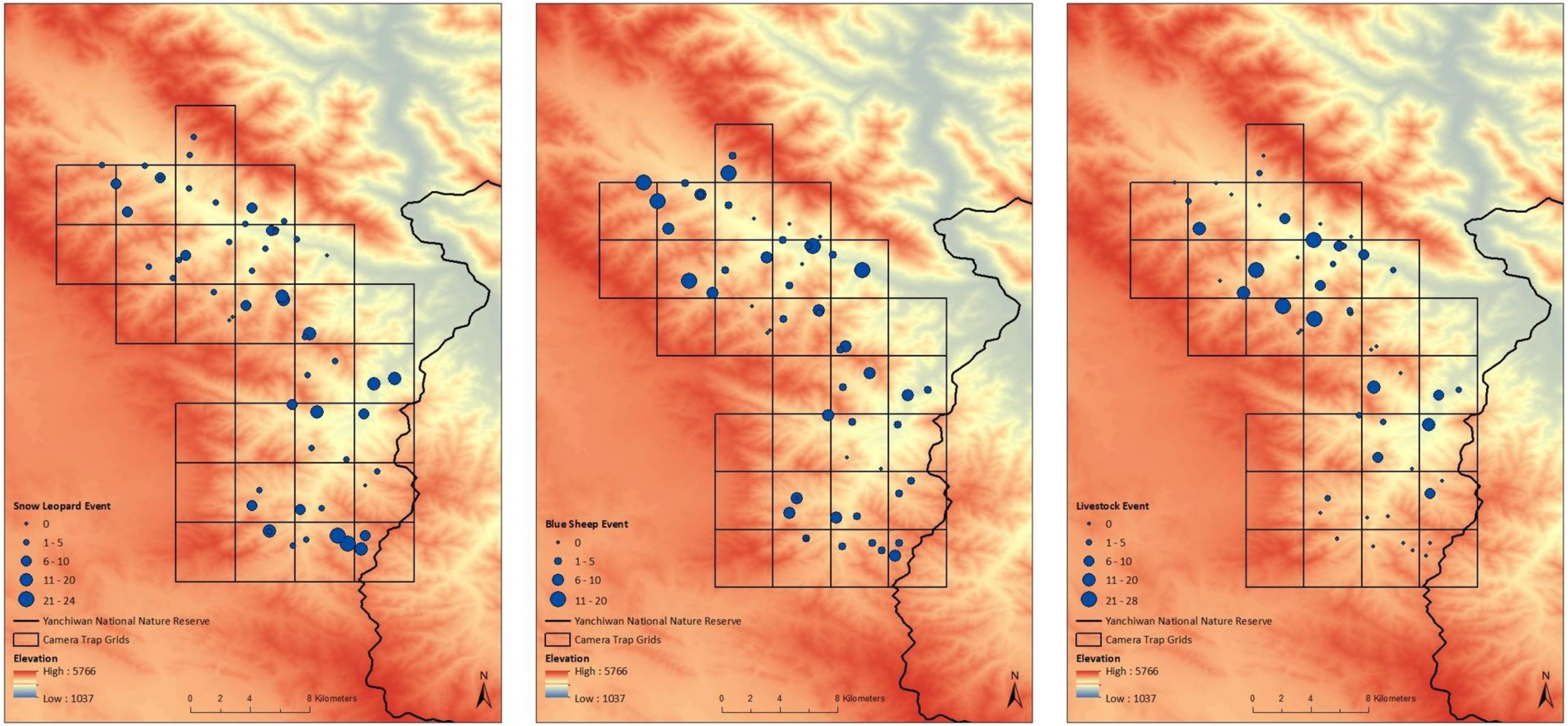
The ensemble SECR model (Figure 2.4g) suggests that snow leopards were mainly distributed in the south of the study area, with occurrences in the middle and northern areas less widespread and restricted to key landscape features and areas. From trapping records, it appears that capture of individuals was not restricted to the south, with a relatively wide distribution of captures across the area (Figure 2.2a).

Table 2.1. Candidate spatial explicit capture recapture models ranked based on Akaike's Information Criterion (AIC) of snow leopard density using camera trap data collected in Yanchiwan National Nature Reserve, Gansu Province, China.

Models are described using the following notation: bse = number of blue sheep capture events; lse = number of livestock capture events; elv = elevation; elv² = square of elevation (used to test the potential nonlinear relationship between snow leopard density and elevation), slp = slope positon; slp² = squared slope; tri = terrain roughness index (TRI); tri² = squared TRI; D = snow leopard density; lambda0 = snow leopard encounter rate at distance zero from activity center; sigma = spatial scale of detection function for snow leopards. Number of parameters in each model is given by "npar", log-likelihood estimates for each model is given as "logLik". AIC, corrected AIC (AICc), change in corrected AIC between models of decreasing rank (dAICc) and corrected AIC weightings (AICcwt) are also shown.

model	detectfn	npar	logLik	AIC	AICc	dAICc	AICcwt
d.bse.lambda.tri	haard halfnormal	5	-236.134	482.267	489.767	0.000	0.424
d.tri.lambda.tri	haard halfnormal	5	-236.842	483.684	491.184	1.417	0.209
d.lse.lambda.tri	haard halfnormal	5	-237.362	484.725	492.225	2.458	0.124
d.tri².lambda.tri	haard halfnormal	6	-234.269	480.537	492.537	2.770	0.106
d.elv.lambda.tri	haard halfnormal	5	-237.990	485.980	493.480	3.713	0.066
d.slp.lambda.tri	haard halfnormal	5	-238.065	486.131	493.631	3.864	0.061
d.slp².lambda.tri	haard halfnormal	6	-236.651	485.302	497.302	7.535	0.010
d.elv².lambda.tri	haard halfnormal	6	-237.890	487.780	499.780	10.013	0.000
f0	haard halfnormal	3	-247.267	.534	502.934	13.167	0.000
d.bse	haard halfnormal	4	-245.515	499.030	503.475	13.708	0.000
d.tri	haard halfnormal	4	-246.415	.829	505.274	15.507	0.000
d.lse	haard halfnormal	4	-246.714	501.428	505.872	16.105	0.000
d.bse.lambda.bse	haard halfnormal	5	-244.506	499.012	506.512	16.745	0.000
d.slp	haard halfnormal	4	-247.238	502.475	506.919	17.152	0.000
d.elv	haard halfnormal	4	-247.255	502.511	506.955	17.188	0.000
d.bse.lambda.elv	haard halfnormal	5	-244.835	499.671	507.171	17.404	0.000
d.tri²	haard halfnormal	5	-245.120	.240	507.740	17.973	0.000
d.bse.lambda.lse	haard halfnormal	5	-245.324	.647	508.147	18.380	0.000
d.bse.lambda.slp	haard halfnormal	5	-245.449	.898	508.398	18.631	0.000
d.tri.lambda.bse	haard halfnormal	5	-245.652	501.305	508.805	19.038	0.000
d.tri.lambda.elv	haard halfnormal	5	-245.699	501.399	508.899	19.132	0.000
d.slp²	haard halfnormal	5	-245.768	501.535	509.035	19.268	0.000

d.lse.lambda.bse	haard halfnormal	5	-245.974	501.947	509.447	19.680	0.000
d.tri.lambda.lse	haard halfnormal	5	-246.186	502.373	509.873	20.106	0.000
d.lse.lambda.elv	haard halfnormal	5	-246.202	502.403	509.903	20.136	0.000
d.lse.lambda.lse	haard halfnormal	5	-246.348	502.696	510.196	20.429	0.000
d.tri.lambda.slp	haard halfnormal	5	-246.353	502.706	510.206	20.439	0.000
d.slp.lambda.bse	haard halfnormal	5	-246.410	502.820	510.320	20.553	0.000
d.elv.lambda.bse	haard halfnormal	5	-246.427	502.854	510.354	20.587	0.000
d.elv.lambda.elv	haard halfnormal	5	-246.614	503.228	510.728	20.961	0.000
d.slp.lambda.elv	haard halfnormal	5	-246.628	503.255	510.755	20.988	0.000
d.lse.lambda.slp	haard halfnormal	5	-246.669	503.338	510.838	21.071	0.000
d.slp.lambda.lse	haard halfnormal	5	-247.030	504.060	511.560	21.793	0.000
d.elv.lambda.lse	haard halfnormal	5	-247.045	504.090	511.590	21.823	0.000
d.slp.lambda.slp	haard halfnormal	5	-247.194	504.388	511.888	22.121	0.000
d.elv.lambda.slp	haard halfnormal	5	-247.209	504.419	511.919	22.152	0.000
d.elv^2	haard halfnormal	5	-247.240	504.481	511.981	22.214	0.000
d.tri^2.lambda.bse	haard halfnormal	6	-244.206	.412	512.412	22.645	0.000
d.tri^2.lambda.elv	haard halfnormal	6	-244.376	.753	512.753	22.986	0.000
d.tri^2.lambda.lse	haard halfnormal	6	-244.832	501.663	513.663	23.896	0.000
d.tri^2.lambda.slp	haard halfnormal	6	-245.163	502.327	514.327	24.560	0.000
d.slp^2.lambda.bse	haard halfnormal	6	-245.295	502.589	514.589	24.822	0.000
d.slp^2.lambda.elv	haard halfnormal	6	-245.416	502.832	514.832	25.065	0.000
d.slp^2.lambda.lse	haard halfnormal	6	-245.801	503.602	515.602	25.835	0.000
d.slp^2.lambda.slp	haard halfnormal	6	-246.324	504.648	516.648	26.881	0.000
d.elv^2.lambda.bse	haard halfnormal	6	-246.434	504.869	516.869	27.102	0.000
d.elv^2.lambda.elv	haard halfnormal	6	-246.607	505.215	517.215	27.448	0.000
d.elv^2.lambda.lse	haard halfnormal	6	-247.077	506.154	518.154	28.387	0.000
d.elv^2.lambda.slp	haard halfnormal	6	-247.198	506.396	518.396	28.629	0.000



a b c

Figure 2.2. The frequency and distribution of (a) snow leopard, (b) blue sheep and (c) livestock capture events of camera trap stations in study area in Yanchiwan National Nature Reserve, Gansu Province, China.

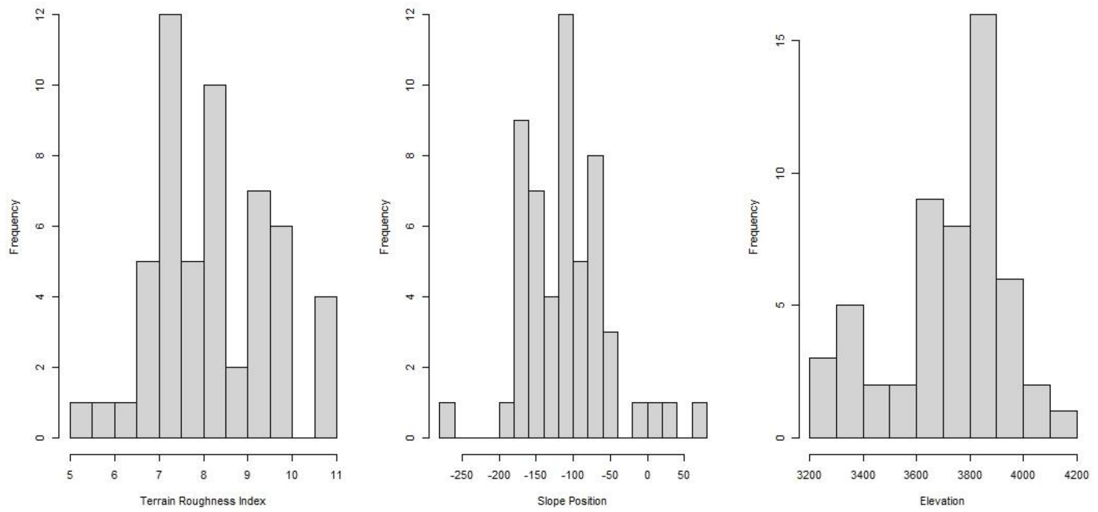


Figure 2.3. The frequency of camera trap stations placement of the three geographic covariates.

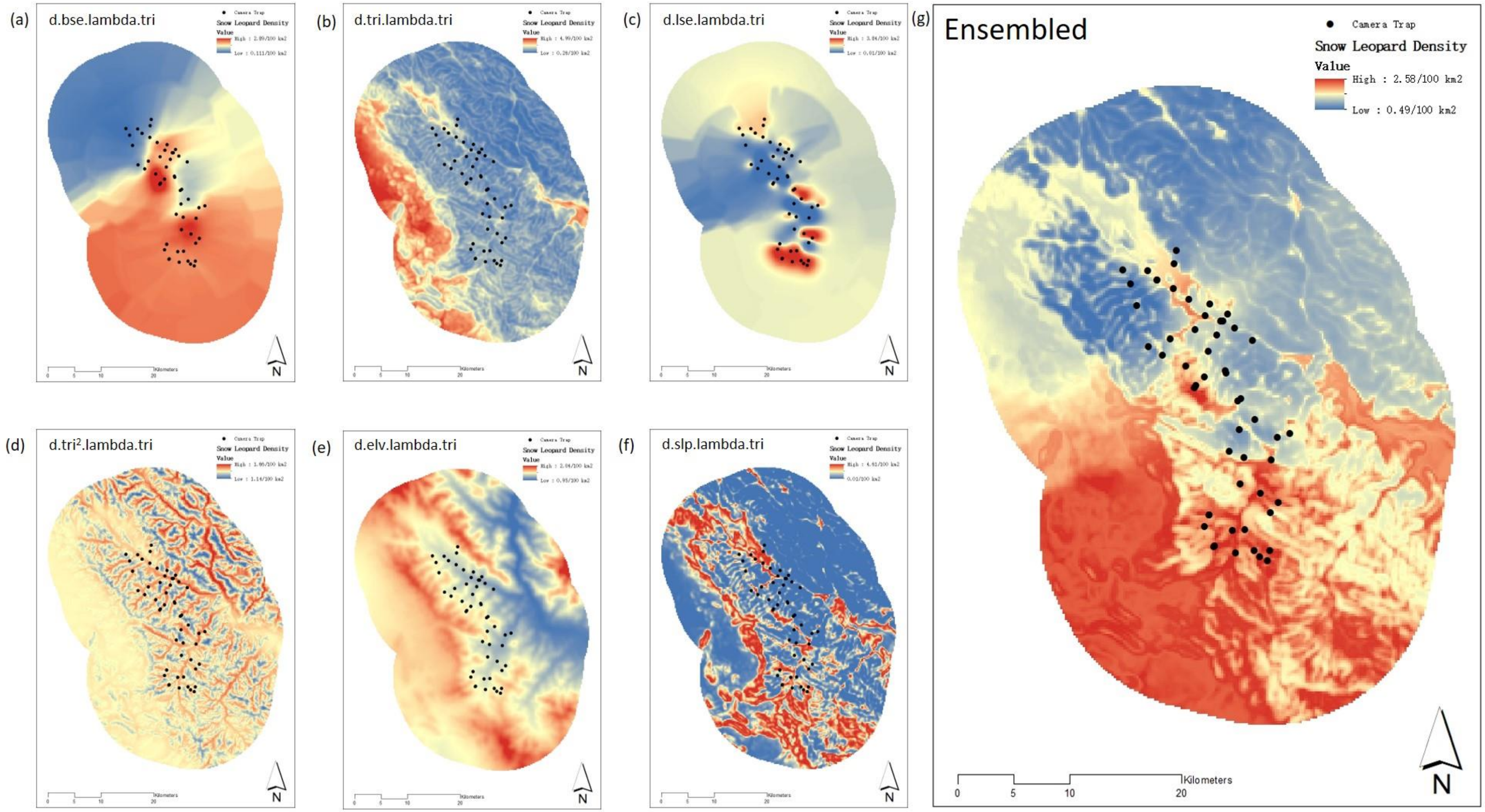


Figure 2.4. Snow leopard density surfaces produced from the top six models and ensembled according to the AICc weight of each model.

2.4 Discussion

This study explored the impact of geographical and wild and domestic prey covariates on density, encounter rate at activity center and activity range of snow leopard, based on camera trap data. Previous studies showed that prey (wild and/or domestic) could have big impact on snow leopard's density and distribution (Alexander et al., 2015; Sharma et al., 2021). In this study, the blue sheep had the largest impact on density (0.424 of AICc weight), combined with livestock, the prey covariates occupied more than half of the AICc weight. The fact that the impact on domestic prey was much less then wild prey, could be explained as: (1) the big capture event number and wide distribution of blue sheep; (2) the low-level of grazing intensity and limited grazing area, manifested as small amount of livestock number, and fewer but clustered distribution of camera sites.

Elevation, slope position and terrain roughness index were recognized as the important geographic factors than impact snow leopard distribution (Alexander et al., 2015b; McCarthy and Mallon, 2016; Sharma et al., 2021). However, it was noticed that in this study, the terrain roughness index monopolized the impact on activity centers (lambda0). The statistic of geographic covariates of the camera sites indicated that most of the cameras were set up in valleys located in broken area but with small elevation difference. Due to the relative even character of elevation and slope, the impact of the two factors could hardly showed in the models. It's possible that the impact of elevation and slope position were under-estimated caused by the low degree of difference. However, the occurrence of snow leopard trapping events was spatially relatively even and thus models were not therefore apparently overly influenced by clusters of captures and reflect a reasonable interpretation of the influence of covariates.

The apparent influence of a wild prey species, the blue sheep, on snow leopard occurrence and density gave some confidence in the models. The high-elevation ecosystem in which snow leopards occur has relatively low-productivity (Mishra et al., 2009), with prey tending to be widely and thinly distributed (Suryawanshi et al., 2012) resulting in large snow leopard home ranges. As a top-predator, snow leopard reliance on prey is not a surprise, and this is seen in other solitary large felids, such as leopard (e.g., Akrim et al., 2018; Kshettry et al., 2018; Rostro-García et al., 2018; Sidhu et al., 2015) and jaguar (e.g., Azevedo, 2008; López González and Miller, 2002; Miranda et al., 2018; Weckel et al., 2006). Perhaps more surprising is the small scale in which the snow leopards encountered here demonstrate this influence. Given the nature of these studies and the logical constraints of working in these challenging environments, the study areas are often small relative to anticipated snow leopard movements, leading to biases in data quantities and survey effort (Riordan et al, 2015), or population parameter estimates (Alexander et al., 2015a). Elsewhere, effects of study scale on density estimates have been highlighted (Shawn Smallwood and Schonewald, 1998) and we have to accept that this area might be a 'hotspot' for snow leopard and blue sheep in the region. Certainly, the distribution of blue sheep across the study area was less even than that of snow leopard.

Only a few of studies that used CR and SECR methods for estimating snow leopard density/abundance (Table 2.2). Two previous studies conducted in Indian Trans-Himalaya revealed similar density estimates of 4.5-8.5/100 km^2 (Jackson et al., 2006) and 0.50/100 km^2, SE=1.01 (Sharma et al., 2021). In Xinjiang, China McCarthy et al., (2008) estimated snow leopard density of 0.74/100 km^2, whilst in the Tien Shan Mountains of China and Kyrgyzstan McCarthy et al., (2008) estimated a greater range of estimates, from 0.15-0.87/100 km^2). Janečka et al., (2011) estimated snow leopard density in the Gobi Desert region of Mongolia at 0.70-1.50/100 km^2, and Sharma et al., (2014) estimated densities of 0.44-0.59km^2 (SE: 0.02-0.14) in the Tost Mountains of Mongolia. The density estimates in this study fall within the ranges of those estimated in these previous studies, suggesting that snow leopard is an intrinsically low density (naturally rare) species throughout their range. And also, the high estimated snow leopard density in the study area

(1.40/100 km^2 (SE=0.30, 95% CI 1.02-2.30)) representing this region was a significant stronghold for the species.
However, compared with previous research in this region (Alexander et al., 2015a) the density of snow leopards here appears relatively low, perhaps half. Density estimates in Qilianshan to the east of Yanchiwan often exceeded 3 animals 100 km^{-2}, again apparently driven by wild prey abundance. Alexander et al., (2015a) used a different SECR algorithm, implemented in the SPACECAP package (Gopalaswamy et al., 2012), compared to the implementation in the secr package (Efford, 2020) used here. Whilst the general analytical principles of SECR may be similar, relaxing some of the requirements for CR estimation, attention needs to be given to the parameter function used to derive density estimates (Efford and Schofield, 2020). Furthermore, given the potential for snow leopard to range widely, it is unclear how these animals organize themselves in territories at these densities, so there is more information needed to interpret 'densities' from a more functional perspective, such as movement and connectivity addressed in later chapters.

Table 2.2. Summary of studies on snow leopard density/abundance estimation with Capture-Recapture (CR) and Spatially Explicit Capture-Recapture algorithms.

ID	Study Site	Source	Density (Individuals/100 km^2)	Method
1	Trans-Himalaya, India	Jackson et al., 2006	4.45-8.49	CR
2	Xinjiang, China	McCarthy et al., 2008	0.74	CR
3	Tien Shan Mountains of China and Kyrgyzstan	McCarthy et al., 2008	0.15-0.87	CR
4	Gobi Desert, Mongolia	Janečka et al., 2011	0.70-1.50	CR
5	Tost Mountains, Mongolia	Sharma et al., 2014	0.44-0.59 (SE: 0.02-0.14)	CR
6	Qilian Mountain, China	Justine et al., 2015a	3.31 (SE=1.01)	SECR
7	Trans-Himalaya, India	Sharma et al., 2021	0.5 (SE=0.13)	SECR

The apparent importance of livestock presents more of a problem. In other areas increasing livestock densities/presences leads to decreased densities/presences of wild ungulate prey species (Bhattacharya et al., 2012; Wang et al., 2012; Karimov et al., 2018; Rovero et al., 2020; Ren et al., 2021). It is therefore not unexpected that, in the absence of wild prey, snow leopard densities might be influenced by livestock. Snow leopards are selective among different types of livestock, preferring sheep/goat with smaller size and avoiding yaks in large body in general (Chetri et al., 2017; Wang et al., 2019). In this study, over 84% of the livestock capture events were contributed by yaks, which could be a reason of the livestock covariate had low impact on snow leopard density in SECR models.

From this study, we have several suggestions on the future studies and survey design. In this case, the covariates of livestock and wild prey, were generated from camera trapping data, as a compromise of missing of livestock census and wild ungulate density estimation in the field. The covariates of domestic and wild prey come from the ground survey, should have better ecological representativeness. Another point we learned from this study, was the importance of geographic heterogeneity in the survey. We got a great success on identifying the good locations for setting up camera trap stations, although those locations were with similar geographic attributes. The homogeneity could be the primary cause of that some of the geographic covariates were "masked" by others covariates with more differences. From the lessons learned from this study, we suggest that for the future snow leopard density estimation survey, the livestock census and wild ungulate density survey should be done, in an area that is big enough to cover the mask/buffer of the sampling area. Also, the placement of sampling locations should cover areas with geographic heterogeneity, on the premise of enough capture and recapture rates.

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Appendix 2.1. Settings of Empirical Bayesian Kriging method in the ESRI ArcGIS (version 10.6) Geostatistical Analysis tool, used to interpolate blue sheep and livestock capture events across the study area.

subset size	20
overlap factor	2
NO of simulations	1000
output surface type	prediction
transformation	empirical
semivariogram type	K-bessel
neighborhood type	standard circular
max neighbors	10
min neighbors	5
sector type	1 sector
angle	0
radius	20000*

** The radius was bigger than buffer distance to make sure the mask was included in the raster layers made.*

Chapter 3: Predicting Snow Leopard Occurrences with Multi-Scale and Multiple Algorithms in Yanchiwan National Nature Reserve

3.1 Introduction

For the endangered species, accurate species distribution information is required for making conservation policies and management measures (Pouzols et al., 2014; Di Minin et al., 2016). When the conservation target species are top predators, this becomes particularly critical because these species are often considered as flagship or umbrella species, and the entire ecosystem could be benefited from the conservation of them (Pitman, 2012; Sergio et al., 2006, 2008). The snow leopard is an example of endangered flagship species, and therefore, good knowledge of their distribution is extremely important for the conservation of the species and their ecosystems.

The species distribution models (SDMs) are powerful and widely used methods that identify the suitable habitats of a species by building up relationships between species presence data and environmental predictors (Wan et al., 2017; Macdonald et al., 2018; Norberg et al., 2019). The SDMs are the key tools to predict potential occurrence of the species like snow leopard and other top carnivores with only presence-only data available due to sampling and financial limitations (Ashrafzadeh et al., 2020; Macdonald et al., 2018).

The most widely used SDMs including Maximum Entropy (MaxEnt) (Phillips et al., 2006), Random Forest (Ashrafzadeh et al., 2020; Cushman et al., 2017; Williams et al., 2009), Generalized Linear Models (GLM) (Hastie and Tibshirani, 1986; Guisan et al., 2002) and so on. There were some comparations between different SDMs (Bar Massada et al., 2013; De et al., 2020; Kaky et al., 2020; Mi et al., 2017; Shabani et al., 2016; Williams et al., 2009), but there was no conclusion of which was the best SDM, because the SDM with best performance could be different form case to case. Therefore, the ensemble of multiple models was recommended as a safer way to predict species distribution (Shabani et al., 2016).

Apart from the algorithms, there are also some discussions on the scales of predictors in the models. Typically, SDMs using predictors with a fixed scale, but related to biological and ecological requirements, each species will make use of their environment factors at a range of different scales (Johnson, 1980; Addicott et al., 1987; Wiens, 1989; Levin, 1992). The missing or failure of predictor multi-scale optimization can produce incorrect predictions (Wiens, 1989; Thompson and McGarigal, 2002; Wasserman et al., 2013; McGarigal et al., 2016).

Studies on snow leopard distribution models covered the areas of Southern Russia (Kalashnikova et al., 2019), Southern and Eastern border of Kazakhstan (Holt et al., 2018), the Nepalese Himalayas (Aryal et al., 2016), Southern Himalayas (Watts et al., 2019; Sharma et al., 2021) and Qomolangmain Chia (Bai et al., 2018). Apart from region scale, global range wide snow leopard distribution models were made (Li et al., 2016; Li et al., 2020). However, all of the above studies only used one algorithm (Maximum Entropy), none of them considered the multi-scale predictor optimization. Only the latest published snow leopard distribution modelling study in China, which covered the area of Northwester edge of Qinghai-Tibet Plateau and Qomolangma National Nature Reserve located in Tibet, China, employed multi-scale optimization in MaxEnt (Atzeni et al., 2020).

This chapter describes the use of three SDMs with multi-scale optimization, to explore the snow leopard distribution in Yanchiwan National Nature Reserve. The objectives of the chapters are:

1. identify the best variables which are related to snow leopard habitat suitability;
2. identify the best scales of the predictors selected in different SDMs;
3. create prediction map from ensembles of three SDMs.

This will be the first case using multiple algorithms with multi-scale species distribution models on snow leopard.

3.2 Materials and Methods

3.2.1. Study area

This work was carried out in Yanchiwan National Nature Reserve (YNNR, Figure 3.1) is located in Subei Mongolian Autonomous Count, Gansu Province, China (N38°33′ – 39°10′, E95°19′ – 97°13′). YNNR lies to the west of the Qilian Mountain range (Qilianshan) at the north-eastern margin of the Qinghai-Tibet Plateau. YNNR is about 13,600 km^2 in extent, with mean elevation of 3800 m and is listed as one of the global snow leopard landscapes by Global Snow Leopard & Ecosystem Protection Program (GSLEP, https://globalsnowleopard.org/). Full details of YNNR were provided in Chapter 2.

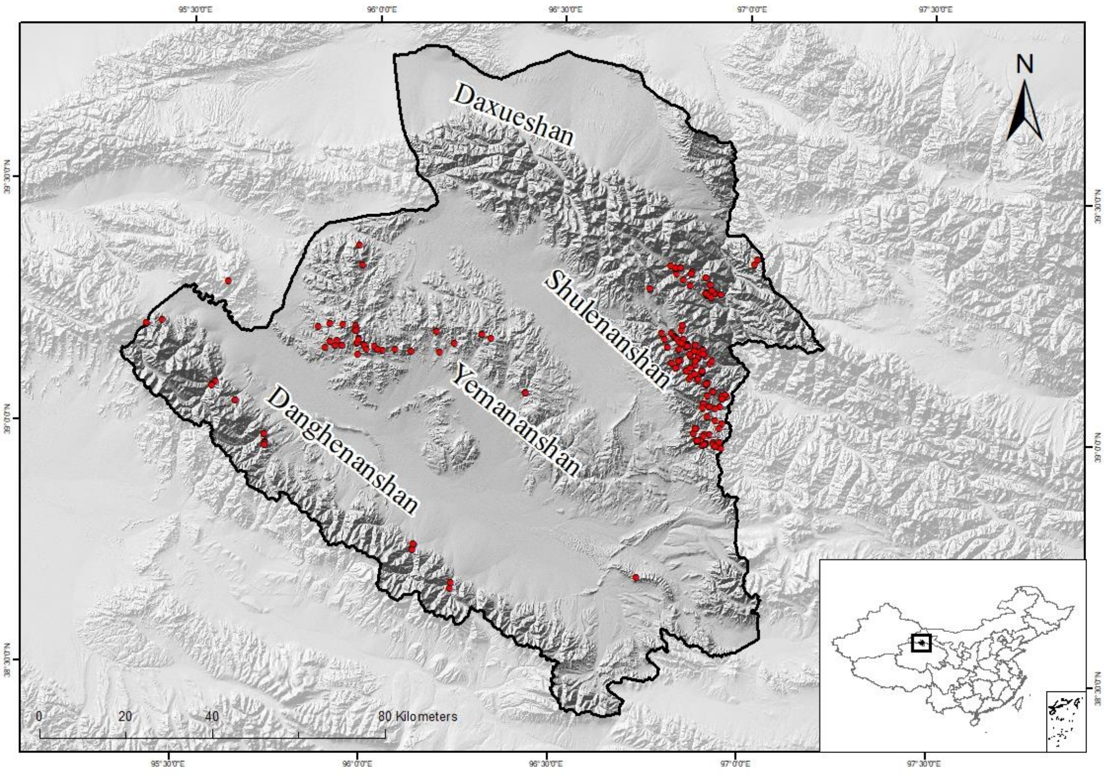

Figure 3.1 Map of Yanchiwan National Nature Reserve, Gansu Province, China, with snow leopard presence points displayed as red dots.

3.2.2. Snow Leopard Surveys

Field work was conducted in YNNR from 2014 to 2017 to survey snow leopards with occurrence data collected using remote camera trapping, described in Chapter 2, and walking / horseback transects. Transects were carried out along predefined routes, following valleys and ridgelines. Positions of snow leopard and other predator scats and sign (including footprints and scrapes) were recorded using a handheld global positioning system (GPS: Garmin eTrek 10). Scats suspected as being snow leopard and those of other predators were collected in the field and subsequently analyzed for genetic characteristics and species confirmation/identification using laboratory procedures described in Bai et al., (2018).

For the further analyses here, the geographic locations corresponding to definite photographic or genetically identified snow leopards were solely used as presence points. Data from other sign were insufficient or unevenly collected, so were not deemed reliable enough to be used in further models. A total of 249 confirmed snow leopard presence points was used.

3.2.3. Data Analysis

3.2.3.1. Environmental Predictors

Following the approach developed by Atzeni et al., (2020), snow leopard presence points were assessed against an array of environmental variables at a range of spatial scales. A total of 27 environmental variables, grouped into five categories were selected as plausible predictors of snow leopard presence, based on previous literature (Table 3.1). Each predictor variable was parameterized at in a buffer surrounding each snow leopard presence point at multiple spatial scales: 300 m, 600 m, 1,200 m, 2,400 m, 4,800 m, 9,600 m, 14,400 m (Atzeni et al., 2020).

Additionally, a grazing fence distribution map of Subei County was provided by Grassland Management Bureau of Subei County, and digitized into a shapefile in ArcGIS 10.6.

3.2.3.2. Maximum Entropy (MaxEnt) Models

Initially, full models were run using Maxent 3.4.1(Phillips et al., 2017; Phillips et al., 2006) with all variables included at all scales. A scale selection process was undertaken using the ‘dismo’ function for each environmental predictor, which indicated the optimum scales for each variable in terms of the highest value of Area Under the ROC Curve (AUC). Full model was run with variables with best scale. The variables with model contributions of less than 1% were subsequently discarded. MaxEnt models were then run using ‘MaxentVariableSelection’. The settings for this were 50% test data, with 10 subsampling replicates, and 20,000 background points. Both linear and quadratic functions were defined for all variables to ensure capture of non-linear and linear relationships with features. Additional parameter values were specified, including a contribution threshold ≤ 1; a correlation threshold ≤ 0.7; and beta multiplier = seq (1, 5, 0.5). A bias file with a kernel radius of 4,800 m around presence points was create using SDM toolbox in ArcGIS. Model selection was based on AIC and AUC (Bai et al., 2018).

3.2.3.3 Random Forest

A random forest analysis of the predictors of snow leopard presence was implemented using the ‘randomForest’ package version 4.6-14 (Naimi, 2017) in R. A sample of 2,490 random points (10 times of presence points) were created within the 14,400 m buffer surrounding the present points to establish a set of ‘pseudo-absence’ points. A training dataset was created using 70% of points, with the remaining 30% used for testing the resultant models. Univariate scaling was applied across all variables using the method of Model Improvement Ratio (MIR, Murphy et al., 2010). MIR is a measurement of how the model performance be improved by involving a variable, and it’s comparable among models. Scale(s) of importance value > 0.9 will be retained as best scale(s).

Package ‘usdm’ (version 1.1-18) in R was used to determine the variance inflation factor (VIF) using a correlation threshold of 0.7 (VIF> 3.3) and ‘prune’ the set of predictors (Naimi, 2017). Package VSURF (Variable Selection Using Random Forests) (McGarigal et al., 2012) was used to select the final set of predictor variables by running subset evaluations of variables to find the best fit (Speiser et al., 2019). Model fit procedure was run using 10,000 trees (ntree=10,000).

3.2.4 Generalized Linear Model

Using the 249 confirmed presence points and 2,490 derived pseudo-absence points from the random forest models above, GLM models were constructed with univariate scaling across all variables and only linear interactions tested. Correlation structure using Pearson's test, between variables was assessed using the 'cor' function in R and a threshold of 0.7 was set, above which only the most influential variables from highly correlated pairs were retained for models. The best variables in each correlated variable set were compared and selected based on the lowest AIC values. A 'dredge' procedure was applied to final models, with subsets selected based on deltaAIC < 4. Model averaging from selected model subsets was used to determine predictor values and were used to create visualization maps.

3.2.5 Model ensemble

An ensemble model output was created from the MaxEnt, RF and GLM predictor outputs by summing the resultant GIS layers using the raster calculator in ArcGIS (version 10.6). The ensemble model values were then rescaled to between 0 and 1.

Table 3.1 List of 27 variables used in the study. For the class level landcover, metrics has been calculated for each landcover type. Category appreciations: Bare Land (Br), Snow and Ice (Sn), Grassland (Gr), Shrubland (Shr), and Fenced Area (Fe). Detailed description of each variable provided in Appendix 3.2.

Category	Variable	Abbreviation	Layer Source
Linear and point features	Density of highways and national roads	DENS_rd	Berman, 2009
	Density of human settlements	DENS_set	OpenStreetMap
	Density of rivers	DENS_riv	www.DIVA-GIS.org
Topographic	Slope position	SLP	NASA'S SRTM v.4 (Jarvis et al., 2008)
	Focal mean of elevation	ELEV	
	Roughness	ROUGH	
	Compound topographic index	CTI	
	Dissection	DISS	
Climatic	Annual mean temperature	TEMP	WorldClim Version 2 (Fick & Hijmans, 2017)
Landcover (Landscape level)	Aggregation index	AI	ESA GlobalCover 2009 v2.3 (Arino et al., 2008)
	Contrast-weighted edge index	CWED	
	Patch density	PD	
Landcover (Class Level)	Area-weighted mean	AREA_AM_(Br, Sn, Gr, Shr, Fe)	ESA GlobalCover 2009 v2.3 (Arino et al., 2008) & Grassland Management Bureau of Subei County
	Percentage of landscape	PLAND_(Br, Sn, Gr, Shr, Fe)	
	Radius of gyration (mean area)	GYR_AM_(Br, Sn, Gr, Shr, Fe)	

3.3 Results

From surveys carried out between 2014 and 2017, a total of 249 confirmed snow leopard present points was derived in the Shulenanshan, Yemananshan and Danghenanshan mountain ranges (Figure 2.1), including 116 camera trap locations (153 camera trap stations) and 133 fecal samples with snow leopard species identification success.

3.3.1 MaxEnt

After the univariate scaling and variable selection process, a total of 12 variables were selected for the final model (Table 3.2). In terms of the best scale, six variables had the large scale (9600 m and 14400 m). Predictors of slope, roughness and mean temperature got 1200 m as best scale. The compound topographic index had over 50% percent contribution over all predictors, followed by dissection and slope position (Table 3.3). Response of predictors were showed as Figure 5.2. Results of variables Jackknife of AUC of the MaxEnt model was plotted as Figure 5.3. With the 12 predictors, the final model had an AUC value of 0.965 (SD = 0.007) (Figure 5.4), indicating the good model fit. The snow leopard distribution model produced using MaxEnt algorithm is showed as Figure 5.9-a.

3.3.2 Random Forest

Eight variables were selected after the scaling analysis and covariate selection, including one linear feature (road), elevation and other wo topographic features at two scales (slope and roughness), one landscape level feature (Contrast Edge Weighted Density, CWED) and a class level landcover feature (area-weighted mean for snow and ice, area_am_Sn) (Table 3.2). Within the eight predictors, three had the best scale of 9600 m, three got small scales (300 m and 600 m). Variable importance was evaluated through the “Mean Decreased Accuracy” and Mean Decreased Gini” (Strobl et al, 2007). Slope position (at two scales) and focal mean of elevation leaded scaled variable importance in both calculations (Figure 3.5). Lowess smooth fit curve of the eight selected predictors are showed as Figure 5.6. Multi-scale random forest algorithm-based snow leopard distribution map was plotted as Figure 3.9-b. For the model validation, the model Kappa = 0.7732, ‘out-of-bag’ (OOB) error was 0.034, the model error variance = 1.26×10^{-6}.

3.3.3 Generalized Linear Model

A total of 15 variables were picked up after the univariate scaling and variable selection for GLM, including of linear and point features and topographic features were selected, six class level landcover features and one landscape level landcover feature (Table 3.2). In term of the best scale, six predictors had large scale (9600 m and 14400 m) and five got small scale (300 m and 600 m) (Table 3.2). Lowess smooth fit curve of the 15 selected predictors are showed as Figure 3.7. AUC value of the GLM model was 0.93 (Figure 5.8). Multi-scale GLM algorithm-based snow leopard distribution map in Yanchiwan National Nature Reserve was plotted as Figure 3.9-c.

3.3.4 Ensemble map

Based on above three snow leopard distribution maps, ensemble map was produced by adding up the three maps and then normalized the value to the range from zero to one. Shulenanshan Mountain (east) had the largest area with high quality of suitable habitat for snow leopard, and formed a contiguous snow leopard high quality area with areas outside of the nature reserve in the east. Meanwhile, Yemananshan (middle) emerged as lesser quality, smaller areas ofhabitat, with a much poorer connection with Shulenanshan. Danghenanshan Mountain (west) was also classified as lesser quality areas along the mountain range distribution, and appeared much more isolated from the other two mountain ranges (Figure 3.9-d).

Table 3.2 AIC, AUC and importance values of the variables selected after the univariate scale selection, conducted on different predictors at each of the seven scales considered. In bold the predictors selected after collinearity test (r≥0.7) for GLM, variable selection with contribution threshold=1, correlation threshold=0.7 for MaxEnt, and variable selection use random forest (VSURF) for Random Forest method.

Category	**Variables**	**Class**	**MaxEnt**		**Random Forest**		**Generalized Linear Model**	
			Best scale	AUC	Best scale	Importance	Best scale	AIC
Linear and Point features	DENS_riv		4800	0.598	4800	1	**600**	**1627.497**
	DENS_rd		**14400**	**0.62**	**9600**	**1**	**9600**	**1639.476**
	DENS_set		14400	0.549	9600 14400	1 0.974	**4800**	**1664.729**
Topographic	CTI		**9600**	**0.875**	300 2400	1 0.916	**9600**	**1351.223**
	SLP		**1200**	**0.834**	**9600** **600**	**1** **0.908**	**4800**	**1425.887**
	ROUGH		**1200**	**0.792**	**600** **4800**	**1** **0.945**	**14400**	**1646.949**
	DISS		**600**	**0.796**	9600	1	**300**	**1467.022**
	ELEV		**14400**	**0.825**	**300**	**1**	**300**	**1634.197**
Climatic	TEMP		**1200**	**0.842**	600	1	300	1655.884
Landcover (Landscape level)	CWED		9600	0.745	9600 **2400**	1 **0.945**	14400	1659.723
	AI		14400	0.737	2400 9600	1 0.961	**14400**	**1552.6**
	PD		9600	0.748	9600	1	14400	1638.035
Landcover (Class level)	PLAND	Br	4800	0.754	4800 2400	1 0.902	**300**	**1657.891**
	AREA_AM	Br	**4800**	**0.736**	9600 2400 1200	1 0.970 0.932	14400	1552.561
	GYR_AM	Br	14400	0.72	1200 9600 600	1 0.998 0.922	4800	1613.046
	PLAND	Sn	**14400**	**0.701**	4800	1	**2400**	**1558.536**
	AREA_AM	Sn	**2400**	**0.612**	4800 **9600**	1 **0.925**	4800	1563.722
	GYR_AM	Sn	14400	0.746	4800	1	4800	1561.926
	PLAND	Gr	9600	0.76	9600	1	14400	1564.207
	AREA_AM	Gr	**14400**	**0.702**	2400	1	14400	1669.444
	GYR_AM	Gr	9600	0.703	2400 9600	1 1	**600**	**1658.736**
	PLAND	Shr	14400	0.588	14400	1	**4800**	**1630.973**
	AREA_AM	Shr	**14400**	**0.577**	9600	1	9600	1614.961
	GYR_AM	Shr	14400	0.583	9600	1	**9600**	**1603.138**
	PLAND	Fe	4800	0.545	300	1	14400	1595.757
	AREA_AM	Fe	4800	0.543	300	1	9600	1616.927
	GYR_AM	Fe	4800	0.545	14400	1	**9600**	**1595.491**

Table 3.3 Percent contribution and permutation importance of 12 selected variables for predicting snow leopard distribution using MaxEnt algorithm with data from Yanchiwan National Nature Reserve, Gansu Province, China.

Variable	Percent contribution	Permutation importance
cti9600	51.4	52.6
diss600	16.8	0.7
slp1200	9.7	1.8
area_am_sn_2400	5.6	4.5
area_am_br_4800	4.7	5.4
rough1200	3.2	1
fme14400	3.1	9.9
rd14400	2.4	1.1
meant1200	1.9	21
area_am_gr_14400	0.7	1.6
pland_sn_14400	0.5	0.3
gyrate_am_shr_14400	0.1	0.1

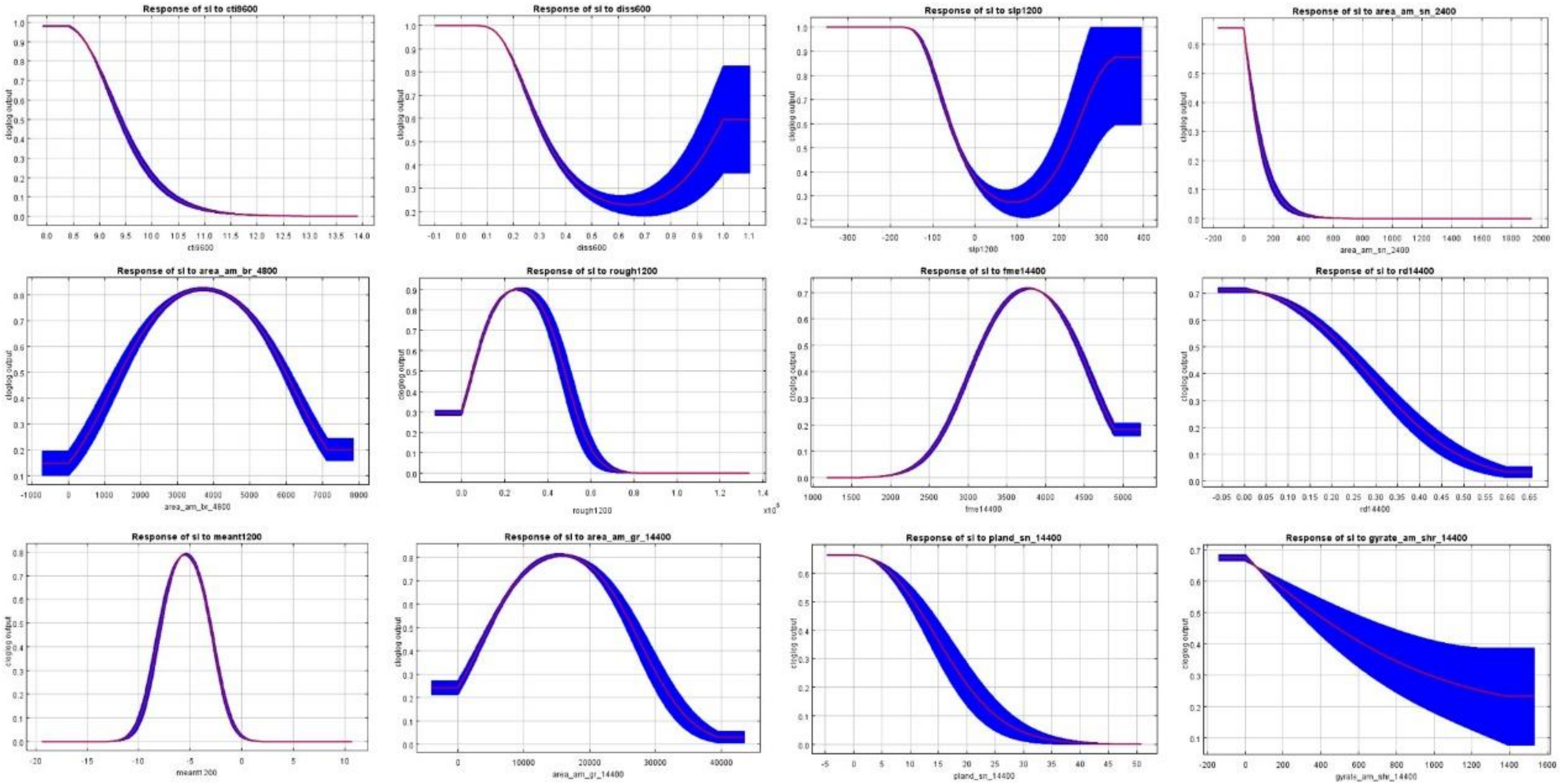

Figure 3.2 Response curves for each of the covariates included in the MaxEnt model in Yanchiwan National Nature Reserve, ordered along the percent contribution.

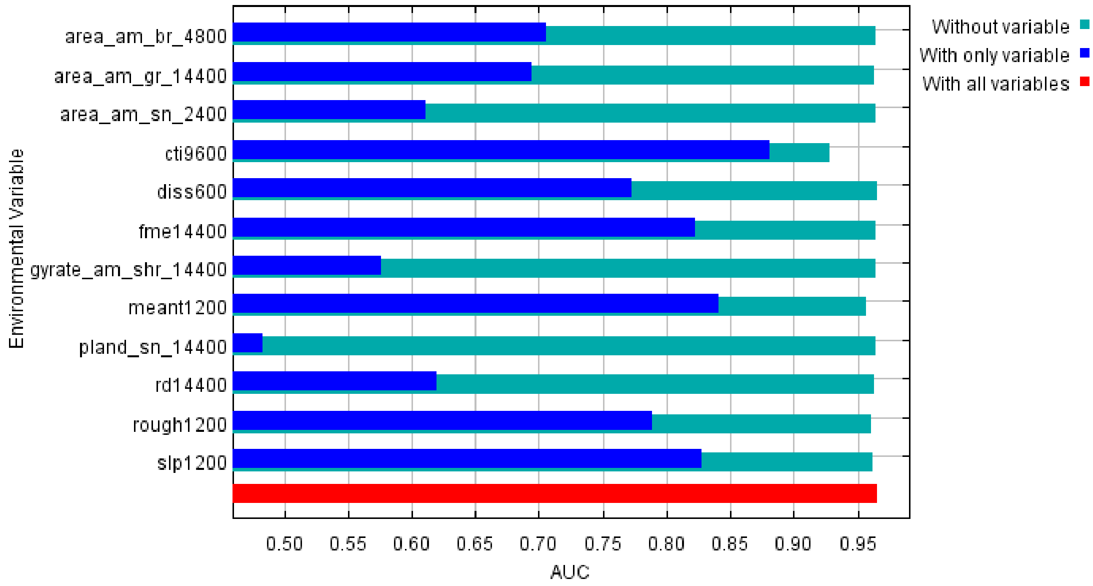

Figure 3.3 Results of variables Jackknife of AUC of the MaxEnt model.

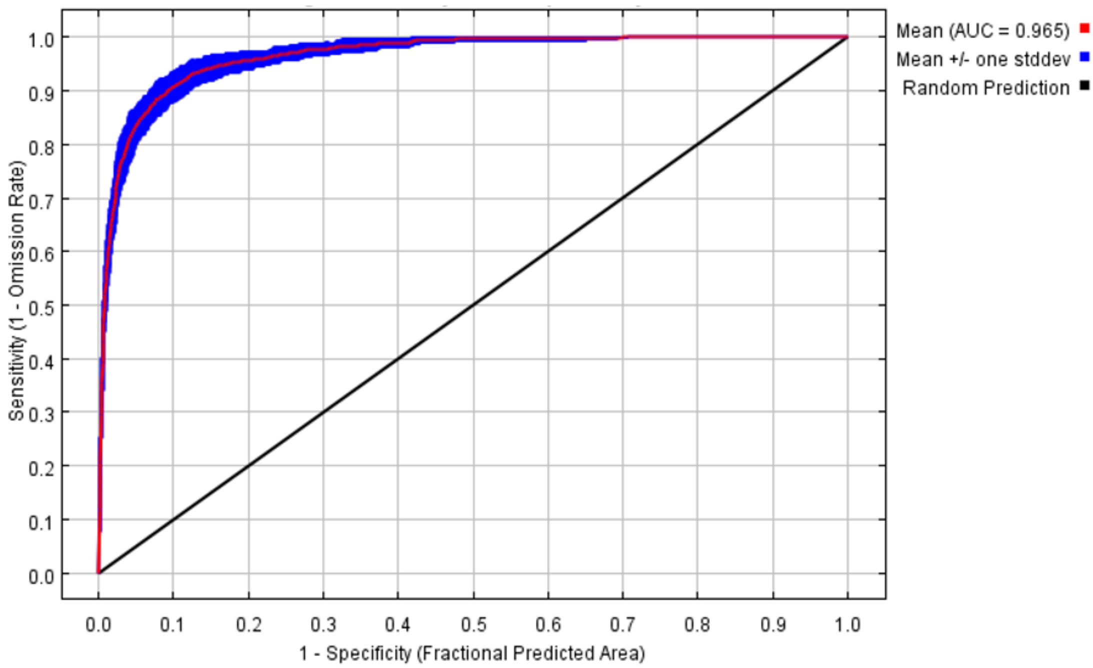

Figure 3.4 The receiver operating characteristic (ROC) curve for the snow leopard presence data from Yanchiwan National Nature, Gansu, China.

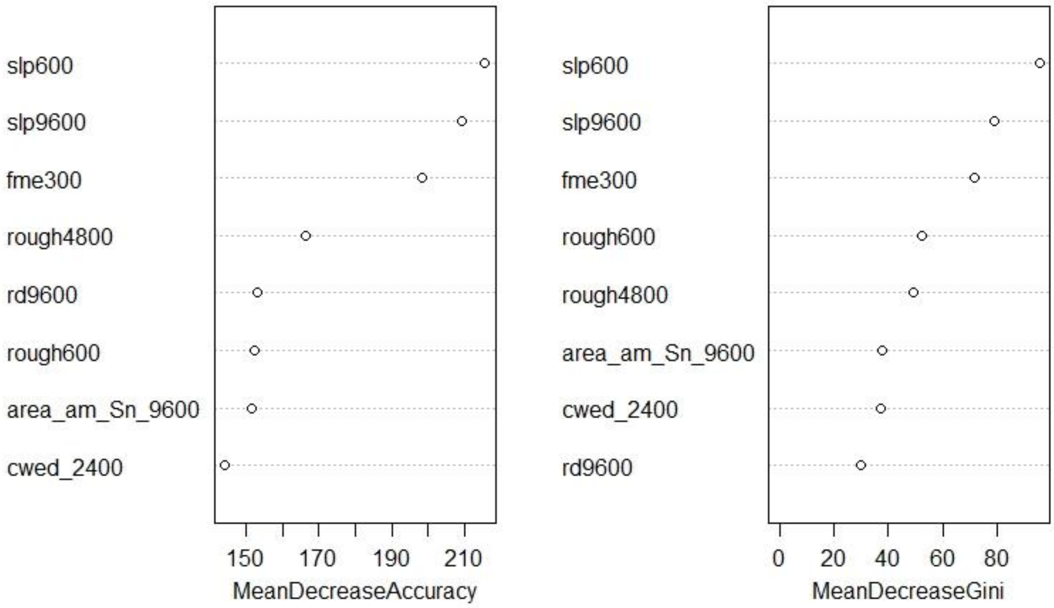

Figure 3.5 Plot of "Mean Decreased Accuracy" and "Mean Decreased Gini" based importance of the predictors for random forest algorithm to predict snow leopard distribution in Yanchiwan National Nature Reserve, Gansu Province, China.

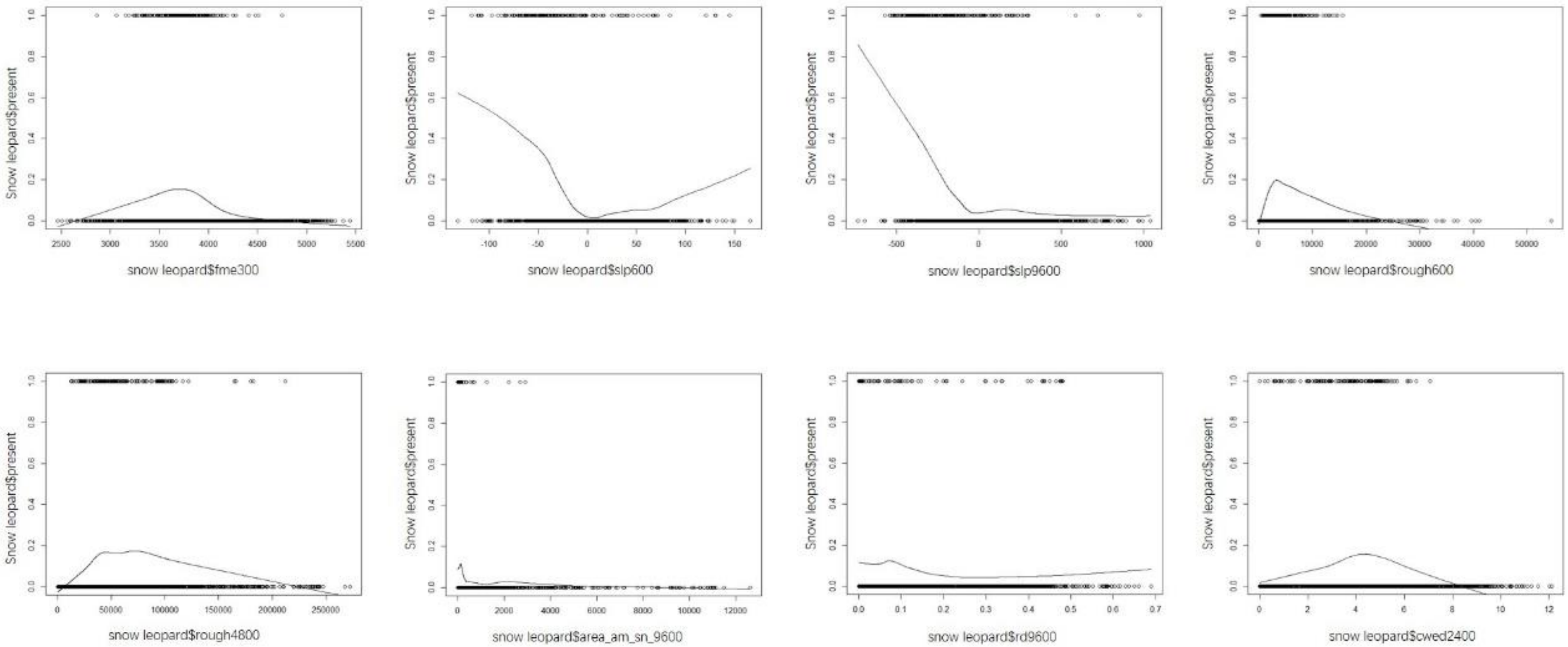

Figure 3.6 Lowess smooth fit curve of the eight selected predictors for random forest algorithm to predict snow leopard distribution in Yanchiwan National Nature Reserve, Gansu Province, China.

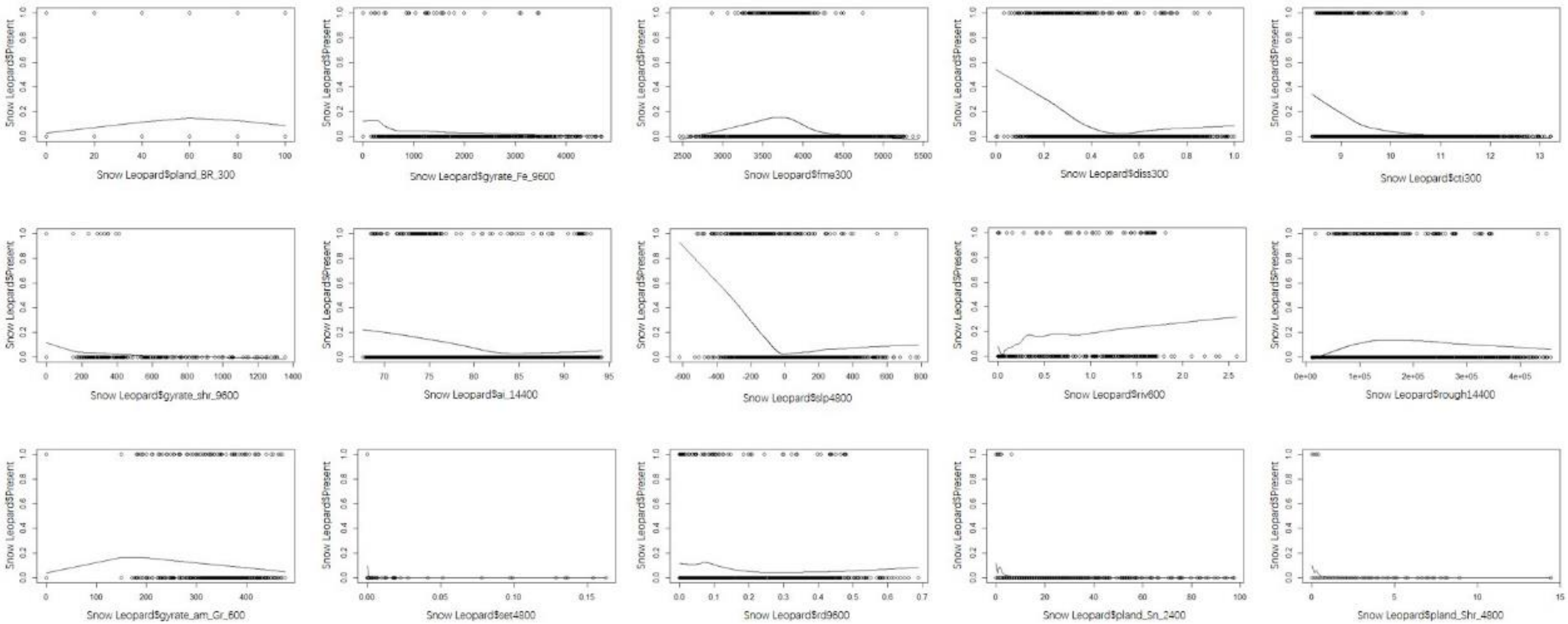

Figure 3.7 Lowess smooth fit curve of the 15 selected predictors for generalized linear model algorithm to predict snow leopard distribution in Yanchiwan National Nature Reserve, Gansu Province, China.

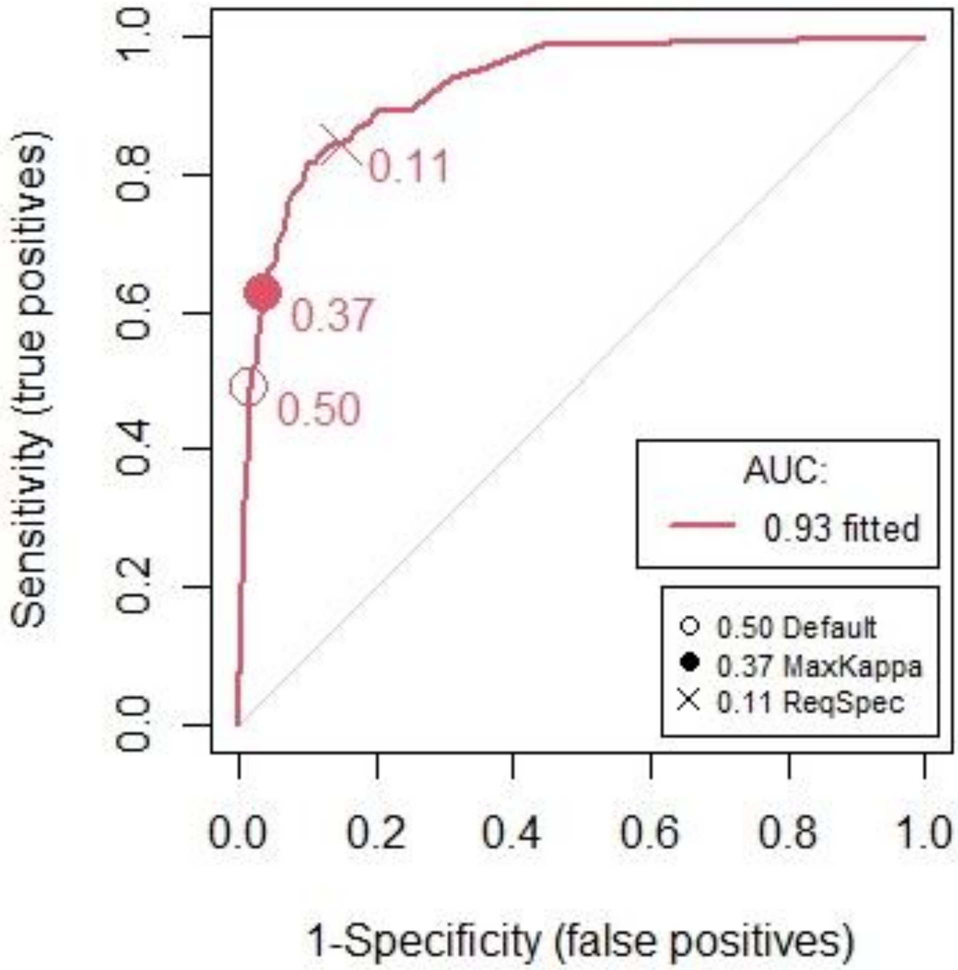

Figure 3.8 The ROC plot produced from Generalized Linear Model with snow leopard presence data from Yanchiwan National Nature Reserve, Gansu Province, China.

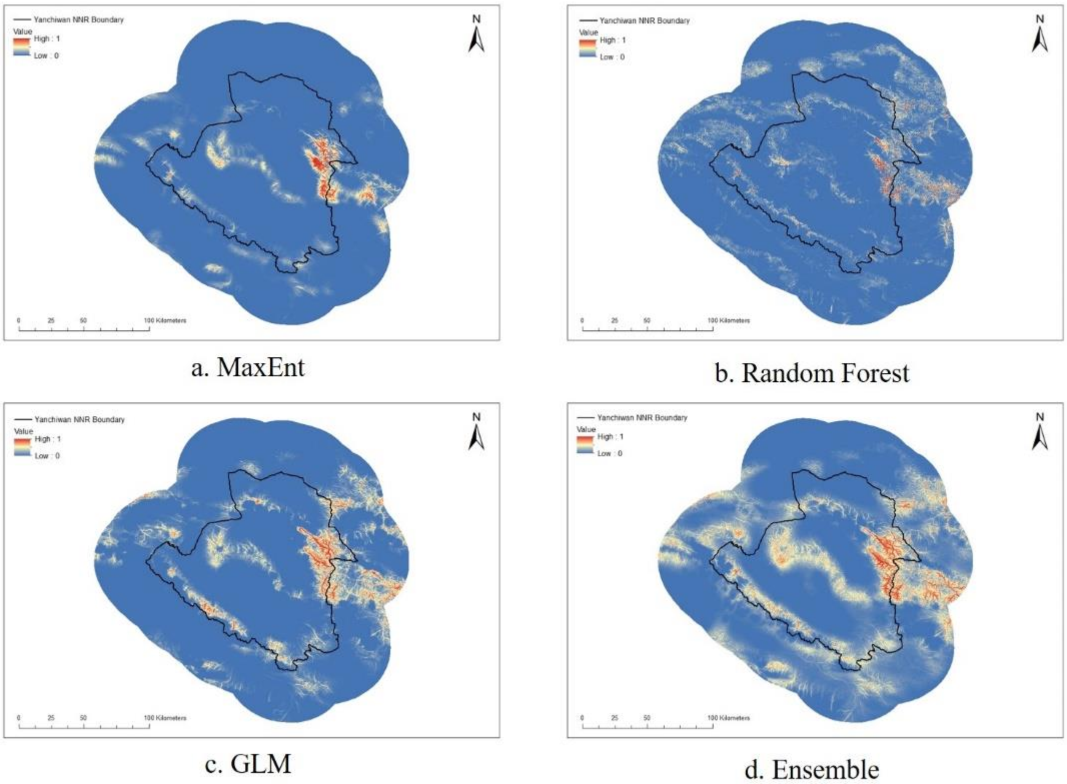

Figure 3.9 Habitat suitability maps for Yanchiwan National Nature Reserve produced by MaxEnt (a); Random Forest (b); Generalized Linear Model (c), and ensemble map (d) based on the above three maps.

3.4 Discussion

Snow leopards were detected, by either camera trap images or genetically confirmed scats, across the three main mountain ranges of Yanchiwan National Nature Reserve: Shulenanshan, Yemananshan, and Danghenanshan. Encounter rates were highest in the Shulenanshan range. These three areas represent somewhat different management approaches in YNNR, with the Shulenanshan range being designated as a 'core area' with no human activity. The other two ranges have limited grazing and mining extraction permitted, although the reserve management indicated that these limits might be exceeded (YNNR Management Authority, pers. comm.). Even in the core area of Shulenanshan, evidence of human activity was found (livestock and people traveling through), however the level of human activity was considerably less than that found in the other two sites.

To assess the influence of landscape and environmental features on snow leopard occurrence, the three methods used (Maximum Entropy, Random Forests and Generalized Linear Models) employ algorithms that are most commonly used in Species Distribution Models. Here, the goal was not to explore differences between modeling techniques too deeply, but rather to develop a suitably robust set of outputs focusing on the ecological character of distribution of snow leopards, which can be developed more widely.

In all models, topographic features were important at a range of scales. Simple elevation featured at the largest scale (14,400 m) in the MaxEnt model, but at the smallest scale (300 m) in both random forest models and GLMs. Other topographic features, such as dissection were also important determinants of snow leopard presence at small scales in both MaxEnt and GLMs (600 m and 300 m respectively). The degree to which snow leopard presence points were autocorrelated might be an important consideration in these models, particularly given these small-scale influences. Nevertheless, these mountain ranges are highly topographically variable, as suggested by the dissection measure. While an attempt to account for spatial autocorrelation might appear useful, the parameterization of influential factors at different scales is an attempt to explore these spatial relationships more fully, without losing potentially important biological information about the species.

Landcover parameters tended to be influential at either intermediate (~4,800 m) or higher (14,400 m) spatial scales, possibly reflecting the residual influence of areas suitable for snow leopard not specifically determined by topography. As highly adapted ambush predators, snow leopards tend to rely on rocky outcrops and bluffs, with which they are camouflaged, particularly near water courses or other areas that prey species congregate. Scrub and open habitats are often less important for snow leopard occurrence, but these may form vital routes and corridors through which animals move between key areas of their home ranges (see also Chapter 4). The Radius of Gyration measure for grasslands did significantly influence snow leopard presence in GLMs, at a relatively small scale of 600m, with an increased probability of snow leopard presence at lower metric values. The radius of gyration is effectively a measure of patch extent (McGarigal et al., 2012), reflecting both patch size and shape. The lower scale influence might again reflect the complex landscape in these mountains and the availability of prey species foraging locations in rocky areas that might facilitate snow leopard predation. Land cover metric tended to be more important in GLMs, compared to either MaxEnt or RFs. Further understanding these differences will be an important step towards more effective conservation actions for snow leopard, but here it is important to capture these differences in ensemble models to ensure maximum information is being contained.

Past studies have emphasized the importance of the topographic factors in snow leopard distribution (Jackson and Hunter, 1996; McCarthy and Chapron, 2003; Kalashnikova et al., 2019; Watts et al., 2019). In this study, variables of road density (DENS_rd), slope position (slp), roughness (rough) and elevation (fme) appeared in the final selected variables of all three species distribution models (Table 3.2), showed the importance of the four variables. The relationship between snow leopard presence and variables could be seen from Figure 3.2, 3.6 and 3.7. Snow leopard presence declined with the increase of road density, indicating the avoidance to roads. For the slope position, valleys (with negative slope position value) were more used than mountains (positive slope position value), flat areas (slp=0) had the off-peak in the curves. The curves of the response to roughness could be described as a unimodal shape, indicating snow leopards prefer terrains with certain level of elevation variability and surface complexity. Similarly, curves of elevation also shaped as single-peak, with the elevation most suitable for snow leopard as 3,700 meters in this case.

Impact of fenced area on snow leopard distribution was only apparent in GLMs method, again taking the radius of gyration for fenced areas, but at an intermediate scale of 9,600 m (gyrate_am_Fe_9600). Whilst occurring in the final predictive variable list, the parameter estimate value of relatively low ($\beta = 6.315e^{-04}$). This suggests that although significant in GLMs, the fenced area had relatively limited impact on snow leopard occurrence and distribution in Yanchiwan NNR. However, similar with other large carnivores, fences could be a potential big impact factor on the movement and dispersal of snow leopards, which will be explored in the following chapter.

Based on the variable scale influence of key environmental factors, this chapter presented significant meaning for conservation and management design and practice in YNNR. Key areas for snow leopard distribution have been identified, along with scale-dependent features that influence them, which establishes a scientific basis for the policy makers. However, to have better effect on the conservation and management planning in Yanchiwan NNR, more information is essential, such as snow leopard activity and use of habitat patches, and connectivity and linkages between areas of suitable habitat, which will be further discussed in the next chapter.

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Appendix 3.2 List of variables adopted in this study
Quoted and adapted from (Atzeni et al., 2020)

1. List of topographical variables

Dissection: Describes dissection in an elevation surface. It represents a modified version of de Martonne's parameter of terrain massiveness – coefficient of dissection (Pike and Wilson, 1971; Evans, 1972):

$DISS = \frac{\bar{Z} - Z_{min}}{Z_{max} - Z_{min}}$; where Z stands for elevation

Slope Position: Also known as Topographic Position Index (TPI) (Weiss, 2001; De Reu et al., 2013), it measures the difference in elevation between the central cell of a neighborhood of radius *R* and the mean of elevation in the same neighborhood.

$SLP = Z_0 - \bar{Z}$; where Z stands for elevation

Quoted from De Reu et al., (2013), p. 42
"*Positive TPI values indicate that the central point is located higher than its average surroundings, while negative values indicate a position lower than the average. The range of TPI depends not only on elevation differences but also on R (e.g. Grohmann and Riccomini, 2009). Large R-values mainly reveal major landscape units, while smaller values highlight smaller features, such as minor valleys and ridges*".

Compound Topographic Index: It is referred to as a steady state wetness index to quantify catenary landscape position.

$CTI = \ln(A_s / \tan\beta)$;

where A_s expresses the catchment area (in m^2) per unit width orthogonal to the flow direction, and *β* is the slope in radians (Gessler et al., 1995). CTI measures the degree to which surface flow across the landscape is funnelled through each pixel (Gessler et al., 1995; Mukherjee et al., 2012). It indicates the accumulated water flow at any point in a catchment, with higher values reached in valley bottoms, where soil has more potential to be saturated (Mukherjee et al., 2012).

Roughness: The Topographic Ruggedness Index (TRI), developed by Riley et al. (1999), expresses the amount of difference in elevation between adjacent cells in a given neighborhood. After calculating all the differences in a neighborhood, these are squared to make them positive, and averaged. A square root is extracted from this value, expressing the average elevation change between any point in that neighborhood and the surroundings cells within the same neighborhood (Evans et al., 2014).

2. List of land-cover derived metrics (McGarigal et al., 2012)

Class-level metrics

Percentage of Landscape (PLAND): A measure of relative landscape composition, useful to compare landscapes of different size. PLAND equals the percentage of the landscape comprised of the corresponding patch type, and ranges from 0 to 100. PLAND equals 100 when the landscape is composed only of a single patch; conversely, it approaches 0 as a patch type becomes increasingly rarer.

Area average weighted mean (AREA_AM): A landscape-centric configuration metric. It expresses the average condition that the focal species would experience if dropped at random on the landscape. It describes the area-weighted mean patch size of patches of the corresponding class, where the proportional area of each patch is based on the total class area. At the class level, it equals the sum of all proportional areas of the class. It is expressed in hectares, without limits.

Radius of Gyration (Area weighted mean) (GYR_AM): A configuration metrics expressed in meters without limits. Also known as Correlation Length, it describes a measure of landscape continuity. In other words, it represents the average distance a focal species can move in any direction from a random starting point without leaving the initial patch. It increases as the shape of the patch becomes more elongated. At the class level, this metric is averaged across all patches of the corresponding type.

Landscape-level metrics

Patch Density (PD): It expresses the number of patches present in the landscape per 100 hectares. It is calculated dividing the number of patches by the total area of the landscape in m^2, multiplied by 10000•100 to convert to 100 hectares. It facilitates the comparison among landscapes of different size.

Aggregation Index (AI): A landscape composition metric expressing degree of aggregation of patches across the landscape, based on the number of like adjacencies of the corresponding class and proportional to the proportion of the landscape comprised of that class. AI equals 0 when all patches are disaggregated, and equals 100 when the landscape is composed by a single patch. At landscape level, each class is weighted by its proportional area and scaled to account for all the possible like adjacencies.

Constrast-weighted edge index (CWED): This metric, expressed in meters per hectare, standardizes edge to a per-unit area basis, allowing the metric to be used to compare different landscape. It is calculated by summing all the meters of edge multiplied by their contrast weights, further multiplied by 10000 to convert to hectares. CWED is 0 when the landscape consists of a single patch type (no edge present).

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Chapter 4: Snow Leopard Activity, Habitat Patches and Linkages in Yanchiwan National Nature Reserve

4.1 Introduction

Habitat fragmentation has become a pervasive feature of modern landscapes, and has been a factor that caused population decline in many species (Ewers and Didham, 2006). Habitat fragmentation across landscapes risks isolating subpopulations of species, reducing breeding opportunities across metapopulations and potentially increasing rates of inbreeding depression (Aguilar et al., 2006; Fischer and Lindenmayer, 2007; Cote et al., 2017). Smaller, isolated populations are also more susceptible to stochastic and demographic perturbations that can extirpate species from habitat fragments, with little probability of recovery (Bender et al., 1998; Fahrig, 2003).

Human-induced habitat fragmentation has been considered as one of the main threats to biodiversity, which can reduce the fragments ecological suitability and increase the isolation of patches (Fahrig, 2003). Substantial land-use changes due to human activities, particularly associated with increased agricultural and extraction activities (e.g., arable and livestock farming, and unsustainable forestry or plant collection, respectively) have driven large-scale fragmentation of natural ecosystems (Skole and Tucker, 1993; Haddad et al., 2015). Large bodied and less mobile species have suffered both due to the loss of habitats and reduced access to resources. Species which require extensive areas of land, including large mammalian carnivores, are more susceptible to human-induced habitat fragmentation in terms of the negative impact on gene flow, demographic exchange and local extinction risk of the species (e.g. Bender et al., 1998; Mateo-Sánchez et al., 2014; Cushman et al., 2016).

Recent conservation efforts have attempted to reconnect fragmented ecosystems, for example developing landscape corridors. The establishment and protection of movement corridors to maintain landscape and patch connectivity has been a main proposed approach to mitigate the negative impact of the human-induced habitat fragmentation (Cushman et al., 2009; Di Minin et al., 2013).

Obtaining reliable predictors of species' population landscape connectivity is often challenging. Firstly, a good understanding of the dispersal ability of the species is needed, for example from the remote tracking of dispersing individuals (e.g., Elliot et al., 2014; Spear et al., 2010), or from data on population genetic structures (Braunisch et al., 2010; Castillo et al., 2014; Cushman et al., 2006). Based on an understanding of the landscape and other determinants of species' movement, an appropriate landscape resistance model can be developed (Spear et al., 2010), which can properly reflect the focal species' biological responses.

Sufficiently detailed quantitative data on both determinants of species movements and adequate mapping of relative landscape features are often lacking. Therefore, expert opinions (e.g., Puyravaud et al., 2017; Zeller et al., 2012) or models on habitat suitability (e.g., Ahmadi et al., 2017; Mateo-Sánchez et al., 2016) have been used as surrogating measures to produce landscape resistance surfaces.

Species associations with landscape and habitat features have been inferred from species presence data, either from dedicated surveys or ad hoc observations using a variety of statistical e.g. (general and generalized linear models) and non-statistical techniques, including MaxEnt (Phillips et al., 2006), and decision trees and random Forests. Outputs derived from these models, linking species presence to measurable habitat variables, can be effectively used to produce source points from which resistance to movement can be estimated and connectivity models can determine critical areas for species occurrence and dispersal (e.g., Cushman et al., 2016, 2014; Khosravi et al., 2018).

Several methods have been used to predict connectivity across the resistance surface, such as least-cost paths modelling (Adriaensen et al., 2003), factorial least-cost path density (Cushman et al., 2009), resistant kernels modelling (Compton et al., 2007), randomized shortest path approach (Saerens et al., 2009; Panzacchi et al., 2016). The least-cost paths is a traditional connectivity modelling approach which mapping the least cost paths between identified patches (Beier et al., 2011; Brodie et al., 2015; Kabir et al., 2017). However, in some cases, the least-cost paths approach is simplistic because we cannot expect the species individuals actually follow those predicted least cost paths (Fahrig, 2007; Kabir et al., 2017). As a contrast, the later developed cumulative resistant kernel approach and factorial least-cost path analysis are particularly suitable to identify core habitat patches and corridors of the species across a landscape (Cushman et al., 2013; Cushman et al., 2014; Cushman et al., 2016; Khosravi et al., 2018). Different from the least-cost paths method which only use a few edge points from identified patches, cumulative resistant kernel approach and factorial least-cost path analysis can not only providing spatial-explicit predictions of movement rates for every single grid across the landscape resistance surface, and provides useful information to complement results of resistant kernel modelling, but also producing the corridors with the most importance and usage between source points of the landscape (e.g., Cushman et al., 2014, 2016; Riordan et al., 2016; Khosravi et al., 2018).

The contribution of core patches to the connectivity across landscape can be quantified by employing the network-based modelling (Baranyi et al., 2011; Bodin and Saura, 2010; Saura et al., 2011). Probability of Connectivity (PC) (Saura and Pascual-Hortal, 2007) and Integral Index of Connectivity (IIC) (Pascual-Hortal and Saura, 2006) are two representative indices which have been used to evaluate the contribution of every single core patch to the landscape connectivity in different aspects (Baranyi et al., 2011; Bodin & Saura, 2010; Saura et al., 2011; Saura & Rubio, 2010).

Considering high sensitivities of mammalian carnivores to habitat fragmentation (Crooks, 2002), the identification of core patches and important potential corridors is momentous for the long-term survival (Zeller et al., 2012), and further the better understanding from it is the basic of conservation plans and actions (e.g., Cushman et al., 2014, 2016; Hand et al., 2014). The studies (see chapter 2 and 3) suggest Yanchiwan National Nature Reserve, as one of the top ten largest national nature reserves in China, could be an important snow leopard habitat. Having better understanding on core habitat patches and important corridors across the landscape, will be crucial for making conservation planning and giving management suggestions on snow leopard in YNNR.

The primary goals of this chapter are to: (1) to identify core habitat patches for snow leopard in Yanchiwan National Nature Reserve (YNNR); (2) to identify corridor networks among core patches of snow leopards; (3) to evaluate the relative importance of core patches and corridors to landscape connectivity for snow leopards in YNNR; and (4) to give management suggestions based on the identified core patches and corridor networks, combined with information of grazing, fence and road network in YNNR.

4.2 Materials and Methods

4.2.1. Study area

This work was carried out in Yanchiwan National Nature Reserve (YNNR, Figure 3.1), details of which are provided in Chapter 3.

4.2.2. Snow Leopard Surveys

Field work was conducted from 2014 to 2017 to survey snow leopards using remote camera trapping, described in Chapter 2 and walking / horseback transects in YNNR, details of which are given in Chapter 3. Snow leopard and other predator scats were collected in the field and subsequently analyzed for genetic characteristics and species confirmation/identification using laboratory procedures described in Bai et al. (2018). For the analyses here, geographic locations corresponding to definite photographic or genetically identified snow leopards were used as presence points.

4.2.3. Data Analysis

Habitat predictors of snow leopard distribution used to analyze potential landscape resistance to movement were taken from models generated in Chapter 3. A geographical information system (GIS) approach was used to create resistance layers based on modeled habitat suitability and comparative random points were created to simulate variable distributions that were compared against actual distributions from survey data.

4.2.3.1. Simulated points

Using ArcGIS (version 10), a random raster layer with pixel values between 0 and 1, was created over the extent of the buffered (14,400m) area of snow leopard occurrence from surveys. Each of the three predictive models (produced from Maximum Entropy, Random Forest and Generalised Linear Model) used for the ensemble in Chapter 3 were subtracted from the random raster and these subtracted outputs were summed to produce a cumulative random surface. A random set of 20,000 points (P_{RAND}) was created across the buffered study area extent, and the pixel values of the cumulative random surface were assigned to each point in P_{RAND}. A further subset of these points (P_{RANDS}) was selected for those occurring on pixels with positive values. Ten groups of 249 points (P_{249}) were randomly selected from P_{RANDS}, from which five sets with the singular ID were retained.

4.2.3.2. Identify the corridor network

Using a predictive ensemble model map created from three species distribution models (Maximum Entropy, Random Forest and Generalised Linear Model) in Chapter 3. In the model contributing to the ensemble model, produced from the summed outputs from each one, topographic features were consistently influential at varying spatial scales, with small-scale landcover features also affecting snow leopard distributions (Chapter 3). Here, an exponential decay (Wan et al., 2019) was used to calculate resistance estimates (*R*) across the study area:

$$R = x^{(-1*\text{Habitat Suitability})}$$

Three values of x were used for the exponential transformations: 10, 100 and 1,000, to represent variable (high, medium and low respectively), yet plausible levels of resistance over three orders of magnitude. The resulting three resistance maps were resampled to a 500 m pixel resolution and resistance values were rescaled from 1 (minimum resistance) to 10 (maximum resistance).

The programme UNICOR (Landguth et al., 2012) was used to produce resistant Kernel connectivity surfaces and Kernel density estimation on least cost paths for each of the three levels of resistance surfaces. The thresholds in resistance and least cost path should reflect the movement and dispersal arability of the focal species. The studies on snow leopard movement based on VHF and satellite telemetry found the average minimum straight-line distance between consecutive-day was 5.1 km, and the maximum daily movement distance was 27.9 km (McCarthy et al., 2005). A dispersal distance of 45-65 km from one snow leopard was also recorded, which was believed made in a single day (McCarthy et al., 2005). Previous researches provided little information about snow leopard lifetime dispersal ability. Riordan et al., (2016) predicted snow leopard population connectivity across global level, with the scenarios that the lifetime movements of individual snow leopard were 100 km, 500 km and 1,000 km. With the above information, the least cost path maps were created with respective thresholds of 250k, 500k, 750k, and 1 million cost units (pixels), which authorized the dispersal ability of 125 km, 250 km, 375 km and 500 km. Resistance Kernel connectivity surfaces were generated by setting edge distance thresholds of 12,500 m, 25,000 m, 50,000 m and 100,000 m, which were supposed large enough to cover the regular movement distance of snow leopards. The above two analysis processes were repeated for each of the five sample-subsets, and the results were averaged for each of the three level resistance surfaces to form ensemble resistance and least-cost pathway models with minimal bias.

4.2.3.3 Identify high quality habitat patches

The ensemble model produced in chapter 3 was reclassified into low, medium and high-quality habitat based on percentiles (<70th, 70th~90th, > 90th). The software FRAGSTATS (McGarigal et al., 2012) was used to assess the following three metrics: (1) percentage of the landscape (PLAND) measuring the proportion of patches occupied by each habitat quality among the total number of habitat patches; (2) correlation length (GYRATE_AM), defined as the area weighted mean patch radius of gyration, represents the mean distance an individual can move in any direction from a random starting point without leaving the initial patch, and then averaged across all patches of the landscape; and (3) largest patch index (LPI), which is the proportion of the largest patch among whole landscape. An area of 28 km^2 of core activity isopleths (30% kernel, with entire Minimum Covex Polygon home range size of 4,530 km^2) based on satellite telemetry was recorded in more open terrain in Mongolia (McCarthy et al., 2005). Considering snow leopard home range could be smaller in Yanchiwan compared with in Mongolian Gobi, habitat patches area over 50 km^2 for medium and high-quality levels were selected for the patch connectivity analysis.

4.2.3.4 Patch connectivity analysis

The program CONEFOR (version 2.6) (Saura and Torné, 2009) was used for snow leopard habitat patch connectivity analysis in Yanchiwan National Nature Reserve. The "Conefor Input" (version 1.0.218) ArcGIS extension was used to generate input files for Conefor. The analysis was restricted within specified distances of 25 km, 50 km, 100 km and 200 km respectively, which were the supposed dispersal ability of snow leopards in four different scenarios. The distance between two patches was defined as the shortest path from patch edges. In the program CONEFOR, we chose "distance" as connection type, set model precision as "high", and set "removal" for link importance. Four scenarios of connectivity distances were tested: 25km, 50km, 100km and 200km, with corresponds to probability of 0.7, 0.5, 0.3 and 0.2 respectively. The integral index of connectivity (IIC) (Pascual-Hortal and Saura, 2006) and the probability of connectivity (PC) (Saura and Pascual-Hortal, 2007) of each of the 12 high-quality patches were calculated under the four scenarios.

The integral index of connectivity (IIC) (Pascual-Hortal and Saura, 2006) was developed specifically for landscapes, it is given by:

$$IIC = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n}\frac{a_i \cdot a_j}{1+nl_{ij}}}{A_L^2}$$

where ai is the area of each habitat patch and nl_{ij} is the number of links in the shortest path between patches i and j. A_L is the total landscape area (comprising both habitat and non-habitat patches). The ICC is based on habitat availability and increases with improved connectivity and threshold dependent (dispersal distance).

The probability of connectivity index (PC) (Saura and Pascual-Hortal, 2007) is a network-based habitat availability index that quantifies functional connectivity. It is defined as the probability of two random points are reachable from each other, with the conditions that they are randomly placed in within the landscape and fall into the habitat patches (interconnected) and given a set of habitat patches (n) and the direct connections (p_{ij}) among them. PC is given by the following expression:

$$PC = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} a_i a_j p_{ij}^{*}}{A_L^2}$$

where a_i and a_j are the areas of the habitat patches i and j, and A_L is the total landscape area (including both habitat and non-habitat patches). p_{ij} is the probability of direct dispersal between patches i and j with no intermediate patch been passed through. The product probability of a path (the path here is a sequence of patches in which every patch is visited only once) is the product of all the values of p_{ij} for all the links in that path. p_{ij}^{*} is the maximum product probability of all the possible paths between patches i and j (including direct dispersal between the two patches).

4.2.3.5 Identify the least cost path between patches

The “Linkage Mapper” (version 2.0.0) toolbox for ArcGIS was used to calculate the least cost path between the identified high-quality habitat patches for snow leopard in Yanchiwan National Nature Reserve. The “Build Network and Map Linkages” tool in the toolbox was used to calculate least cost paths for the three resistance models. The “Cost-Weighted & Euclidean” approach was selected for network adjacency method, and “Cost-Weighted” for the setting of nearest neighbor measurement unit.

4.2.3.6 Identifying areas of grazing activities associated with Yanchiwan Township

Five main villages were identified in Yanchiwan Township: Village One to Village Five (official name). In the end of 2020, the total human population of these villages was 644 people from 221 households, with a total livestock population of 91,372, including 81,342 sheep and goats, and 10,030 large livestock. To understand the extent of grazing activity for the township, we invited Director of Yanchiwan Conservation Station at the time (Mr Dabuxilite) to map out the seasonal grazing areas of each village in Yanchiwan Township. The Director had worked in Yanchiwan for over 20 years and was therefore considered to be able to provide a reliable estimate of grazing from his knowledge.

To estimate grazing activity, a 4 × 4 km fishnet was constructed in GIS, covering the Yanchiwan National Nature Reserve. Director Dabuxilite was then asked to select the grid cells that coincided with the seasonal grazing areas for each village. The data from each of the four seasons from each village were merged to form a total annual grazing impact grid.

4.3 Results

4.3.1 Corridor network

Resistance surfaces were constructed from each of the exponential transformations (base 10, 100 and 1000), representing high, medium and low level of resistance. High resistance level map showed smaller and more fragmented areas of low resistance, whereas the low resistance surface showed greater connectivity (Figure 4.1).

Resistance kernel connectivity surfaces and Kernel density estimations on shortest path with multi-thresholds were calculated based on high (Figure 4.2), medium (Figure 4.3) and low (Figure 4.4) levels of resistance. At each level of resistance, patches revealed from the connectivity surface models were less fragmented and more connected with the increase of threshold from 12.5 km to 100 km, reflecting a relaxation of movement restriction though less favorable habitats.

The eastern part of the nature reserve (Shulenanshan Mountain) occupies the largest connectivity surface. Least-cost pathways were more defined in the eastern mountain areas of the nature reserve, however there was relative consistency between edge-distance thresholds and between low, medium and high resistance levels Western and middle parts of the nature reserve were relatively poorly connected however, with only weak pathways being apparent. The eastern area appeared relatively well connected at all resistance threshold scenarios. Yemananshan Mountain range, in the middle part of YNNR, was identified as potentially important, having the shortest paths at thresholds above 250,000-pixel edge distances at all three levels of resistance (fig 4.2f-h; fig 4.3f-h; fig 4.4f-h). The kernel density estimation on shortest path were relatively consistent at thresholds from 500,000 to 1 million-pixel at low, medium and high resistance levels, while that of 250,000-pixel threshold showed different patterns (fig 4.2e-h; fig 4.3e-h; fig 4.4e-h).

4.3.2 High-quality habitat patches

Low, medium and high-quality habitat patches were identified based on percentiles (<70th, 70th~90th, > 90th) (Table 4.1). Medium quality habitat defined 6,689 patches with the largest patch index = 8.35 and correlation length = 28.55 km (Table 6.1). High quality habitat defined fewer patches (4,317), with smaller largest patch index = 4.00, and correlation length = 12.09 km. There were seven medium quality and 12 high quality patches with areas above 50 km^2 (Figure 4.5, Figure 4.6). These twelve high quality patches were used for further patch connectivity and least cost path analysis.

Table 6.1 Number, largest patch index, and correlation length of low, medium and high-quality patches identified by using program FRAGSTATS.

Habitat Quality	% Suitable Habitat	Number of Patches	Largest Patch Index	Correlation Length (km)
Low	70	4,466	37.74	51.35
Medium	20	6,689	8.35	28.55
High	10	4,317	4.00	12.09

4.3.3 Patch connectivity

Site ranking by IIC and PC in each patch were approximately equivalent to ranking by area (Table. 4.2). Patch 1, with the largest area, had the greatest values for both IIC and PC at all thresholds, indicating the critical importance on connectivity. However, patch 7 had higher IIC and PC values compared with patches with similar areas, in particular, IIC values at the threshold of 25 km ranked in the top two patches. This suggests that patch 7 was also of significant importance in connectivity relative to all patches.

4.3.4 Least cost path between patches

Least cost paths between twelve high quality patches with high, medium and low level of resistance were relatively consistent (Figure 4.7). This suggests the major dispersal paths were obvious and relatively "fixed", and those paths were of great importance for snow leopards at all three scenarios with different resistance levels. Based on the distribution and comparation between above three sets of least cost paths, two key areas (A and B) were identified for patch connections that might require attention (Figure 4.8). These two areas had relatively high path densities, high overlap between three path sets. It was also reported that the paths in these areas would be subject to road development or obstruction due to fences (Dabuxilite, personal communication).

4.3.5 Grazing areas of Yanchiwan Township

Grazing in the nature reserve was reported to mainly occur in the flatter less mountainous areas between the three mountain ranges, and on the lower elevation slopes approaching the higher area that are more easily accessible (Figure 4.9). Grazing areas overlapped with the high-quality snow leopard patches within the nature reserve. Village One mainly grazed in the southern part, while Village Two's grazing land was mainly in the western region. Village Four's grazing areas corresponded with patches 1 and 7, which were the top two snow leopard patches according to their integral index of connectivity (IIC) at the 25 km threshold (Table 4.2). Key path area B (Figure 4.8) was almost entirely covered by village Three's grazing range. Village Five had the smallest grazing area, and the key path area A overlapped with the pastures of both village 5 and 2.

Table 4.2 The area, percentage of total habitat attribute that corresponds to the attribute in that patch (dA), and the connection indices of probability of connectivity (PC) and integral index of connectivity (IIC) with thresholds of 25 km, 50 km, 100 km and 200 km of twelve high quality patches in Yanchiwan National Nature Reserve.

Patch ID	Area(km^2)	dA	dIIC_25km	dPC_25km	dIIC_50km	dPC_50km	dIIC_100km	dPC_100km	dIIC_200km	dPC_200km
1	1575.480	56.041	91.741	86.737	91.006	86.619	84.661	86.056	83.718	85.883
2	313.972	11.168	19.220	19.384	17.132	19.481	16.791	19.897	16.684	20.010
3	168.099	5.979	8.783	11.964	8.346	11.958	8.715	11.927	8.932	11.917
4	135.950	4.836	7.103	11.833	6.750	11.774	7.048	11.502	7.224	11.421
5	111.237	3.957	5.649	8.526	5.378	8.507	5.590	8.418	5.911	8.391
6	92.121	3.277	3.213	4.346	3.980	4.399	4.747	4.643	4.895	4.715
7	88.160	3.136	19.238	9.344	4.625	9.311	4.803	9.128	4.685	9.064
8	78.019	2.775	4.538	4.169	3.137	4.211	3.987	4.399	4.146	4.454
9	71.118	2.530	2.004	2.482	2.256	2.532	2.863	2.773	3.779	2.846
10	65.480	2.329	0.098	2.823	3.611	2.865	3.358	3.061	3.479	3.119
11	58.652	2.086	0.078	1.955	2.267	1.998	2.995	2.204	3.117	2.267
12	53.006	1.885	2.793	3.864	2.758	3.865	2.848	3.865	2.817	3.865

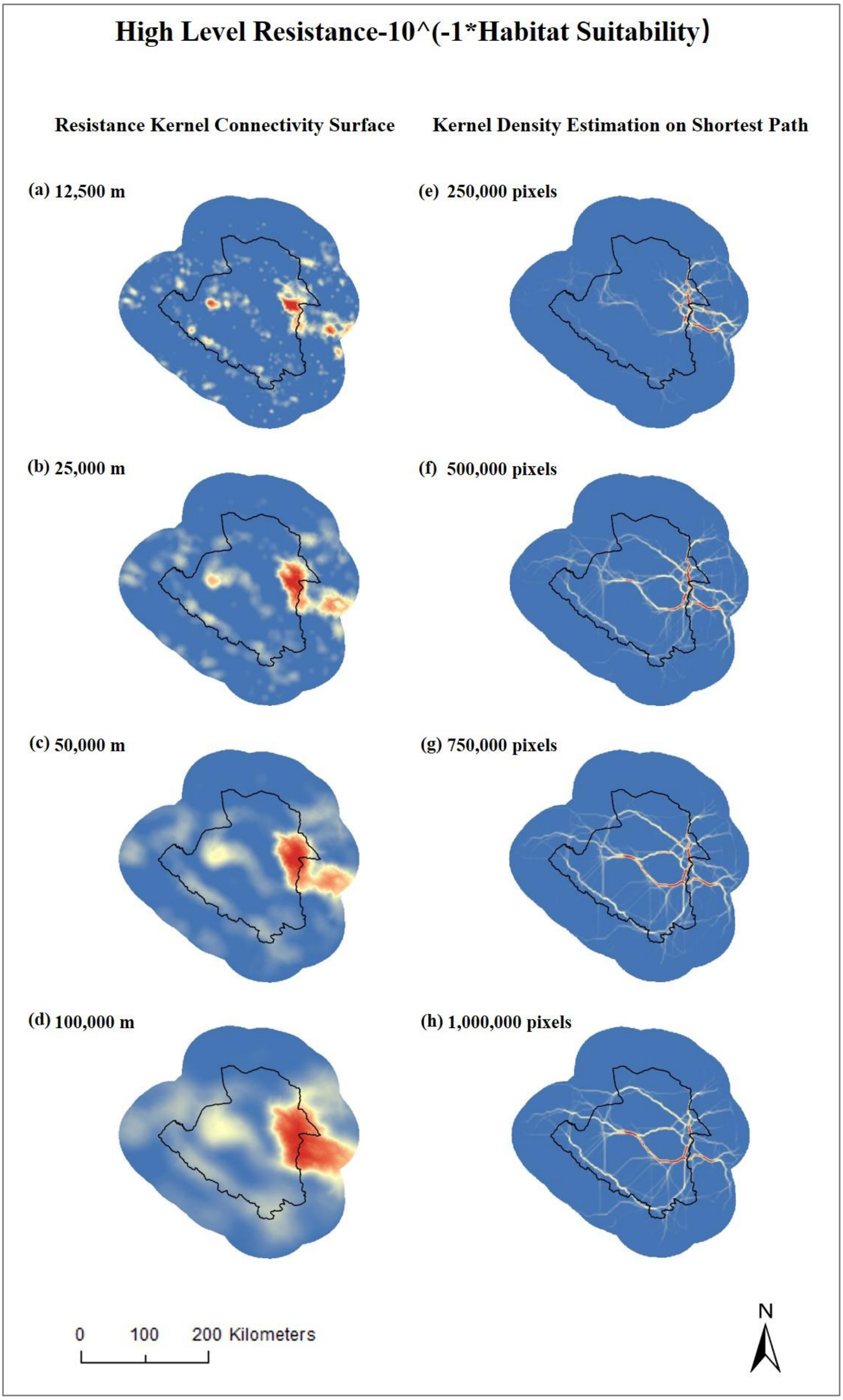

Figure 4.2 The resistance Kernel connectivity surface and Kernel density estimation on shortest path with thresholds based on high level resistance: 10(1-HIS), where HIS is the Habitat Suitability Index.

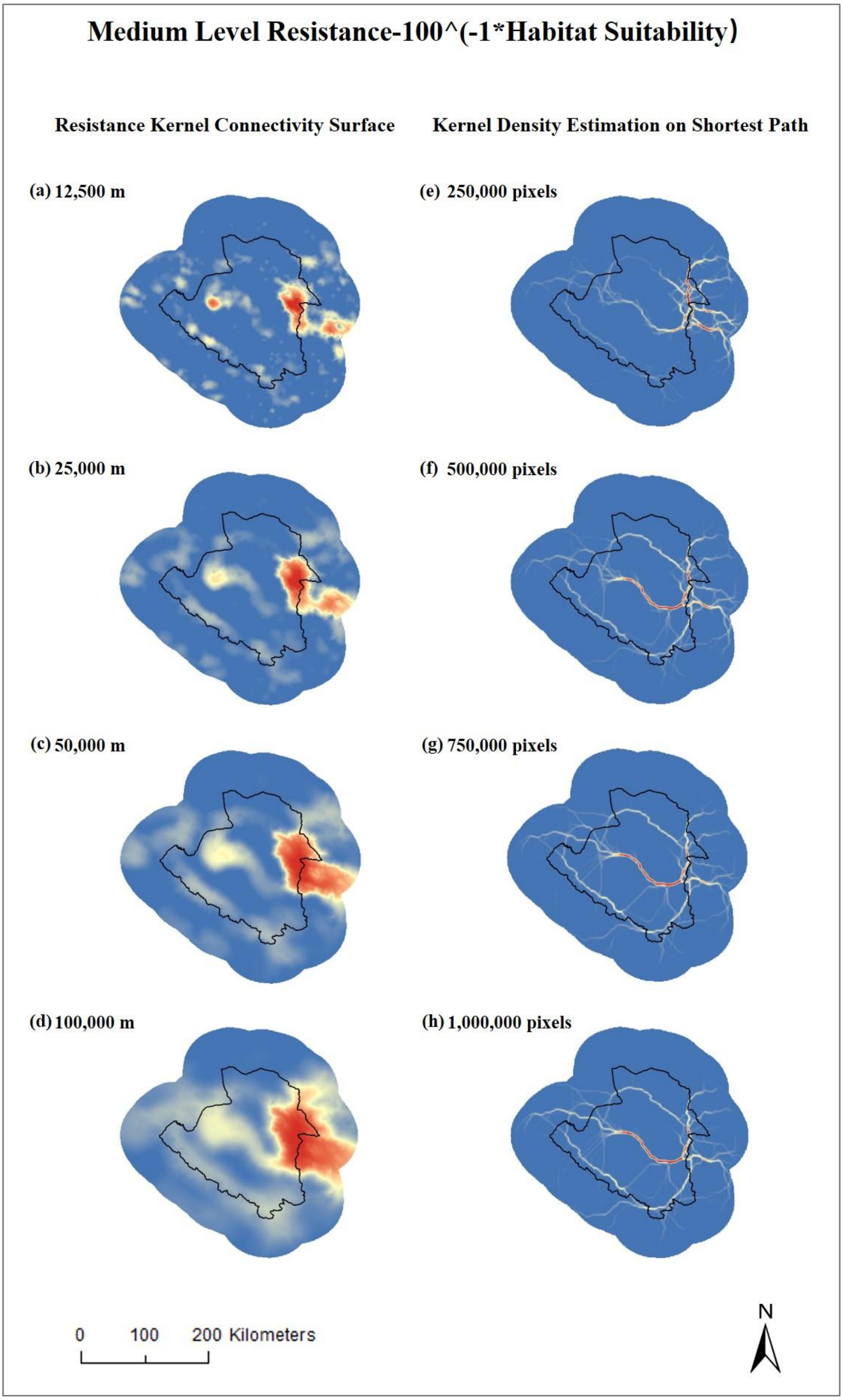

Figure 4.3 The resistance Kernel connectivity surface and Kernel density estimation on shortest path with multi thresholds based on medium level resistance: 100(1-HIS), where HIS is the Habitat Suitability Index.

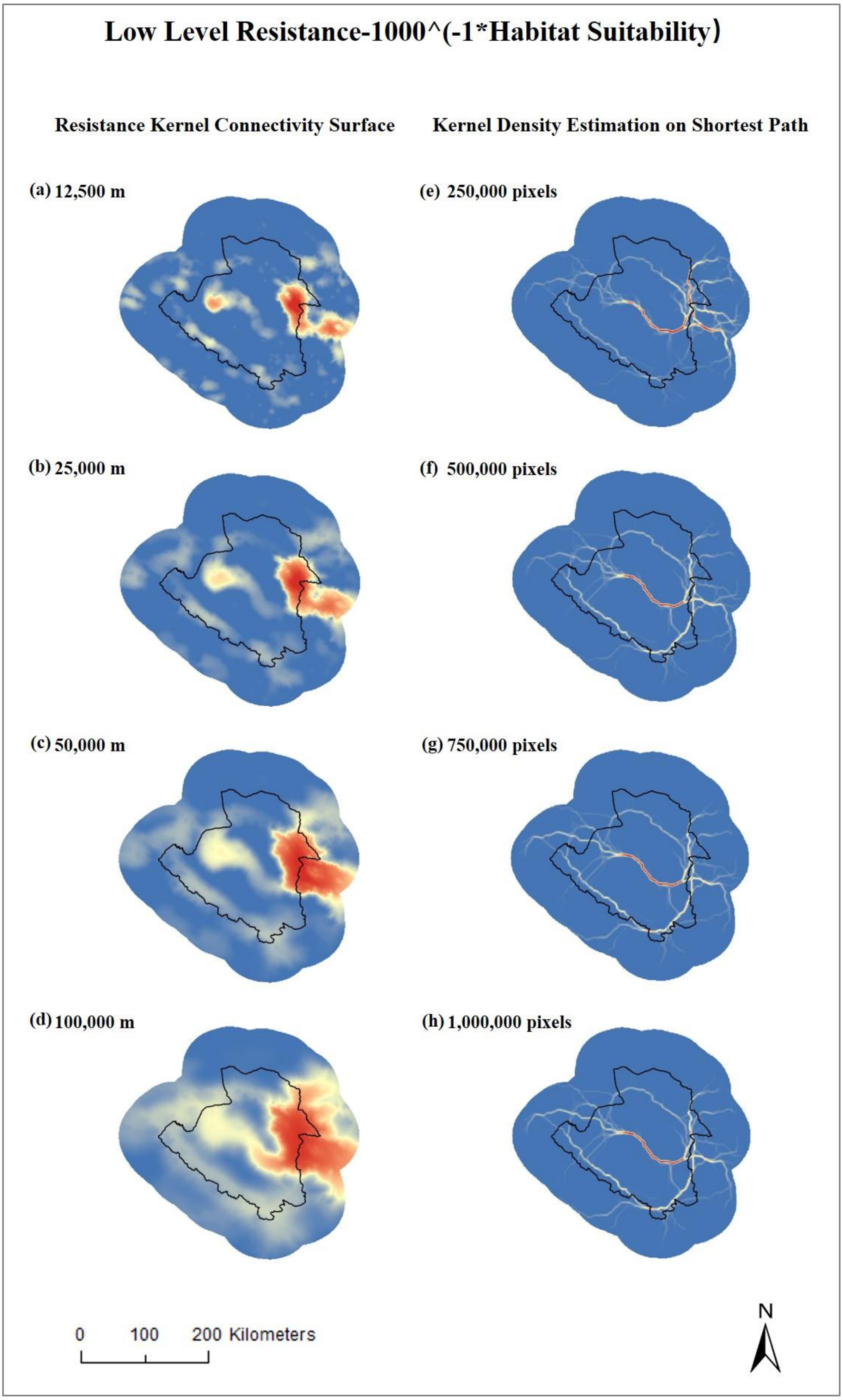

Figure 4.4 The resistance Kernel connectivity surface and Kernel density estimation on shortest path with multi thresholds based on low level resistance: 1,000(1-HIS), where HIS is the Habitat Suitability Index.

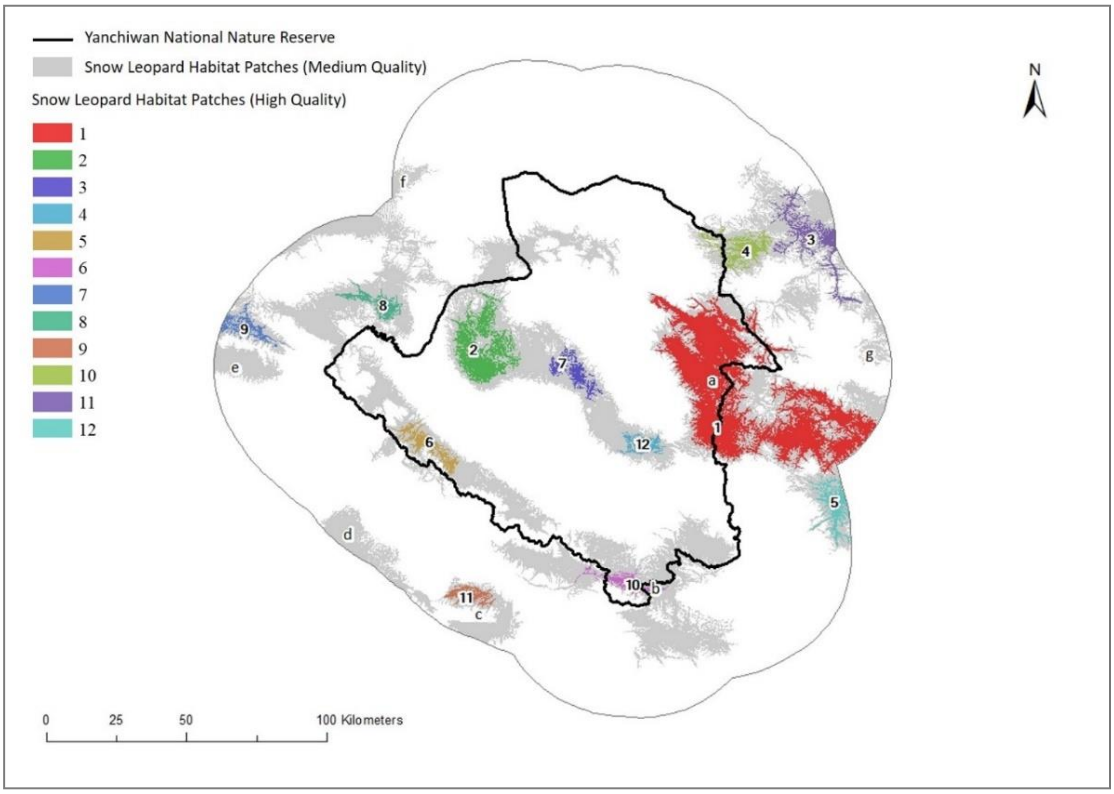

Figure 4.5 Overlap between seven medium quality (from a to g) and 12 high quality (from 1 to 12) snow leopard habitat patches of area over 50 km².

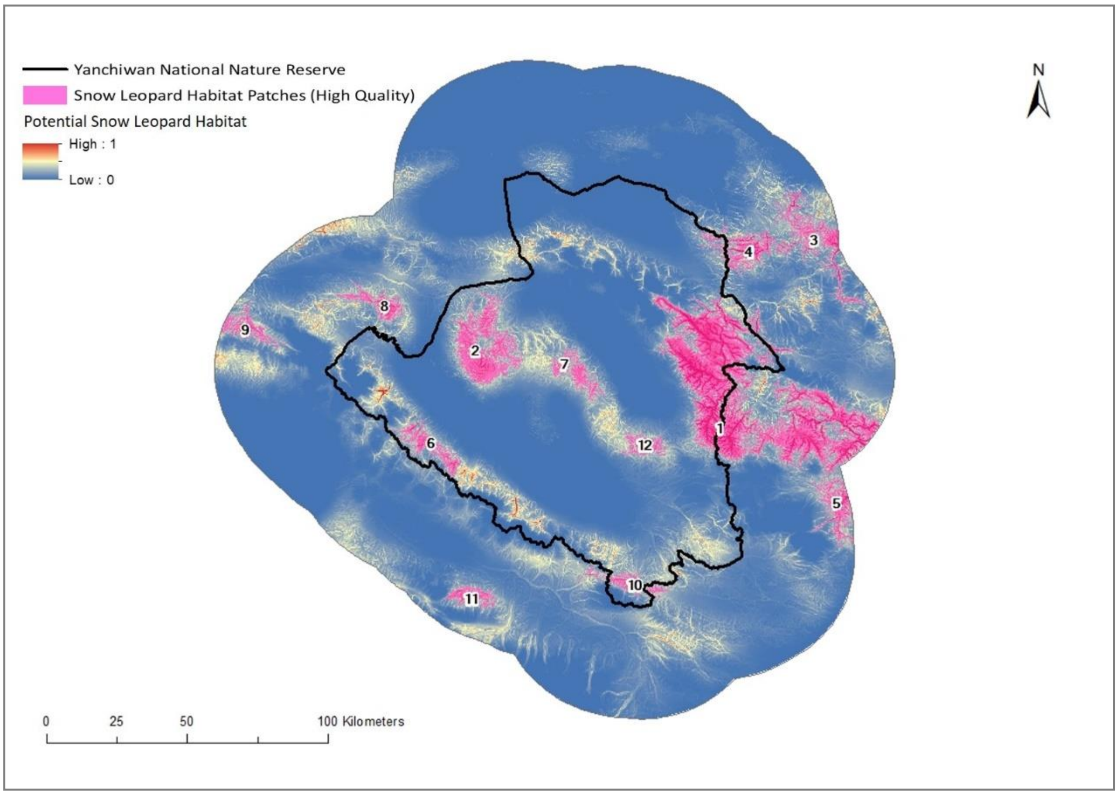

Figure 4.6 Overlap between high quality snow leopard habitat patches and potential habitat in Yanchiwan NNR.

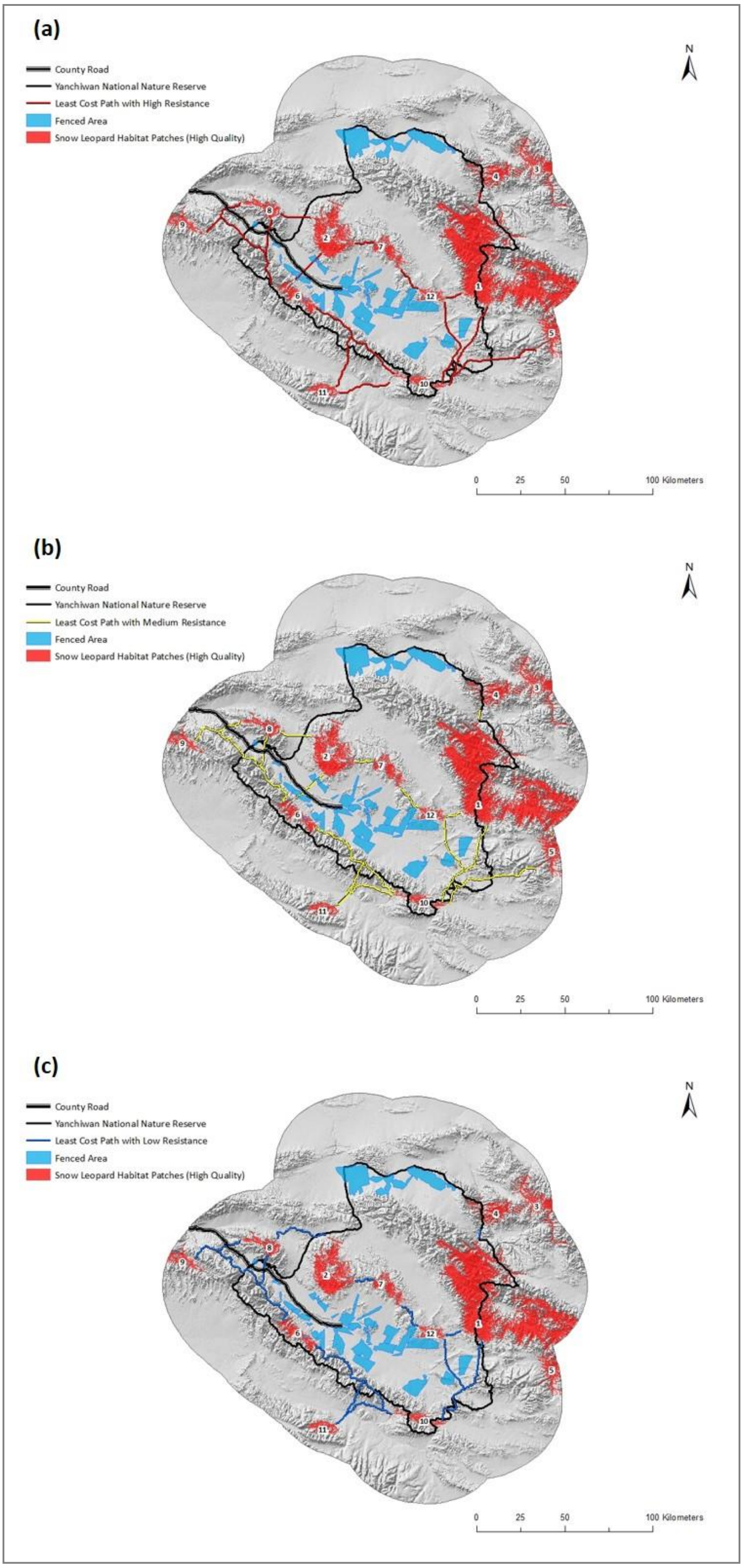

Figure 4.7 Least cost paths between twelve high quality patches (labelled 1 – 12) with (a) high, (b) medium and (c) low resistance levels in Yanchiwan National Nature Reserve.

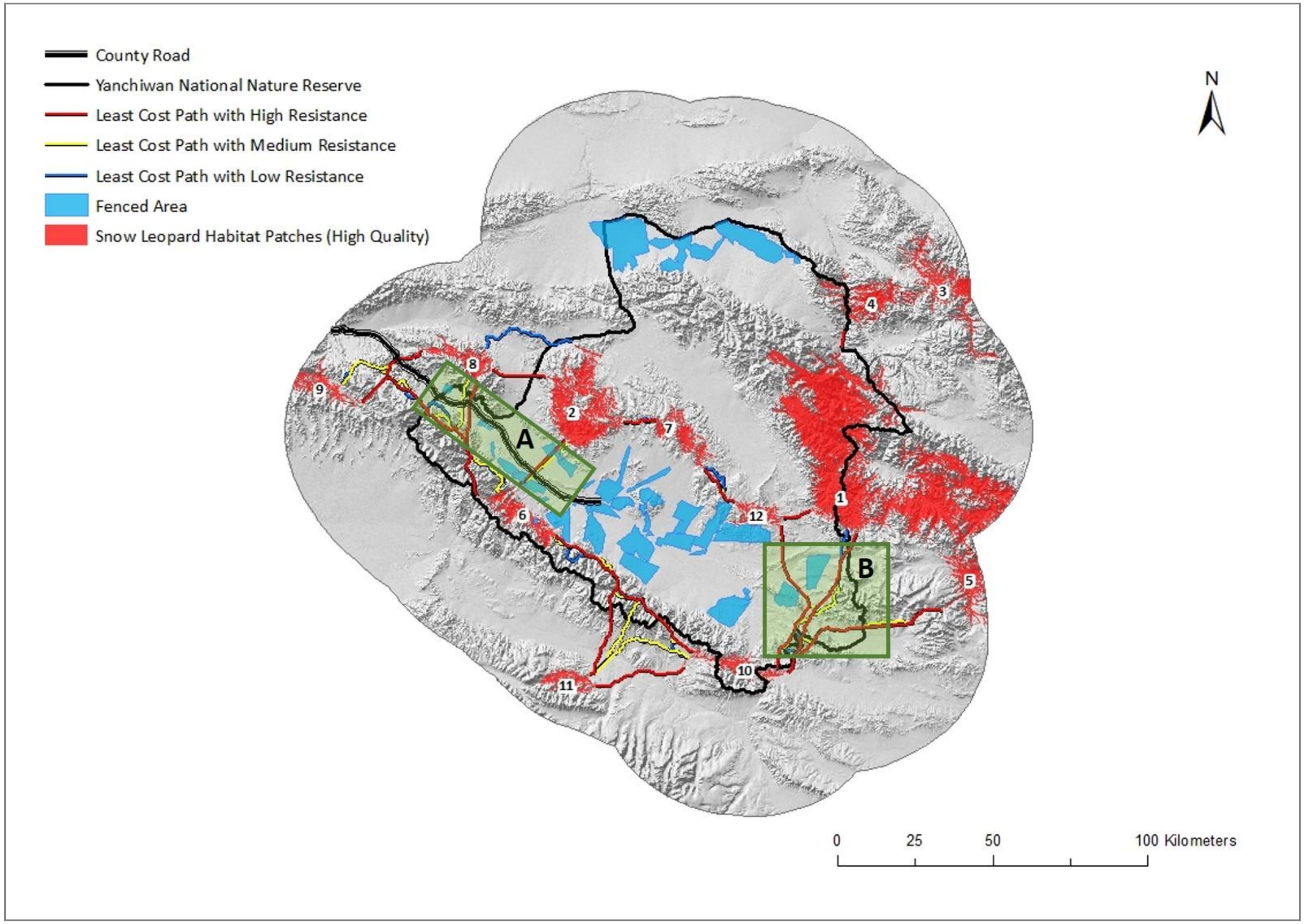

Figure 4.8 Comparation of least cost paths between high quality patches with high, medium and low levels resistance, and identified key areas (A and B) for patch connections.

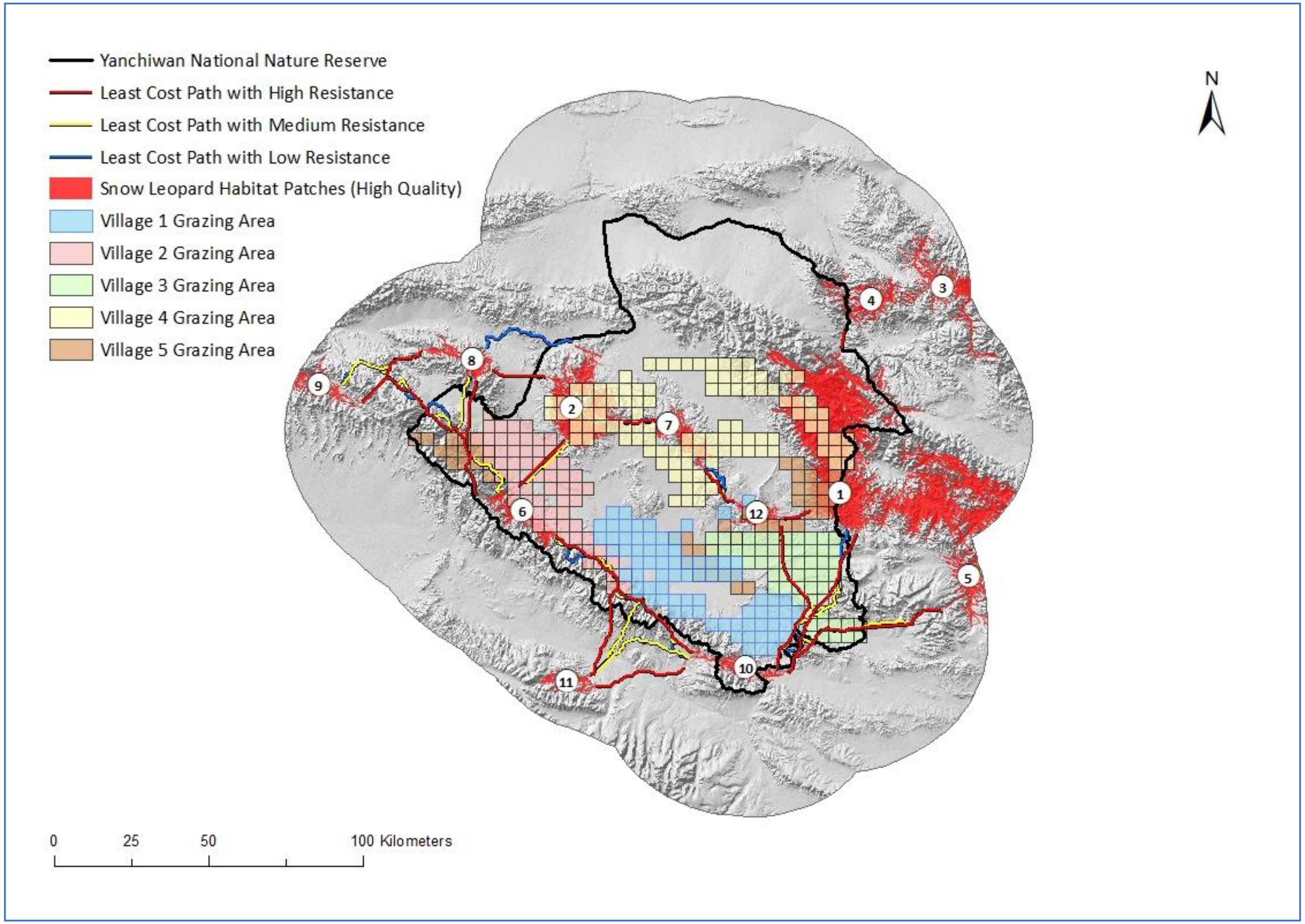

Figure 4.9 The overlap between grazing areas of five villages in Yanchiwan Township, high quality patches (labelled 1 – 12) and least cost paths between patches displayed as colored lines.

4.4 Discussion

Robust pathways and movement corridor definitions were developed from snow leopard distribution models, based on plausible biological parameters. Varying resistance levels, and thresholds were simulated in the analyses, producing apparent consistency at all levels, offering confidence that these parameter definitions provided significant insights to snow leopard movement ability in Yanchiwan National Nature Reserve. Snow leopard movements were largely determined by terrain, in common with previous distribution-based connectivity modelling (Riordan et al, 2015) and more detailed movement studies of collared animals (Johansson et al., 2015; Mccarthy et al., 2005; McCarthy et al., 2017). However, snow leopards are known to be capable of crossing flatter areas, much bigger than those in YNNR. For example, snow leopards have been known to cross the extensive areas of the Gobi Desert (Riordan et al., 2016; Riordan and Shi, 2016; McCarthy et al., 2017). The IUCN Red List (McCarthy et al., 2017) assessment did not record habitat fragmentation as being a major cause for concern for the species, given the recorded ranging behaviors. Snow leopard distributions recorded here in YNNR therefore reflect more local habitat use, such as predation (chapter 3), although highlighting corridors is important to ensure blockages are not put in place through misinformed management, particularly the allowed grazing in the reserve. Further studies on snow leopard collaring in the study area are in progress and will provide more information on movements and habitat use in this particularly area. Those new coming data will be important to improve the models, and help to make management and conservation suggestions with better precisions.

Results from the analysis on resistance Kernel connectivity surface, Kernel density estimation on shortest path, high quality habitat patch and patch linkage showed Shulenanshan Mountain is the most important snow leopard habitat in the nature reserve in terms of habitat quality and patch connections The Yemananshan Mountains lies in the middle of YNNR, and although high quality patch areas were relatively small, it had an important impact on linkages between patches.

For the kernel density estimation on shortest path, the pattern at 250,000-pixel threshold was with obvious difference from the outputs with the rest three thresholds at low, medium and high resistance levels (fig 4.2e-h; fig 4.3e-h; fig 4.4e-h). This indicates that, at the scale of 13,600 km^2 area of YNNR, the supposed 250 km snow leopard lifetime dispersal ability had reached or exceeded the upper limit to shape the final pattern shortest paths. Discussions with preconditions of over 250 km snow leopard dispersal ability would be less meaningful. This is not saying it snow leopards cannot disperse over 250 km, but the threshold was too big in the extent of YNNR. Much larger spatial scale would be more appropriate.

The positioning of least cost paths between high quality patches at low, medium and high resistance levels were with high similarity (fig 4.7), indicated the snow leopard corridors were relatively obvious and “fixed” regardless of proposed resistance levels. Therefore, factors that impact the usage of those dispersal paths needed more attention. Road and fenced area could have impact on the identified two key areas of corridors (Area A and B) (fig 4.8). A county road that connects Subei County downtown and Shibaocheng Township crosses the area between Yemananshan Mountain (middle) and Danghenanshan Mountain (southern). The road and road fence (on both sides, 3 m high metal fence) cut off the least cost paths between the two mountains from east side (fig 4.8, area A in the frame). In eastern side (area B) where had concentrated paths distribution, fenced area may have effect on the paths: some paths go through the very narrow fence gaps. Middle areas between the two mountains had the most fenced area located, further limited activity and connectivity for snow leopards and other mammals like kiangs (*Equus kiang*) and Tibetan gazelles (*Procapra picticaudata*).

The result form pasture mapping indicated the big overlap between grazing areas and high-quality patches (fig 4.9). Studies showed the snow leopard tended to avoid grazing activities (Bhattacharya et al., 2012; Karimov et al., 2018; Rovero et al., 2020), camera trapping based study also detected the interaction between snow leopard and livestock in core area of YNNR (chapter 2). It can be assumed that grazing activity may have direct (direct avoidance) and indirect (competition with livestock) on snow leopards in YNNR, but will require evidence support from further studies.

Therefore, based on the findings from this chapter, we provided the suggestions on further step research and nature reserve management as follow.

a) Continue to collect snow leopard faecal samples across YNNR, and then using molecular genetic analysis method to reveal genetic structure and difference of the individuals from the three mountain ranges. This will provide the insight of the potential isolation caused by the geographic features and negative impact on connectivity found in this study.
b) Conduct snow leopard satellite collaring in YNNR. Satellite collaring is a critical method to study snow leopard, which can provide important information about snow leopard ecology and biology (Grönberg, 2011; Johansson et al., 2015; McCarthy et al., 2010, 2005; Poyarkov et al., 2020; Sharma et al., 2010). Home range, movement, dispersal ability and other information would be greatly helpful to improve the precision of models of distribution, activity and linkage employed in chapter 3 and chapter 4.
c) Gradually reduce the extent and intensity of grazing, especially with the priority of high-quality and areas with high density of dispersal paths. The establishment of nature reserves in China was intended to reduce human disturbance to protect the areas with high ecological and conservation values. However, it's very difficult to implement on the ground with some historical factors. For example, local settlements had already existed before the area been planned and projected in the nature reserve extent. To recover vegetation on grassland, grazing banning has been planned in the *Overall Planning of Qilian Mountain National Park (Draft for comments)* (National Forestry and Grassland Administration of China (National Park Administration of China), 2019). As a key component part of the national park, Yanchiwan will definitely be involved in the grazing banning management measure. With the cooperation from local government and related departments, this will be a good opportunity for management administrations of YNNR to reduce the grazing extent and intensity according to the national park management regulations.
d) Conduct field surveys at the key areas (for example, area A and B in fig 4.8) and key nods within the key areas where the dispersal paths were cut off by road and road fences, or narrowed down due to grazing fences, to collect evidence of the paths usage and the negative impact caused by road and grazing fences. Once this is confirmed, the YNNR administration could start to work on making the mitigation plans. The recommended measures could include the remove of grazing fences, and set up wildlife corridors at the location under the impact of road disturbance.

The molecular genetic study based on faecal sample, and snow leopard satellite telemetry suggested above, are ongoing in YNNR and broader landscape during the processing of this thesis. More detailed information will be provided in chapter 6 of the general discussion.

In chapter 2 and chapter 3, relatively comprehensive studies on density, distribution, activity, habitat patches and linkages of snow leopard in Yanchiwan NNR have been described, which would provide solid scientific support for the conservation and management planning and practice. In 2018, the Qilian Mountain National Park (QMNP) with huge extent (50,200 km^2) was established, which contained the main part of the Qilian Mountain region. Yanchiwan National Nature Reserve, and other seven protected areas were integrated into the national park to form a continuous landscape. The comprehensive ecological research on snow leopard at national park level was urgently needed so as to meet the requirement of providing scientific support for the conservation and management planning and practice in Qilian Mountain National Park. To achieve the requirement, the data, algorithms and principles from chapter 2 and chapter 3 were generalized to a much larger landscape scale of Qilian Mountain National Park, which will be presented in the chapter 5 followed.

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Chapter 5: Qilian Mountain National Park-Snow Leopards in Distribution, Habitat Patches and Linkages

5.1 Introduction

Protected Areas (PAs) have greater richness and/or abundance (or biomass) of species than non-protected areas outside (Mora and Sale, 2011), and have been generally recognized as a key tool to global conservation (IUCN, 2005). Protected areas are critical in protecting biodiversity, safeguarding ecosystem health, providing ecosystem services and local community livelihoods (eg., DeFries et al., 2010; Kearney et al., 2020; (Naughton-Treves et al., 2005; Pittock et al., 2008; Thomas et al., 2012). With their importance has been recognized (Lovejoy, 2006), PAs have been a key element in delivering national and international commitments to Aichi Targets (https://www.cbd.int/sp/targets/) and the United Nations 2030 Agenda for Sustainable Development (https://sdgs.un.org/2030agenda).

According to the World Database on Protected Areas (WDPA), there were 265,940 protected areas over the world (Protected Planet, 2021). However, in the meantime, the total number of other effective area-based conservation measures (OECMs) in the July 2021 release of the WD-OECM was only 343 (Protected Planet, 2021). Mainly due to the lack of effective management and support, a lot of protected areas were often no more than so called “paper parks” (Bruner et al., 2001; Butchart et al., 2015).

Since the first establishment of nature reserve, China had established a system of protected areas composed of nature reserves, forest parks, wetland parks, geoparks, desert parks, water parks, water source reserves, aquatic germplasm resource reserves, ecological public welfare forests, ecological redlines, scenic spots, and cultural forest, etc., and the total number of Chinese PAs was more than 12,000, covered over 2 million km^2 (Ouyang and Xu, 2016). According to the types, protected areas were managed by different government agencies, including National Forestry and Grassland Administration, Ministry of Agriculture and Rural Affairs, Ministry of Water Resources and Ministry of Natural Resources.

Nature reserves were the most important component of PA system in China. At the end of 2017, China had established 2,750 nature reserves at multiple levels, covering 1,471,700 km^2, representing 14.86% of the total land area; the number of national nature reserve (the top-level nature reserve) was 474, covering a total area of 974,500 km^2 (Ministry of Ecology and Environment of the People’s Republic of China, 2018). The area of nature reserves counts for over 70% of the total protected areas in China. Nature reserves have been the most important tool to conserve biodiversity, and have made vital contributions to conservation (Wu et al., 2011; Huang et al., 2019). However, the conservation effectiveness of nature reserves in China has been limited by a variety of problems, including: 1) the small areas accompanied by fragmentation and isolation; 2) overlap in terms of space and management agencies with other types of protected areas; 3) unclear legal confirmation of land ownership; 4) shortage on budget, equipment, professional expertise, and ineffective management et al (Ouyang and Xu, 2016; Quan et al., 2009; Quan et al., 2011).

Across the snow leopard range in China, protected areas were highlighted as being important for the species in all provinces and autonomous regions, accounting for approximately 30% of the range area on average (Riordan and Shi, 2016). Before 2017, all of the PAs reported in the snow leopard range in China were Nature Reserves, at both National and Local levels. In 2017, the National Forestry and Grasslands Administration established a pilot scheme for National Parks in China, which included Qilian Mountain National Park (Ministry of Ecology and Environment of the People’s

Republic of China, 2018; http://www.mnr.gov.cn/).

The newly established national parks in China are expected to establish a comprehensive management system, with the main purpose of protecting the national representative natural ecosystems with large areas (State Council of the People's Republic of China, 2017). By 2020, pilot programs for establishing national parks will be finished; by 2030, the system will be further improved, the management will be more efficient, and the conservation effectiveness will be significantly improved (State Council of the People's Republic of China, 2017). As one of the first ten pilot national parks, Qilian Mountain National Park (QMNP) contains one of the 32 priority areas for biodiversity conservation in China——Qilian Mountain.

Snow leopard is one of the flagship species of the Qilian Mountain National Park. Only sporadic field surveys have been conducted since 2011 in Qilianshan National Nature Reserve (Alexander et al., 2015a; Alexander et al., 2015b; Alexander et al., 2016a; Alexander et al., 2016b) and Yanchiwan National Park (Wildlife Institute of Beijing Forestry University, unpublished data) before the establishment of the national park, explored the biodiversity, wildlife-human conflict, threats, and snow leopard density, but in very limited areas. The lack of data and information formed a bottleneck to the improvement of conservation, management and resource utilization of the national parks.

The lack of data has performed a key limitation to the studies on distribution, movement and connectivity of most large felids, because collecting reliable presence data have always been challenging due to the difficult environment, low density and secretive nature (McCarthy and Mallon, 2016; O'Connell et al., 2011; Weber and Rabinowitz, 1996). Information from desperate sources were used in the big felids' studies, including direct sightings, photographs/videos, camera trap photos, reports/newspaper articles, interviews, sign surveys and radio/satellite telemetry (eg., Cushman et al., 2016; Laguardia et al., 2017; McCarthy et al., 2005; Qi et al., 2015; Riordan et al., 2016). It is also often to have data from different years be combined as dataset and used in the analysis, even from 15 years of surveys (Kittle et al., 2018). Therefore, the using of dataset combined from data with multiple source and different time has been proved as valuable and cost-effective option in studies on large cat species (Cushman and Huettmann, 2010; McCarthy and Mallon, 2016).

Since the establishment of the national park, the managers of QMNP have been facing to big challenges of obtaining robust species and ecological information of snow leopards across the extent of the new national park, with the reasons of large area, limited resources, staff capabilities and training deficit etc. Since 2017, with the support of National Forestry and Grassland Administration of China (NFGA, former State Forestry Administration, SFA), first national park level snow leopard systematic survey was planned and started in the Qilian Mountain National Park areas in Gansu and Qinghai Province. Data on snow leopard presence has been being collected from the field. In this context, the newly collected data, combined with evidences and data from the various separate studies carried out over the previous 10-years within the extent of national park, can be combined to develop generalizable models to inform management in QMNP.

In chapter 3 and 4, we have explored the distribution, habitat patches and connectivity of snow leopards by employing multiple-algorithms and multiple scale and thresholds, in Yanchiwan National Nature Reserve. In this chapter, the analysis above will be upgraded from a component nature reserve to the entire Qilianshan National Park and areas surrounding, to explore the ecological characters of snow leopards in a landscape-broad extent. The goals of this chapter are:
(1) predict the snow leopard distribution in QMNP and areas around;
(2) identify the key areas of activities and the corridor network;
(3) identify the medium and high-quality patches and the patch connectivity pattern;
(4) identify the least cost paths between those patches;
(5) and lastly, provide conservation and management suggestions for the national park.

5.2 Materials and Methods

5.2.1 Study area

This work was conducted in the landscapes that became integrated into the Qilian Mountain National Park (QMNP, N36°29'57''—39°43'39'', E97°23'34''—103°45'49'') (Figure 5.1). Established in 2018, Qilian Mountain National Park was one of the first 10 pilot national parks in China. The national park is located across the boundary area of Gansu Province and Qinghai Province. It lies in the northeast of Qinghai-Tibet Plateau. QMNP has a total area of 50,200 km^2, with 34,400 km^2 in Gansu Province, and 15,800 km^2 in Qinghai Province.

QMNP is composed of eight protected areas in the national park, including three nature reserves: Qilianshan National Nature Reserve of Gansu Province, Yanchiwan National Nature Reserve of Gansu Province, and Qilianshan Provincial Nature Reserve of Qinghai Province; four forest parks: Gansu Tianzhuxia National Forest Park, Gansu Matisi Provincial Forest Park, Gansu Binggouhe Provincial Forest Park, and Qinghai Xianmi National Forest Park, and one national wetland park: Qinghai Qilian Heiheyuan National Wetland Park.

The prevailing southeast monsoon, which has decreasing precipitation from east to west, forms an alpine ecosystem with clear ecological differences between east and west in the national park. QMNP occurs within a plateau continental climate, with strong solar radiation, large temperature differences between day and night, and a long cold winter. The annual average temperature is below 4 ℃, with an extreme maximum temperature of 37.6 ℃, and an extreme minimum temperature of -35.8 ℃. The average annual precipitation is 400 mm and the annual evaporation is between 1137-2581 mm.

There are more than 30 culturally and ethnically distinct communities living in the QMNP, including Tibetan, Mongolian and Uighur as the main inhabitants. According to a preliminary survey results, there are 54,665 permanent residents in the national park, including 37,257 people in Gansu Province, who live in 198 villages in 33 townships, and 17,408 people in Qinghai Province living in 48 administrative villages involving 12 townships (National Forestry and Grassland Administration of China (National Park Administration of China), 2019).

Qilian Mountain National Park is rich in water resources, giving rise to seven major rivers, which provide water to an area of over 6 billion m^3, with over seven million livestock and in excess of six million people. The Qilian Mountain National Park is therefore viewed as critically important for ecological security and resilience of communities downstream.

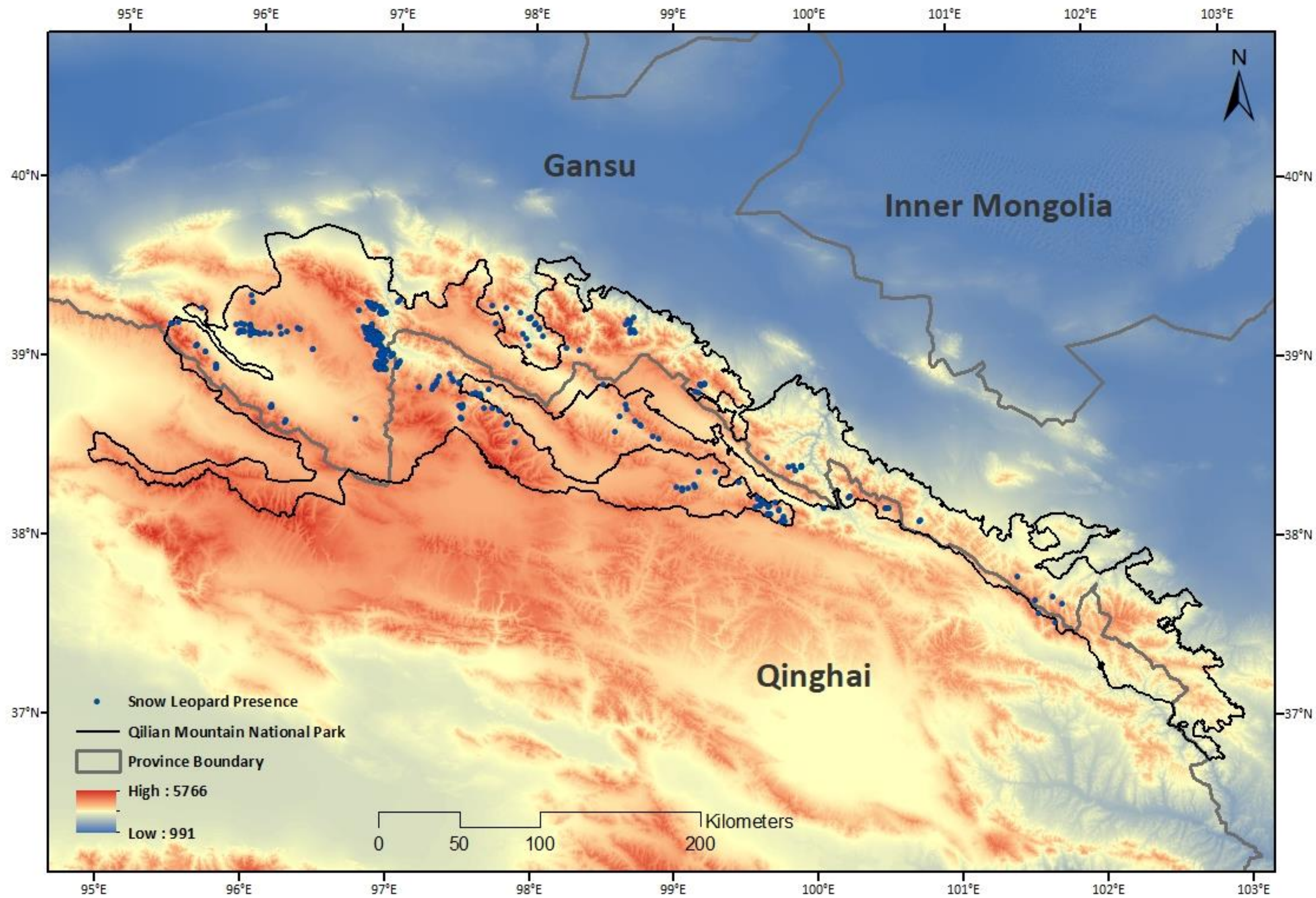

Figure 5.1 Map of the Qilian Mountain National Park located at the boundary area of Gansu Province and Qinghai Province, China, and the snow leopard presence points used in the analysis.

5.2.2. Snow Leopard Surveys

Field work was conducted from 2013 to 2018 to survey snow leopards using remote camera trapping and foot, horseback and vehicle transects across the extended area comprising Qilian Mountain National Park. In Gansu Province, Yanchiwan National Nature Reserve was surveyed from 2013 to 2018; Qilianshan National Nature Reserve was surveyed in 2013 (Alexander et al., 2015a) and 2017, and Minle County was surveyed in 2017 and 2018. In Qinghai Province, field data collection was carried out in Qilianshan Provincial Nature Reserve in 2017 and 2018.

Cameras were set up at locations with snow leopard signs to increase the detection probability (Jackson and Hunter, 1996). Suspected snow leopard scats were collected along the transect surveys, with additional ad hoc sampling made by staff working in each area. Details of scat sampling in the field and subsequent laboratory processing are described in Bai et al., (2018). For the analyses here, geographic locations corresponding to definite photographic or genetic identification of snow leopards were used as presence points.

5.2.3. Data Analysis

5.2.3.1. Species distribution models

7.2.3.1.1Environmental Predictors

A total of 30 environmental variables, grouped into five categories were selected as plausible predictors of snow leopard presence (Aryal et al., 2016; Atzeni et al., 2020; Bai et al., 2018; (Kalashnikova et al., 2019; Li et al., 2016; Li et al., 2020; Sharma et al., 2021; Watts et al., 2019) (Table 5.1). Remote sensing land cover data were downloaded from the Resource and Environment Science and Data Center, Chinese Academy of Science (http://www.resdc.cn/) with grid cell size of 30 m × 30 m. Six land cover classes were selected to use in the analysis farmland (Fa), forest (Fr), grassland (Gr), shrub land (Shr), bare land (Br), and snow & ice (Sn). Each predictor variable was parameterized at multiple spatial scales: 300 m, 600 m, 1200 m, 2400 m, 4800 m, 9600 m, 14400 m, 19200 m and 28800 m. Details of the processing are described in Atzeni et al., (2020).

5.2.3.1.2. Maximum Entropy (MaxEnt) Models

Models were run using Maxent 3.4.1 (Phillips et al., 2017; Phillips et al., 2006). Initially, full models were constructed with all variables included at all scales. A scale selection process was undertaken using the 'dismo' function for each environmental predictor, which indicated the optimum scales for each variable in terms of the highest value of Area Under the ROC Curve (AUC). Then a full model was run with the best-scale variables, and variables with a model contribution less than 1% were subsequently discarded. MaxEnt models were then run using 'MaxentVariableSelection'. The settings for this were 50% test data, with 10 subsampling replicates, and 20,000 background points. Both linear and quadratic functions were defined for all variables to ensure capture of non-linear and linear relationships with features. Additional parameter values were specified as: contribution threshold < 1; correlation threshold < 0.7; beta multiplier = seq (1, 5, 0.5). Model selection was based on AIC and AUC (Bai et al., 2018).

5.2.3.1.3 Random Forest

A random forest analysis of the predictors of snow leopard presence was implemented using the 'randomForest' package version 4.6-14 (Naimi, 2017). A sample of 39,300 random points (10 times of presence points) were created within the 28,800m buffer surrounding all present points to create a set of 'pseudo-absence' points. We used a 70-30 partition to train and test the models, respectively. Univariate scaling was applied across all variables using the Model Improvement Ratio (MIR, Murphy et al., 2010), the scale with top mir value will be selected as the best scale for that variable. The function "rf.modelSel" from R package "rfUtilities" (Evans and Murphy, 2019) was used to select the final set of predictor variables. Settings of the function were: "mir" for type of calling for importance values, vector of importance percentiles to test used value from zero to one with 0.1 intervals, number of trees was 5,000. The function will generate several sets of variables, the set with least "out-of-bag" (OOB) error was selected for model prediction.

5.2.3.1.4 Generalized Linear Model (GLM)

Using the 393 presence and 3, 930 pseudo absence points described in the random forest models above, GLM models were constructed with univariate scaling across all variables and only linear interactions tested. Correlation structure (Pearson) between variables was assessed using the 'cor' function and a threshold of 0.7 was set. The best variable in each correlated variable set was compared and selected based on the lowest AIC values. A 'dredge' procedure was applied to final models, with subsets selected based on delta AIC < 4. Model averaging from selected subsets was used to create predictor values and create a raster visualization.

5.2.3.1.5 Model ensemble

An ensemble model was created from the MaxEnt, RF and GLM predictor outputs by summing the resultant GIS layers using the raster calculator in ArcGIS (version 10.6). The ensemble model values were then rescaled to between 0 and 1.

5.2.3.2 Identify the corridor network

The process of identifying the possible corridor network followed that described in Chapter 4. Using ArcGIS (version 10.6), a random raster layer with pixel values between 0 and 1, was created over the entire extent. The ensemble distribution map produced from MaxEnt, RF and GLM models (§5.2.3.1.5) was subtracted from the random raster and the subtracted output was summed to produce a cumulative random surface. A random set of 100,000 points (P_{RAND}) was created across the study area extent, and the values of the cumulative random surface were assigned to each point in P_{RAND}. A further subset of these points (P_{RAND}) was selected based on those occurring on pixels with positive values. Ten groups of 393 points (P_{393}) were randomly selected from P_{RAND}, from which five sets were retained.

The exponential decay transformation was used to generate a resistance (R) map:

$$R = x^{(-1*\text{Habitat Suitability})}$$

The based value (x) of 1000 for the exponential transformations were used. The resistance map was resampled to a 500 m pixel size and resistances were rescaled from 0 (minimum resistance) to 1 (maximum resistance).

The programme UNICOR (version 2.6) (Saura and Torné, 2009) was used to produce resistant Kernel connectivity surfaces and Kernel density estimation on shortest paths for each of the three levels of resistance surfaces. Considering we have much larger landscape extent then Yanchiwan National Nature Reserve describe in chapter 2-4, we gave larger setting of thresholds (compared with analysis for YNNR in chapter 4, §4.2.3.2) in this analysis. The least cost path maps were created with respective thresholds of 250, 500, 1,000 and 2,000 cost units (pixels), authorized presumed snow leopard dispersal ability of 250 km, 500 km, 1,000 km and 2,000 km. Resistance Kernel connectivity surfaces were generated by setting edge distance thresholds of 25 km, 50 km 100 km and 200 km. The above two analysis processes were repeated for each of the five point-subsets, and the results were averaged formed as final result.

5.2.3.3 High-quality patches identification and patch connectivity analysis

5.2.3.1.1 Identify high-quality habitat patches

Due to the large extent of the analysis, a lot of non-national park areas with low suitability for snow leopard were included in the analysis. To mitigate the potential bias, the ensemble model produced in step 5.2.3.1.5 was reclassified into very low, low, medium and high-quality habitat based on percentiles (<75th, 75th~85th, 85th~95th,> 95th). The software FRAGSTATS (McGarigal et al., 2012) was used to assess the following three indexes: (1) percentage of the landscape (PLAND) measuring the proportion of patches occupied by each habitat quality among the total number of habitat patches; (2) correlation length (GYRATE_AM), defined as the area weighted mean patch radius of gyration, it gives the average distance one individual can move from an random starting point and traveling in a random direction without leaving the patch, and then averaged across all patches of the landscape; and (3) largest patch index (LPI), which is the proportion of the largest patch among whole landscape. Habitat patches area over 100 km^2 for medium and high-quality levels were selected for the patch connectivity analysis. For those selected high-quality patches, the areas, correlation lengths and percentage of the patch areas among the high-quality class were calculated.

5.2.3.1.2 Patch connectivity analysis

The program CONEFOR (version 2.6) (Saura and Torné, 2009) was used for snow leopard habitat patch connectivity analysis across Qilian Mountain National Park, using the approach described in Chapter 4 for connectivity modeling in Yanchiwan National Nature Reserve. Input file preparation and model settings were carried out using the same methods as for YCW. The integral index of connectivity (IIC) (Pascual-Hortal and Saura, 2006) and the probability of connectivity (PC) (Saura and Pascual-Hortal, 2007) of each patch were calculated. The patch connectivity analysis was conducted for both high-quality and medium-quality patches identified.

5.2.3.4 Identify the least cost paths between patches.

The “Linkage Mapper” (version 2.0.0) toolbox for ArcGIS was used to calculate the least cost paths between the identified high-quality and medium-quality habitat patches for snow leopard in Qilian Mountain National Park. The “Build Network and Map Linkages” tool in the toolbox was used to calculate least cost paths for the three resistance models. The “Cost-Weighted & Euclidean” was selected as the network adjacency method, and the “Cost-Weighted” method was used for the nearest neighbor measurement unit.

Table 5.1 List of 30 variables used in the study. For the class level landcover, metrics has been calculated for each landcover type. Land cover class codes are given according to the Resource and Environment Science and Data Center, Chinese Academy of Science: 1 (Farmland), 2 (Forest), 3 (Grassland), 4 (Shrubland), 9 (Bare Land), and 10 (Snow & Ice). Detailed description of variables provided in Appendix 3.2 in chapter 3.

Category	Variable	Abbreviation	Layer Source
Linear and point features	Density of highways and national roads	DENS_rd	Berman, 2009
	Density of human settlements	DENS_set	OpenStreetMap
	Density of rivers	DENS_riv	www.DIVA-GIS.org
Topographic	Slope position	SLP	NASA'S SRTM v.4 (Jarvis et al., 2008)
	Focal mean of elevation	FME	
	Roughness	ROUGH	
	Compound topographic index	CTI	
	Dissection	DISS	
Climatic	Annual mean temperature	TEMP	WorldClim Version 2 (Fick & Hijmans, 2017)
Landcover (Landscape level)	Aggregation index	AI	Resource and Environment Science and Data Center, Chinese Academy of Science (http://www.resdc.cn/)
	Contrast-weighted edge index	CWED	
	Patch density	PD	
Landcover (Class Level)	Area-weighted mean	AREA_AM_(1, 2, 3, 4, 9, 10)	Resource and Environment Science and Data Center, Chinese Academy of Science (http://www.resdc.cn/)
	Percentage of landscape	PLAND_(1, 2, 3, 4, 9, 10)	
	Radius of gyration (mean area)	GYR_AM_(1, 2, 3, 4, 9, 10)	

5.3 Results

5.3.1 Snow leopard surveys

Based on photographic or genetic identification, a total of 393 snow leopard presence locations were confirmed and used in the analysis (Figure 5.1). Among them, 210 points were from camera traps, and the remaining 183 were confirmed from genetic identification of scats. Of the total, 92 points were located in Qinghai province, and 301 points were collected in Gansu province (Figure 5.1).

5.3.2 Species distribution models

5.3.2.1 Maximum Entropy (MaxEnt) Model

After the univariate scaling and variable selection process, 15 out of 30 variables were selected for the final model (Table 5.2). In terms of best scales, nine variables had the large scale (9,600 m, 14,400 m and 28,800 m). For the five covariates with 1,200 m and 2,400 m as best scales, four of them belonged to topographic and climatic categories. Aggregation index got about 20% contribution, followed by other four covariates contributed over 10%, including compound topographic index, focal mean of elevation, temperature and dissection (Table 5.3). Covariate of temperature had the highest permutation importance of 62.7 % (Table 5.3). Aggregation index (ai_9600), compound topographic index (cti28800), focal mean of elevation (fme14400), annual mean temperature (temp2400) and dissection (diss1200) the top five among all variables ordered along the percent contribution, with their values above 10 (Figure 5.2). Results of variables Jackknife of AUC of the MaxEnt model was plotted as Figure 5.3. With the 15 predictors, the final model had an AUC value of 0.954 (SD = 0.005) (Figure 5.4), indicating the good model fit. The snow leopard distribution model produced using MaxEnt algorithm was showed as Figure 5.9-a.

5.3.2.2 Random Forest

In total 12 variables were selected after the scaling analysis and covariate selection. The selection of variables showed strong tendency on some categories: 11 out of 12 features of topographic, landscape-level land cover and class-level land cover categories were picked up (Table 5.2). Only three of the selected variables had best scale in small (300 m and 600 m) (Table 5.2). The "Mean Decreased Accuracy" and Mean Decreased Gini" based variable importance was plotted as Figure 5.5. Slope position (slp) took the lead in the mean decrease accuracy, and compound topographic index (cti) ranked at the top in mean decrease Gini. Lowess smooth fit curve of the 12 selected predictors are showed as Figure 5.6. Multi-scale random forest algorithm-based snow leopard distribution map was plotted as Figure 5.9-b. For the model validation, the model Kappa = 0.702, 'out-of-bag' (OOB) error was 0.043, the model error variance = 8.07×10^{-7}.

5.2.3.3 Generalized Linear Model

There were 14 variables selected after the univariate scaling and variable selection for GLM, including three linear and point features, four topographic features, temperature, aggregation index, and five class-level features (table 5.2). Seven predictors had large scale (9,600 m and above) and three got small scale (300 m and 600 m) as best scales. Lowess smooth fit curve of the 14 selected predictors are showed as Figure 5.7. AUC value of the GLM model was 0.91 (Figure 5.8). Multi-scale GLM algorithm-based snow leopard distribution map in Qilian Mountain National Park was plotted as Figure 5.9-c.

5.2.3.4 Ensemble model

Based on above three snow leopard distribution predictive maps, ensemble map was produced by adding up the three maps and then normalized the value to the range from zero to one. Within the national park, most of the predicted high quality snow leopard habitat mainly occurred middle-western mountain areas, especially the Shulenanshan Mountains in Yanchiwan National Nature Reserve (Figure 5.9-d). The high quality areas extended from the middle to the east along mountain range distributions. Fewer suitable snow leopard habitat areas were identified in the western part of the national park. Also, it was worth noting that, a large patch of high quality suitable area could be seen at the south to the national park.

5.3.3 Corridor network

Map of resistance surface with 1,000 based values for exponential transformations was made (Figure 5.10), representing low level of resistance. Figure 5.11 showed the resistance Kernel connectivity surface and Kernel density estimation on shortest path with multi thresholds based on the low-level resistance.

Similar with the result from Yanchiwan National Nature Reserve, the patches in the connectivity surfaces were less fragmented and more connected with the increase of threshold, from 25 km to 200 km. The middle-western area, which identified with more occupation of high-quality habitat in the previous step, had the largest and best connectivity surface (Figure 5.11). There were three best areas with 25 km threshold and they merged into one while the threshold increased. The same area also had the most of the paths with the threshold of 250 pixels, presenting a “center” or “hub” of the corridor network. With the increase of the threshold, the network extended, especially to the eastern narrow area of the national park, and the southern area outside the national park (Figure 5.11). Patterns of kernel density estimation on shortest path did not change a lot from 1,000 to 2,000 pixels thresholds.

5.3.4 Medium and high-quality habitat patches identification and patch connectivity

Very low, low, medium and high-quality habitat patches were identified based on percentiles (<75th, 75th~85th, 85th~95th, and > 95th respectively: Table 5.4). The medium quality habitat definition contained 36,458 patches with a largest patch index=0.89 and correlation length=25.87 km. The high-quality habitat definition had 8,603 patches, with largest patch index=1.95, and correlation length=25.51 km.

Of the habitat patches with areas > 100 km^2, the medium-quality habitat definition produced 27 patches, whilst the high-quality habitat definition yielded 16 patches. Of high-quality patches, seven were located within the national park boundary (patch ID 1, 5, 6, 10, 11 and 15) (figure 5.12). The largest patch was located in the mid-west of the national park, with the area of 6,114 km^2. The top two high-quality patches in total occupied half of entire high-quality patch area, with correlation length over 25 km (Table 5.5), indicating the good suitability for snow leopard in terms of area and movement.

The 16 high-quality patches were subsequently used for patch connectivity and least cost path analysis (Table 5.6). Patch 1 occupied over half of the total high-quality habitat patch area. Patch 1 and 2 were the top two patches with the highest integral index of connectivity (IIC) at all thresholds. Patch 10 was the third most important patch of IIC except at the thresholds of 200 km, but the IIC values were always below 10. Similarly, in terms of probability of connectivity (PC), patch 1 and 2 occupied the top two positions; patch 10 and 5 had higher ranking within the rest patches, showed relative importance in connection (table 5.4). The result suggested patch 1, 2, 5, and 10 were the most important patches in terms of connectivity within QMNP and surrounding areas.

5.3.5 Least cost paths between patches

Least cost paths between high-quality and medium-quality patches were identified (Figure 5.13).

The high-quality patch paths were more concentrated in the eastern area where some patches were clustered. In the eastern and southern part where high-quality patches were more separated, the paths were fewer but longer. Most of the high-quality patch paths went through medium-quality patches. Medium-quality patch paths were shorter compared with the paths between high-quality patches.

Table 5.2 The AIC, AUC and importance values of the variables selected after the univariate scale selection, conducted on different predictors at each of the seven scales considered. In bold the predictors selected after collinearity test (r≥0.7) for GLM, variable selection with contribution threshold=1, correlation threshold=0.7 for MaxEnt, and variable selection use random forest (VSURF) for Random Forest method.

Category	Variables	Class	MaxEnt		Random Forest		Generalized Linear Model	
			Best scale	AUC	Best scale	Importance	Best scale	AIC
Linear and Point NLFatures	DENS_riv		**9600**	**0.654**	14400	1	**600**	**2564.614**
	DENS_rd		**9600**	**0.558**	14400	1	**14400**	**2598.393**
	DENS_set		14400	0.547	19200	1	**4800**	**2615.504**
Topographic	CTI		**28800**	**0.898**	**9600**	**1**	**9600**	**2327.737**
	SLP		**2400**	**0.803**	**19200**	**1**	**4800**	**2291.437**
	ROUGH		**2400**	**0.867**	**600**	**1**	**4800**	**2606.377**
	DISS		**1200**	**0.73**	19200	1	**300**	**2335.199**
	ELEV		**14400**	**0.876**	**300**	**1**	28800	2617.066
Climatic	TEMP		**2400**	**0.885**	**600**	**1**	**28800**	**2613.856**
Land Cover (Landscape level)	CWED		9600	0.777	**19200**	**1**	9600	2616.069
	AI		**9600**	**0.775**	**19200**	**1**	**300**	**2577.801**
	PD		**9600**	**0.794**	**19200**	**1**	9600	2572.200
Land Cover (Class level)	PLAND	Farmland	**9600**	**0.592**	19200	1	**14400**	**2553.011**
	AREA_AM		4800	0.588	14400	1	14400	2573.392
	GYR_AM		28800	0.592	14400	1	2400	2593.821
	PLAND	Forest	600	0.507	19200	1	28800	2587.007
	AREA_AM		600	0.507	14400	1	**19200**	**2585.588**
	GYR_AM		**28800**	**0.697**	19200	1	9600	2596.400
	PLAND	Grassland	4800	0.769	9600	1	14400	2531.632
	AREA_AM		**1200**	**0.732**	**9600**	**1**	9600	2476.194
	GYR_AM		2400	0.744	14400	1	14400	2476.161
	PLAND	Shrubland	28800	0.573	14400	1	28800	2622.483
	AREA_AM		28800	0.574	14400	1	**9600**	**2623.294**
	GYR_AM		28800	0.577	14400	1	9600	2614.250
	PLAND	Bare Land	4800	0.765	**19200**	**1**	14400	2504.782
	AREA_AM		**4800**	**0.761**	**19200**	**1**	19200	2512.985
	GYR_AM		**14400**	**0.655**	**19200**	**1**	**9600**	**2474.801**
	PLAND	Snow & Ice	28800	0.79	14400	1	**2400**	**2554.288**
	AREA_AM		28800	0.792	14400	1	2400	2556.127
	GYR_AM		28800	0.8	14400	**1**	2400	2557.466

Table 5.3 Percent contribution and permutation importance of 15 selected variables for predicting snow leopard distribution using MaxEnt algorithm with data from Qilian Mountain National Park, China.

Variable	Percent contribution	Permutation importance
ai_9600	19.6	0.9
cti28800	13.4	7.3
fme14400	12.4	5.3
temp2400	11.2	62.7
diss1200	10.7	1.4
slp2400	7.8	0.4
gyrate_am_9_14400	5.7	0.3
area_am_9_4800	4.4	9.6
pland_1_9600	4.2	0.2
pd_9600	2.6	6.9
area_am_3_1200	2	1.2
rough2400	1.9	0.7
rd9600	1.5	0.5
gyrate_am_2_28800	1.4	0.7
riv9600	1.3	1.9

Table 5.4 Number, largest patch index, and correlation length of low, medium and high-quality patches identified in Qilian Mountain National Park and surrounding areas, by using program FRAGSTATS.

Habitat Quality	Percentage of Area	Number of Patches	Largest Patch Index	Correlation Length (km)
Very Low	75	22032	47.29	165.91
Low	10	43550	1.68	17.11
Medium	10	36458	0.89	25.87
High	5	8603	1.95	25.51

Table 5.5 The area, correlation length and patch percentage of the 16 high-quality patches identified in Qilian Mountain National Park and surrounding areas with areas above 100 km^2. Patch percentage was calculated by dividing patch area by total area of high-quality patches.

Patch ID	Area (km^2)	Correlation Length (km)	Patch Percentage
1	6114.2	47.9	38.9
2	1744.6	32.6	11.1
3	477.5	13.0	3.0
4	431.8	10.0	2.7
5	344.6	21.8	2.2
6	321.8	15.0	2.0
7	310.4	13.3	2.0
8	306.4	8.6	1.9
9	248.1	9.4	1.6
10	199.2	9.7	1.3
11	148.8	7.9	0.9
12	125.0	5.8	0.8
13	114.7	7.3	0.7
14	114.3	7.1	0.7
15	112.8	5.1	0.7
16	111.1	4.7	0.7
Total	**11225.1**	**-**	**71.4**

Table 5.6 The area, percentage of total habitat attribute that corresponds to the attribute in that patch (dA), and the connection indices of probability of connectivity (PC) and integral index of connectivity (IIC) with thresholds of 25 km, 50 km, 100 km and 200 km of 16 high-quality patches in Qilian Mountain National Park.

Patch ID	Area (km^2)	dA	dIIC_25km	dPC_25km	dIIC_50km	dPC_50km	dIIC_100km	dPC_100km	dIIC_200km	dPC_200km
1	6114.180	54.469	88.680	86.760	88.258	86.680	87.664	86.269	83.412	84.998
2	1744.580	15.542	7.470	16.165	7.407	16.450	24.934	17.810	23.212	21.174
3	477.503	4.254	1.258	5.047	1.356	5.131	6.135	5.521	5.974	6.432
4	431.754	3.846	0.401	3.211	0.785	3.293	4.795	3.692	5.707	4.737
5	344.623	3.070	4.613	7.466	3.547	7.456	5.186	7.394	4.387	7.146
6	321.829	2.867	0.812	4.055	0.914	4.115	4.449	4.386	4.254	4.956
7	310.376	2.765	0.281	2.412	0.564	2.476	3.153	2.781	4.103	3.560
8	306.366	2.729	0.853	2.946	0.846	3.003	2.979	3.271	3.833	3.920
9	248.095	2.210	1.062	2.086	1.053	2.127	2.454	2.331	3.159	2.871
10	199.203	1.775	6.986	8.724	7.275	8.630	2.449	8.172	2.549	6.948
11	148.757	1.325	1.193	2.585	1.531	2.591	1.829	2.618	1.894	2.655
12	124.959	1.113	1.773	2.629	1.762	2.621	1.551	2.585	1.659	2.484
13	114.728	1.022	0.329	1.517	0.326	1.535	1.483	1.620	1.516	1.799
14	114.283	1.018	0.028	0.787	0.028	0.809	1.001	0.920	1.040	1.207
15	112.801	1.005	0.298	2.163	0.296	2.178	1.473	2.235	1.491	2.289
16	111.108	0.990	0.101	0.809	0.202	0.830	1.100	0.935	1.463	1.212

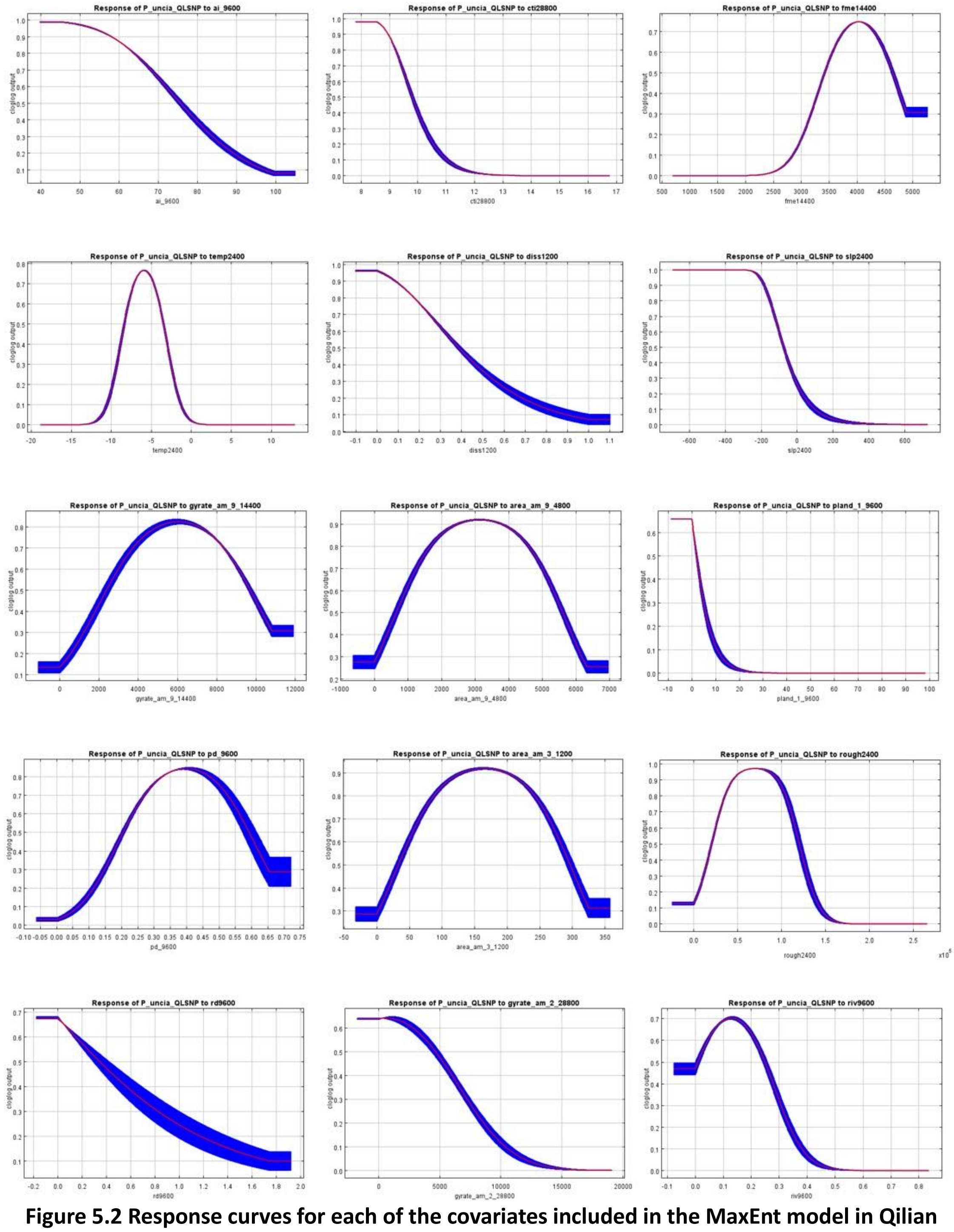

Figure 5.2 Response curves for each of the covariates included in the MaxEnt model in Qilian Mountain National Park, ordered along the percent contribution.

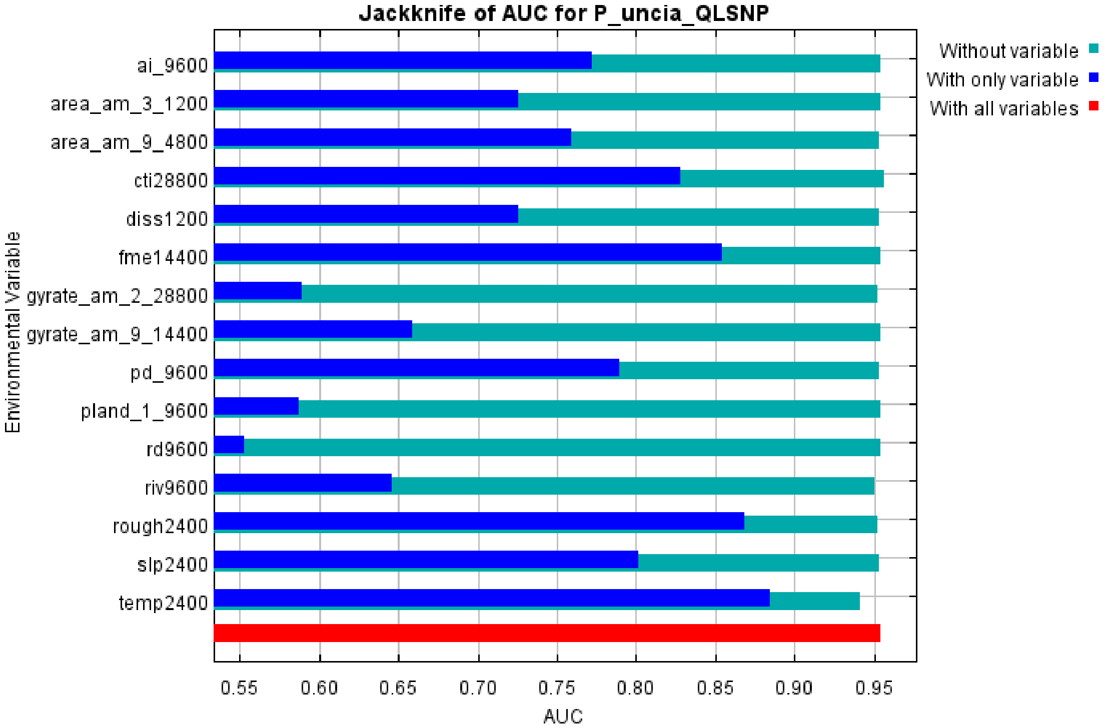

Figure 5.3 Results of the variables jackknife test of AUC of the MaxEnt model, with snow leopard presence data from Qilian Mountain National Park, China.

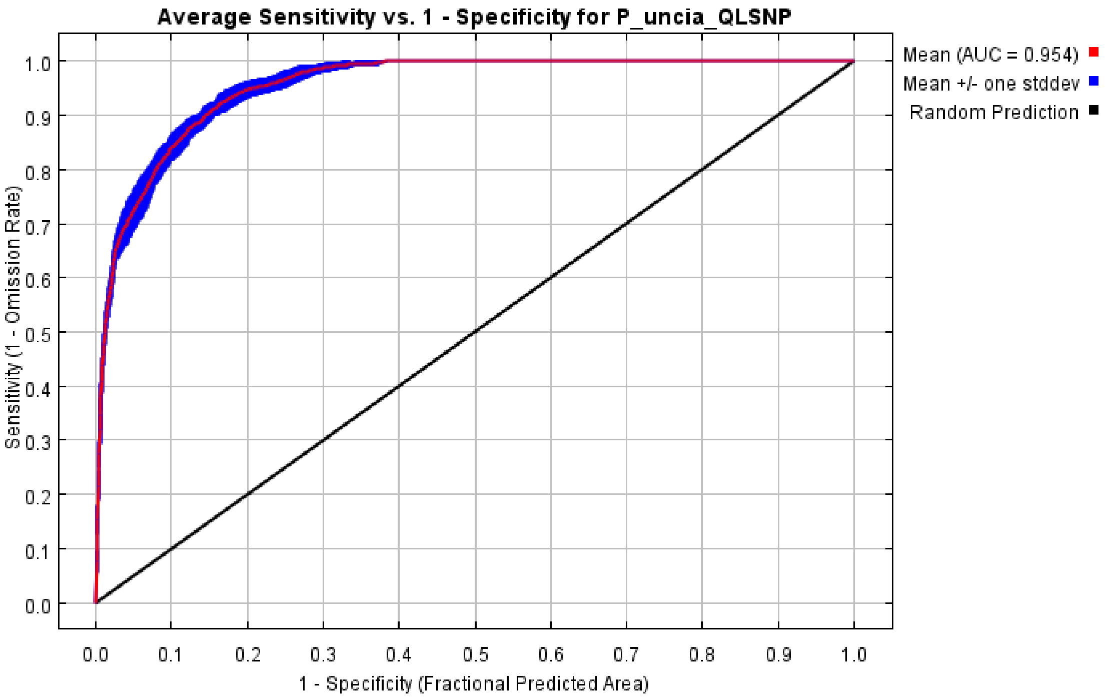

Figure 5.4 The receiver operating characteristic (ROC) curve for the snow leopard presence data from Qilian Mountain National Park, China.

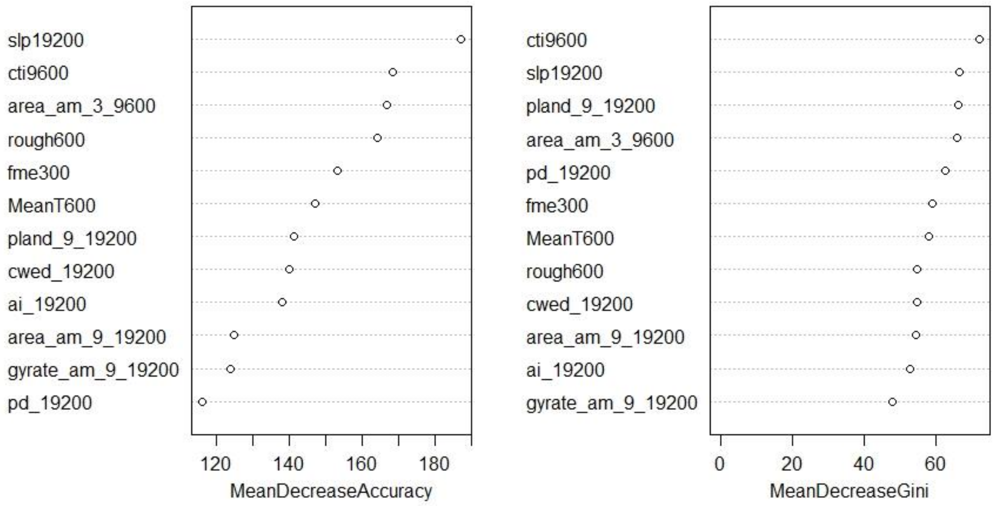

Figure 5.5 Plot of "Mean Decreased Accuracy" and "Mean Decreased Gini" based importance of the predictors for random forest algorithm to predict snow leopard distribution in Qilian Mountain National Park, China.

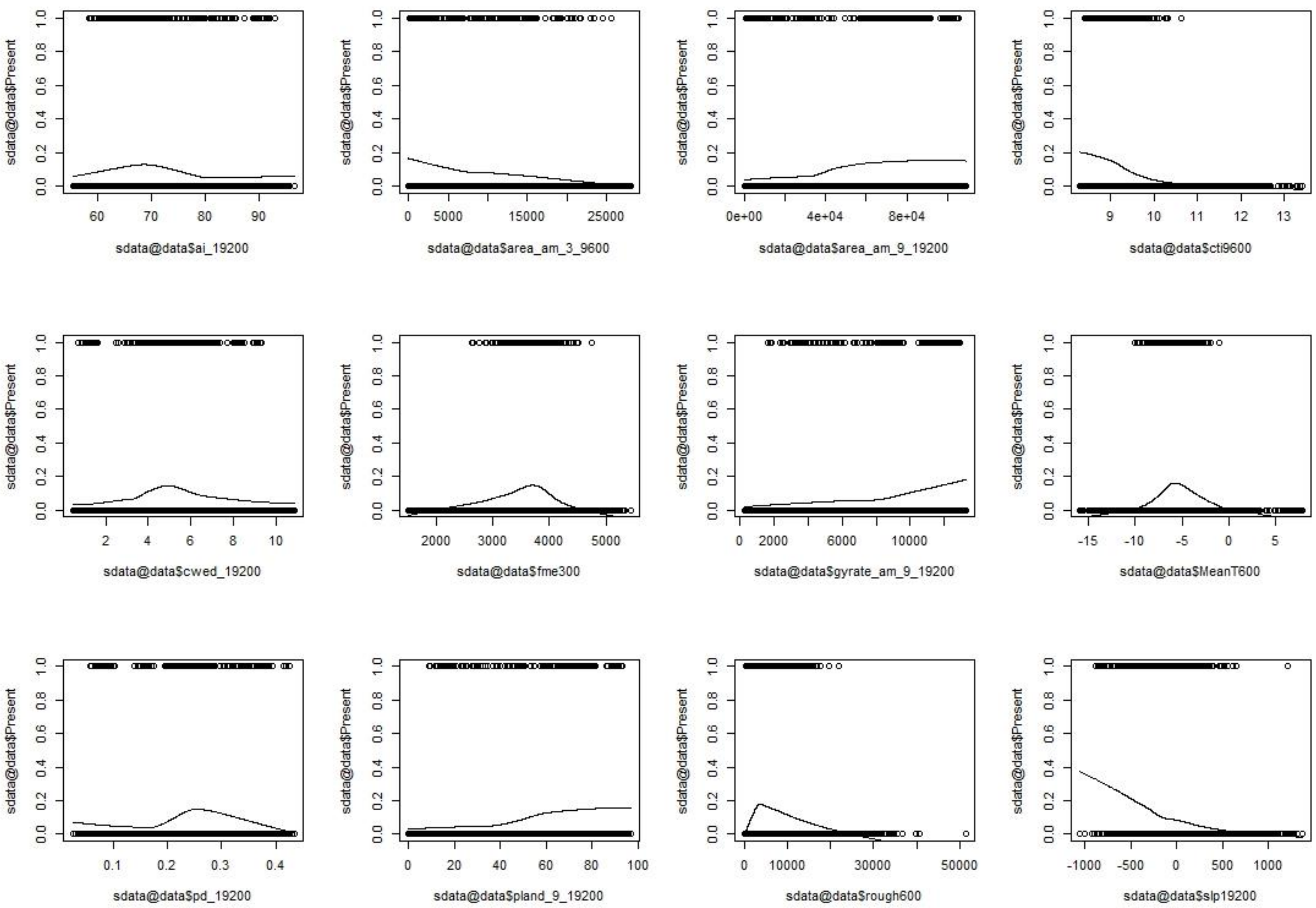

Figure 5.6 Lowess smooth fit curve of the 12 selected predictors for random forest algorithm to predict snow leopard distribution in Qilian Mountain National Park, China.

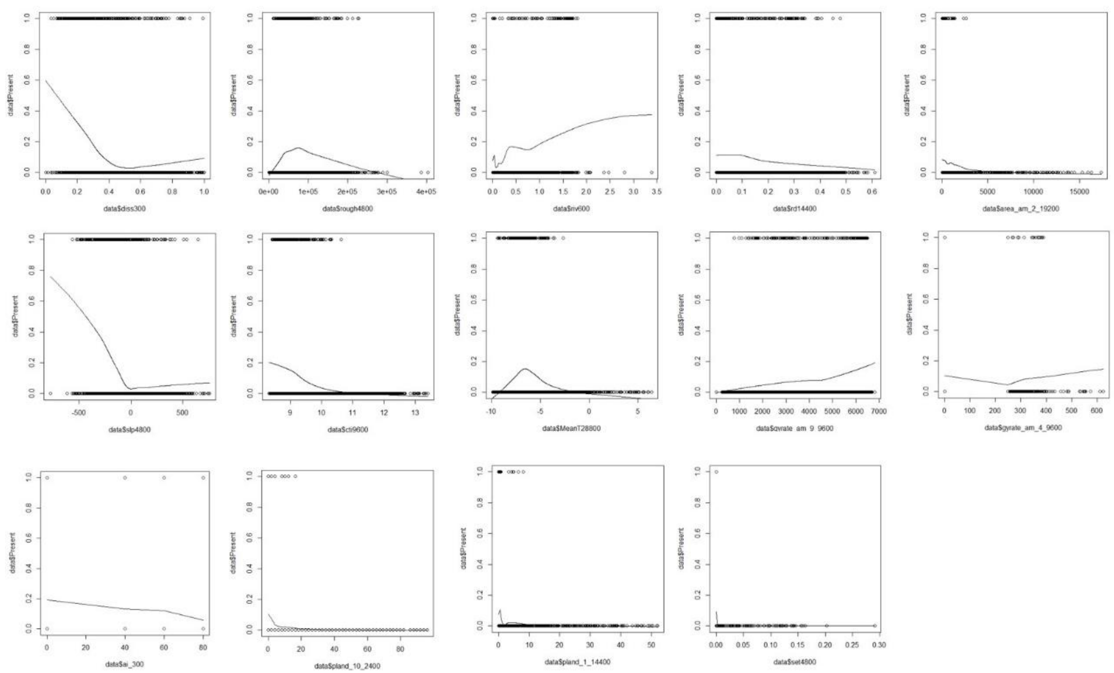

Figure 5.7 Lowess smooth fit curve of the 14 selected predictors for Generalized Linear Model algorithm to predict snow leopard distribution in Qilian Mountain National Park, China.

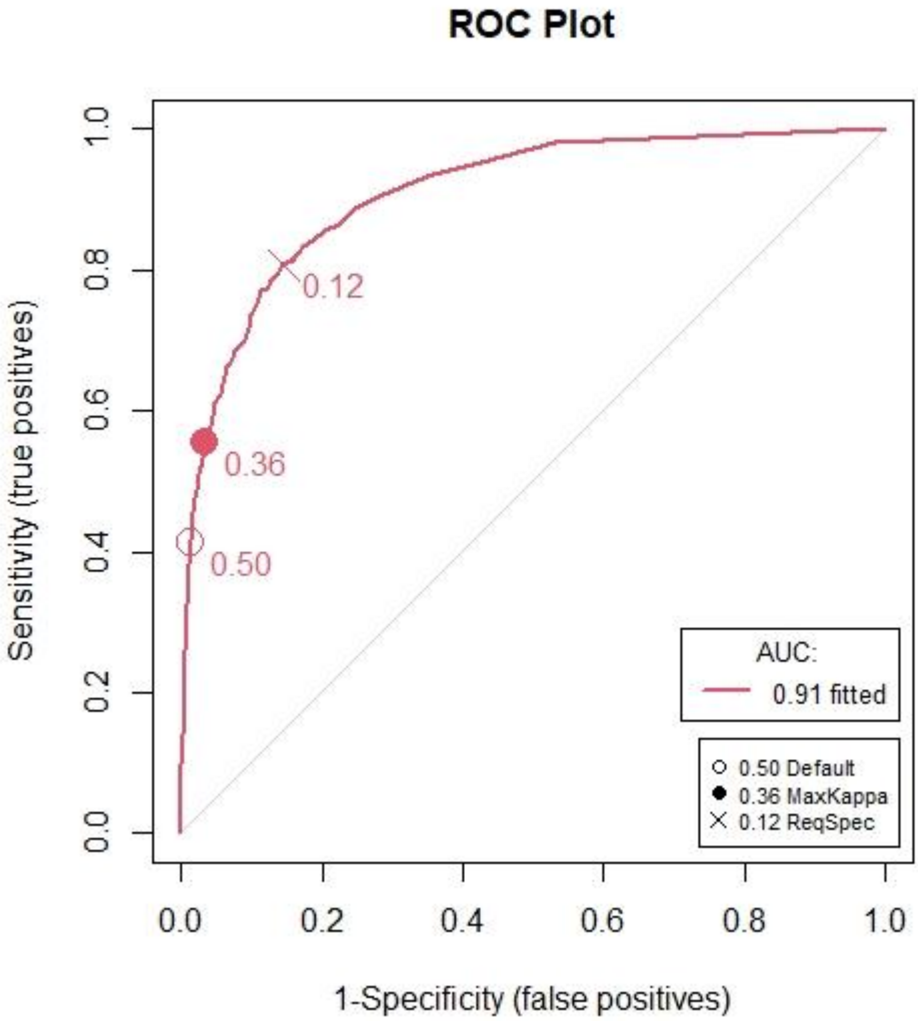

Figure 5.8 The ROC plot produced from Generalized Linear Model with snow leopard presence data from Qilian Mountain National Park, China.

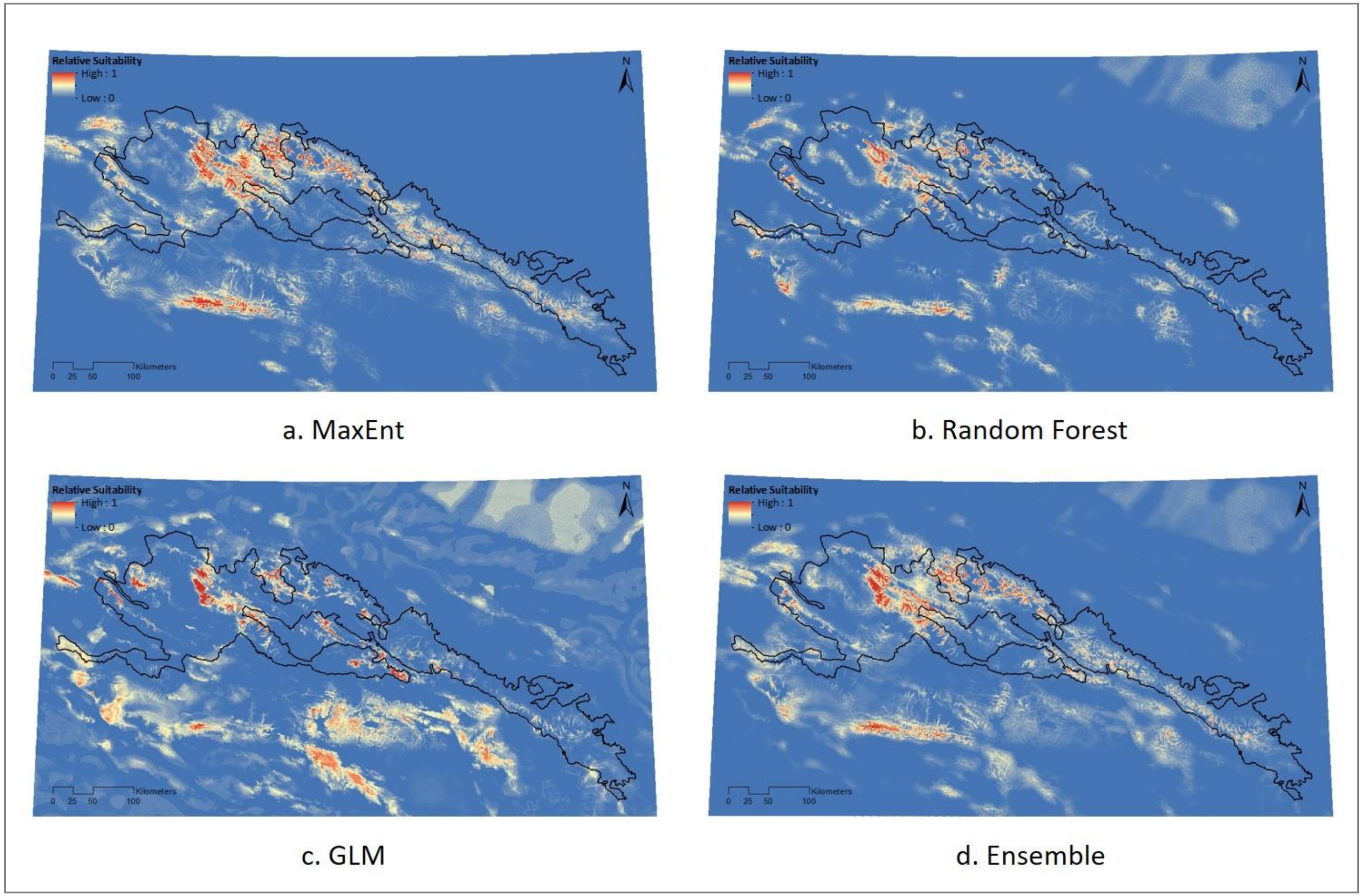

Figure 5.9 Habitat suitability maps for Qilian Mountain National Park produced by MaxEnt (a); Random Forest (b); Generalized Linear Model (c), and ensemble map (d) based on the above three maps.

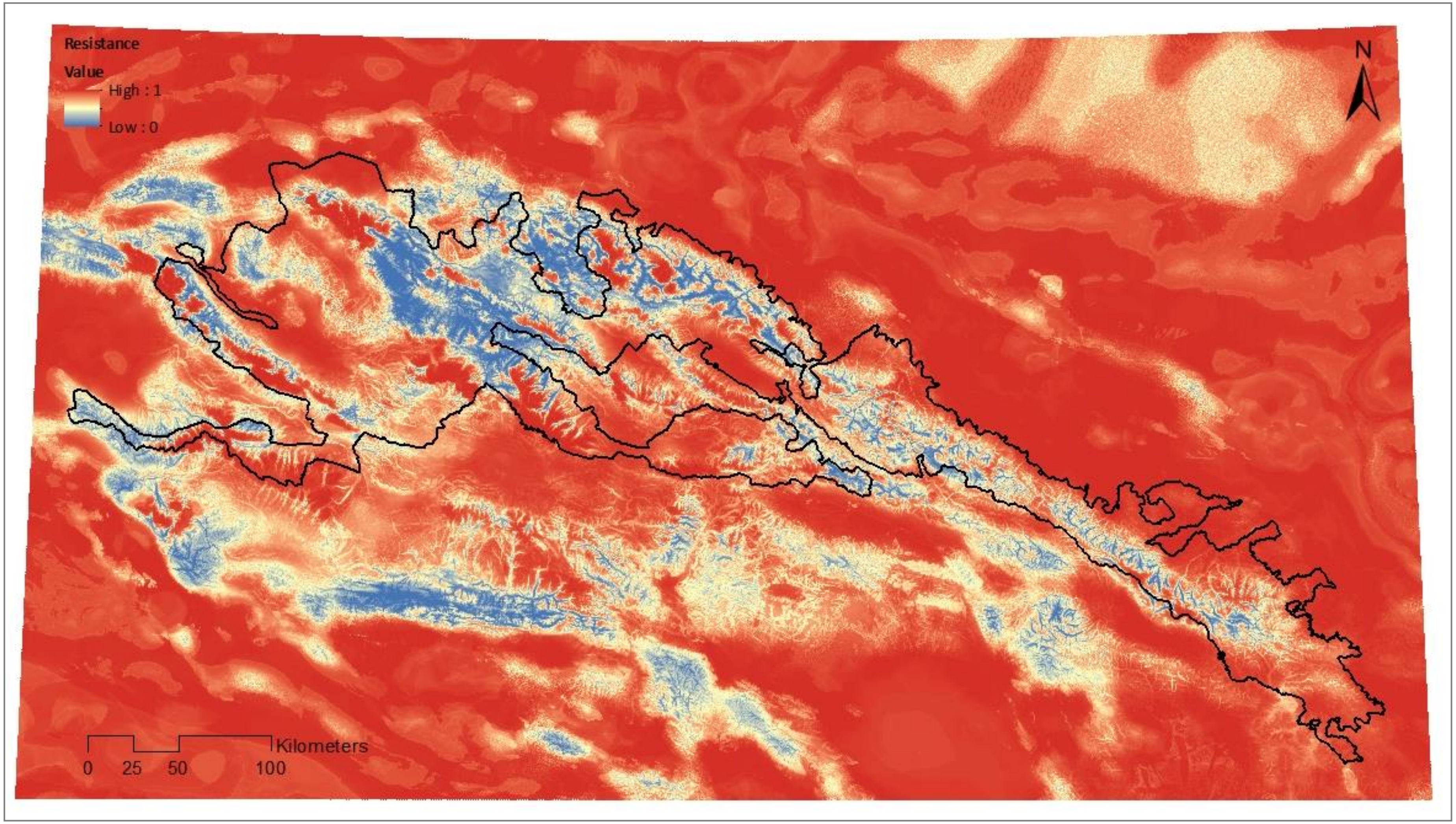

Figure 5.10 Resistance surface with 1000 based value exponential transformation. Resistance values increases from low (blue) to high (red).

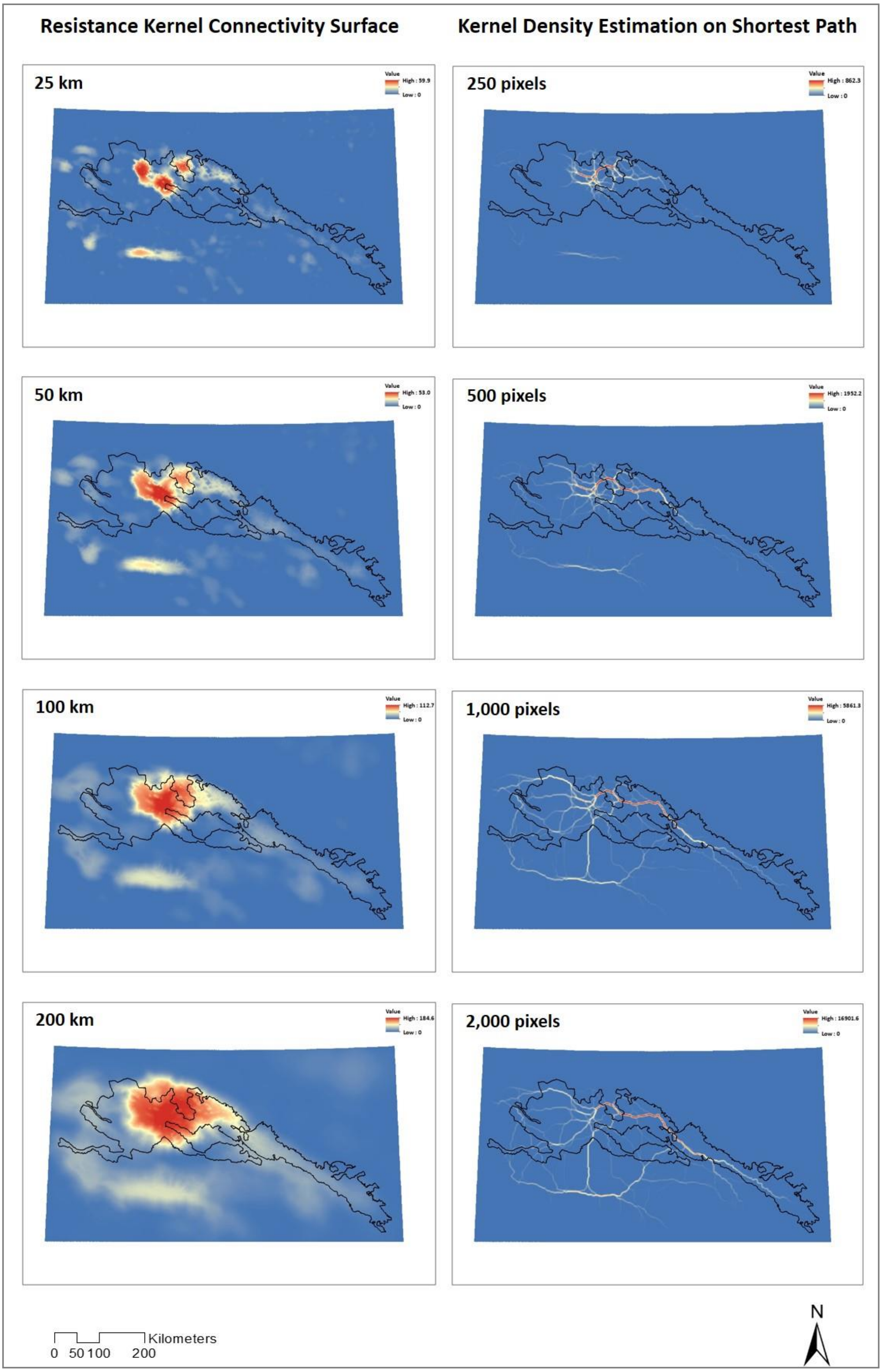

Figure 5.11 Resistance Kernel connectivity surface and Kernel density estimation on shortest path with multi thresholds based on low level resistance in Qilian Mountain National Park, China.

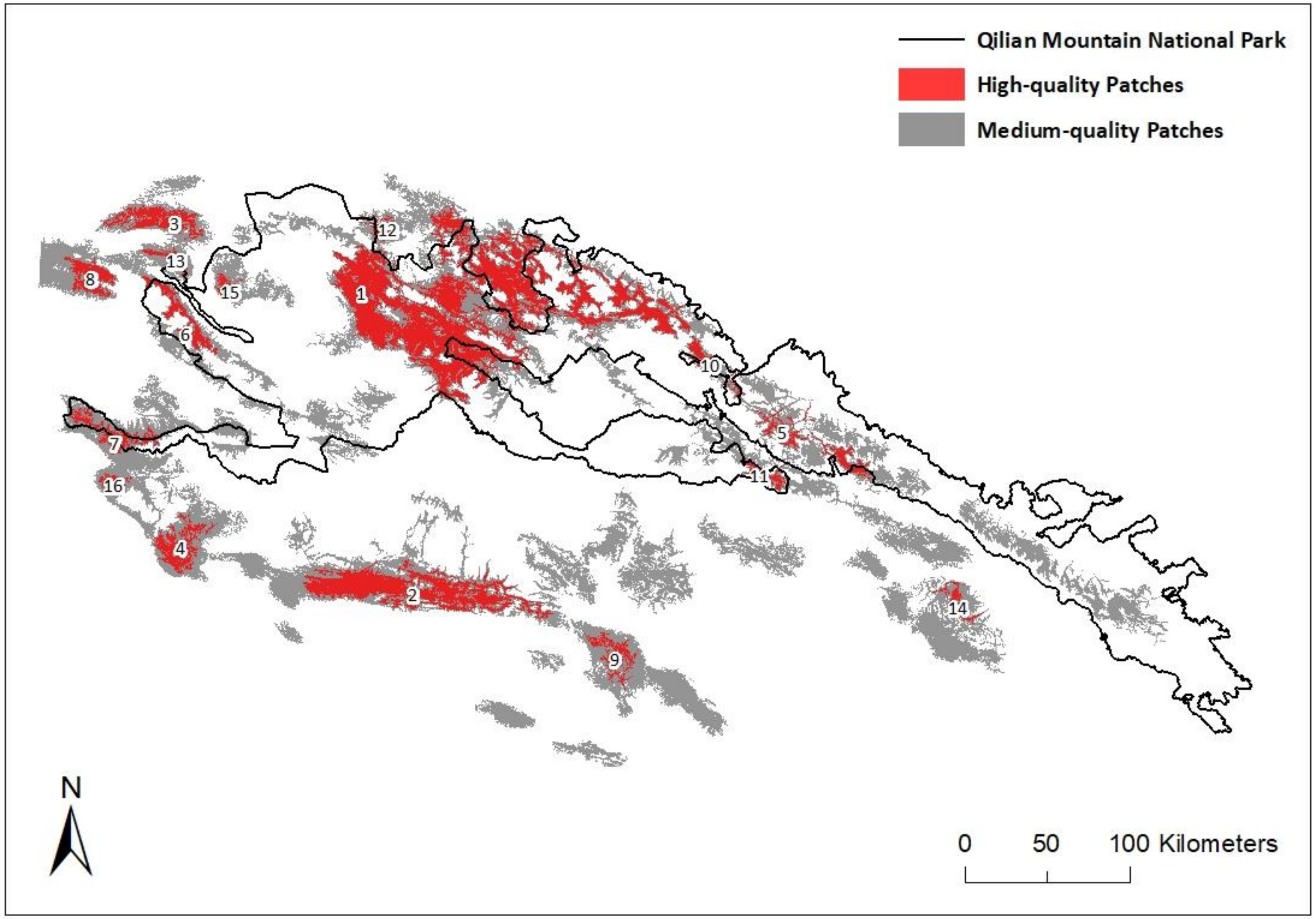

Figure 5.12 High and medium-quality snow leopard habitat patches identified in the area of Qilian Mountain National Park, China.

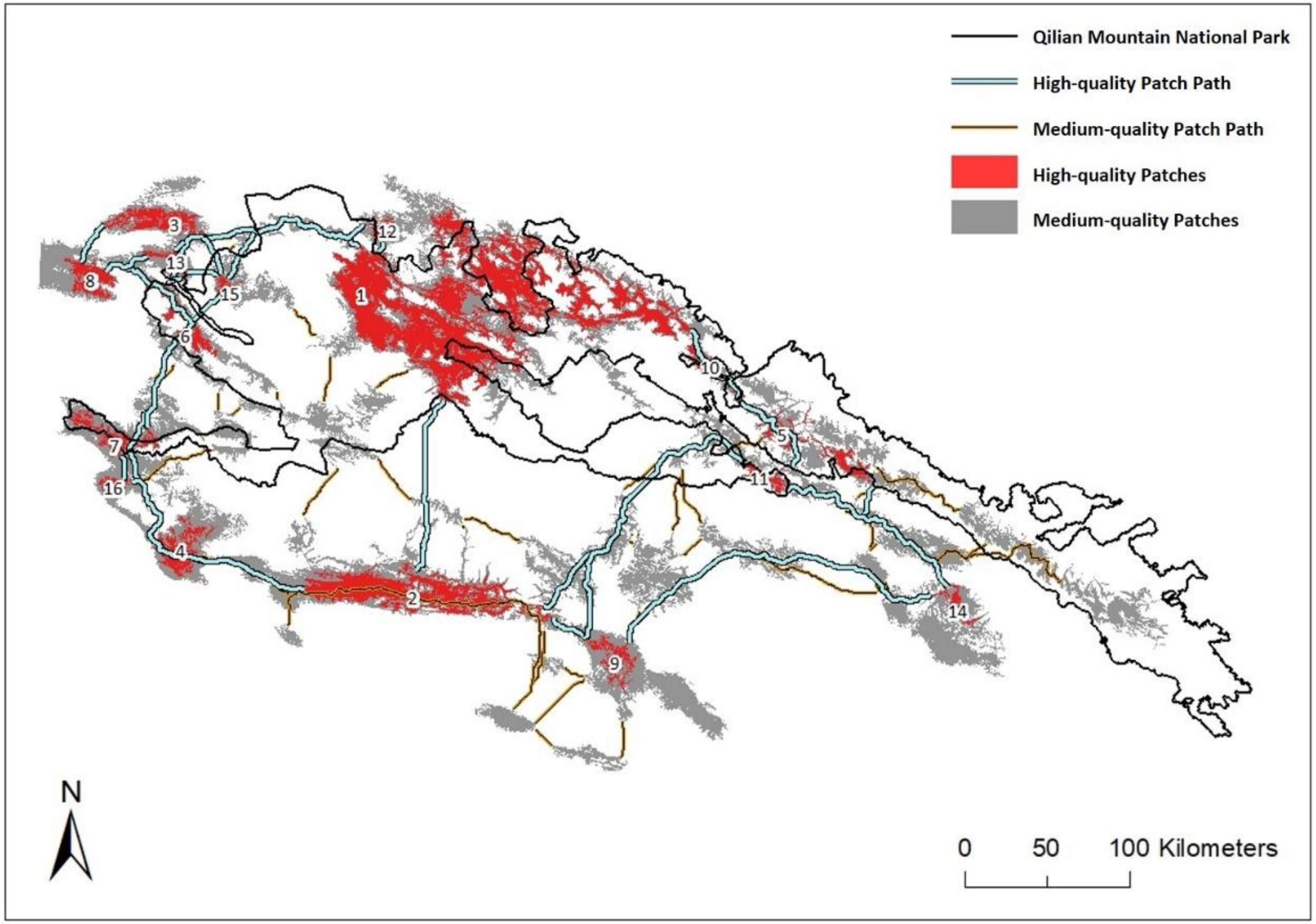

Figure 5.13 Least cost paths between high-quality and medium-quality snow leopard habitat patches in Qilian Mountain National Park, China.

5.4 Discussion

In this study, three algorithms of species distribution models were employed to predict snow leopard distribution in QMNP and surrounding areas. The results from three methods showed commonalities and differences. Results from the three SDMs showed that, areas in the mid-western of QNNP, including Shulenansnan Mountain in Gansu province and continues areas in Qinghai province, were identified as the most suitable habitat for snow leopards by all three SDMs, and also with some suitable areas distributed along the long narrow part of in the east (Figure 5.9). In the areas out of QMNP, MaxEnt and Random Forest also identified a long-shaped big suitable area in the south (Figure 5.9a-b), meanwhile GLM predicted much larger suitable areas then the other two methods (Figure 5.9c). Differences also appeared in the north-eastern region, Random Forest and GLM results presented big "cloud" of areas with certain degree of suitability (Figure 5.9b-c), but result from MaxEnt showed the area as "clean" (Figure 5.9c). The differences from the results could be caused by the variance with principles of calculation, predictors and their best scales selected, percentage of contribution of predictors, et al. There were some comparations between different SDMs (Bar Massada et al., 2013; De et al., 2020; Kaky et al., 2020; Mi et al., 2017; Shabani et al., 2016; Williams et al., 2009), but there was no conclusion of which was the best SDM, because the SDM with best performance could be different form case to case. Therefore, the ensemble of multiple models was recommended as a safer way to predict species distribution (Shabani et al., 2016). With the limited knowledge about snow leopards and limited dataset available for the analysis, this study used the model ensembled form three SDMs, to reduce the risk of selecting unproper SDM and the further impact on the following analysis on habitat patches and connectivity.

Global level snow leopard distribution modeling has been conducted (Li et al., 2016; Li et al., 2020). The result from Li et al., (2016) showed much larger suitable snow leopard habitat in Qilian Mountain. In the other study, although some parts of Qilian Mountain were defined as global snow leopard conservation landscapes with priority, detailed snow leopard global distribution map was not displayed in detail (Li et al., 2020). Furthermore, the predictors used in the above two studies were different from our case. Above reasons made it difficult to compare with the result from our study. A study discussed snow leopard distribution in QMNP by using MaxEnt with same dataset of this case (Atzeni et al., 2020). Results from multiple models in the study (Atzeni et al., 2020) showed much larger extent of suitable snow leopard habitat compared with the ensemble model of this study. Different from this chapter, the study focused on methodological exploration on meta-replication, sampling bias and multi-scale model selection on snow leopards, no variable selection process was conducted (Atzeni et al., 2020). That could be the reason of the big difference between these two studies. As a result, snow leopard distribution maps in QMNP and surrounding areas produced from previous studies were not easily comparable with this study, due to the reason of scale or methodologies. The result from this study, with multiple algorithms based on detailed dataset from the extent, will definitively have more important significance on the support of management and conservation planning.

In total six predictors were selected by all three SDMs: compound topographic index (CTI), slope position (SLP), roughness (ROUGH), annual mean temperature (TEMP), aggregation index (AI), and radius of gyration (mean area) of bare land (GYR_AM9) (Table 5.2). Another six predictors were picked by two SDMs: density of roads (DENS_rd), density of rivers (DENS_riv), dissection (DISS), focal mean of elevation (FME), percentage of landscape of farm (PLAND1), area-weighted mean of grassland (AREA_AM3) and bare land (AREA_AM9) (Table 5.2). Topographic features were highly influential in snow leopard distribution models across all scales and using all three modeling approaches. This is consistent with findings from Yanchiwan National Nature Reserve (YNNR) in Chapter 4 and with previous studies that have found snow leopard movements to be significantly determined by topography (e.g., McCarthy et al., 2005; Johansson et al., 2015; Riordan et al., 2016). The topographic details of river density and dissection were highlighted in the Generalized Linear Models at relatively fine-scale (600m and 300m respectively), as in YNNR, suggesting use of habitats that affect snow leopard predation. At wider scales, landcover features, including forest areas appear to feature, which was not the case in YNNR, where forest cover is lower than over the wider QMNP. Snow leopards tend to avoid forested areas, although some evidence of forest use has been found in the north of their range, particularly the Altai Mountains, which have a lower elevation than those ranges in the south of the snow leopard range, meaning snow leopards will need to pass through forests to move between other mountain patches (Snow Leopard Network, 2014).

The SDM results suggest that the mountain area in the mid-eastern (Shulenanshan in Gansu and the continuous area in Qinghai) is the biggest and most important snow leopard habitat in the region. The results of resistance kernel connectivity surface and kernel density estimation on shortest path also revealed that the central area was potentially acting as activity center. Therefore, the biggest patch could be a population source and “pump” individuals to the patches around through the well-developed path network. This hypothesis was supported by the evidence from genetic analysis of snow leopard scats across the QMNP and surrounding areas (Atzeni et al., 2021, submitted). It was noticed that some parts of the biggest high-quality areas (in the middle) were excluded from the national park range. This could be mainly due to the existence of a large iron ore called the Tiejingshan Iron Deposit, which was discovered in 1955 with over 400 million tons of iron ore (Shaofeng et al., 2014). The Jingtieshan Iron Deposit is one of the most famous iron mines in China with the largest production scale and the highest mechanization degree. A railway was built to connect the iron deposit with outside. In the meantime, a provincial highway crossed through the area as well. Therefore, this area was excluded from QMNP range possibly due to the above reasons.

Another big high-quality snow leopard habitat patch was identified in the south outside of the QMNP (Figure 5.12, patch 2). The mountain of patch 2 was called “Zhongwunongshan” Mountain, located in Delingha, Qinghai Province. This patch was isolated with 250 pixels threshold but connected with the main part in the park with threshold of 1,000 pixels and above (Figure 5.11). The QMNP located in the northern edge of Qinghai-Tibet Plateau. The Qaidam Basin in the south acts as a barrier for the connection between the national park with the main part of Qinghai-Tibet Plateau (Riordan et al., 2016). The high-quality patch 2 and surround patches may play the role of bridge or step stones for the snow leopard population communication between the national park and the main part of Qinghai-Tibet Plateau. At present, the Zhongwunongshan Mountain contains a Baishushan Forest Geopark of 1,000 km^2, with the major function of providing places for recreation and relax for the public. No snow leopard survey has been conducted in the area so far, but two snow leopard presence information were recorded in 2020, including a directing sighting by local herder (cellphone videos) (Chinanews, 2020a), and camera trap videos with camera trap set by photography enthusiast (Chinanews, 2020b). Those reports indicated the potential occupation by snow leopards in the Zhongwunong Mountain. A rapid assessment or systematic survey is recommended and will be important to identify the snow leopard distribution. And further, the role of the area in snow leopard population communication between QMNP and the main part of Qinghai-Tibet Plateau can be explored by employing genetic biology methods.

Based on the results from this study, following suggestions on study, conservation and management planning and practice were provided:

a) The use of models at multiple scales, used across different extents and data collection intensities, between YNNR and QMNP, demonstrates their application to provide wide-ranging insights for snow leopard. This is important for a species that ranges over 2.6 million km^2 and for which obtaining robust data from the field has always proven challenging. The consistency between models, across techniques, spatial scales and study areas gives some confidence that these results at least provide a reasonable insight into the use of habitats by snow leopard in this part of their range. As previously discussed, the application of these results to connectivity and snow leopard movement through these environments is also vital to ensuring effective management in protected areas and beyond. Snow leopard are well known to be able to cross large open spaces (Riordan et al., 2016; Riordan and Shi, 2016) and perhaps even more densely human populated areas (McCarthy et al., 2005), but their reliance on ambush predation as a principle method of hunting relies on access to complex rocky areas, as evidenced by the consistency with which topographic features appeared in all models.

b) This combination of landscape features within snow leopard habitats means that they need large-scale complexity that is often threatened by human activities. As well as pathways along which animals are able to move, disperse and find mates, snow leopards also require habitat patches in which to find food that are sufficiently large to potentially maintain a number of individuals. As highly specialized and adapted top predators in this low productivity ecosystem, these patches might be necessarily large, often beyond the extent of smaller protected areas.

c) Result of least cost path analysis showed that most of the high-quality patch paths went through medium-quality patches (Figure 5.13), indicating the potential step stone function of the medium-quality patches for snow leopard individuals' dispersal. The principle of conserving high-quality patches as population source, and conserving medium-quality patches as dispersal step stones, would be important in conservation and management planning and practice in QMNP.

d) In the "Overall Planning of Qilian Mountain National Park (Draft for comments)" (National Forestry and Grassland Administration of China (National Park Administration of China), 2019; no known updates since then), the following conservation and management activities will be conducted: 1) promoting the prohibition of grazing with an area of 3,640 km^2, including 2,640 km^2 in Gansu and 1,000 km^2 in Qinghai. Promote the seasonal rotational grazing with an area of 2,740 km^2, including 1.940 km^2 in Gansu and 800 km^2 in Qinghai.) Conduct 200 km^2 habitat restoration for snow leopards and other wildlife, including 100 km^2 in Gansu and 100 km^2 in Qinghai. 3) Carry out the wildlife corridor connection project, remove grassland and forest farm fence 7,000 km (5,000 km in Gansu and 2,000 km in Qinghai), and build 3,000 wildlife corridors within the QMNP. Due to the lack of some key basic information, for example, the layers of grazing area, depredated habitat range, distribution of fences et al., we couldn't provide more detailed suggestions on grazing management, habitat restoration and wildlife corridor connection project. However, through this study, key areas of snow leopard activity, medium and high-quality habitat patches, and the linkages between patches had been identified in QMNP and surrounding areas. Those planned conservation and management activities will be more efficient and focused with the important outcomes from this study, contributing to make better usage of limited resources in management and conservation in QMNP.

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Chapter 6: Discussion

The overall aim of this research is to explore the snow leopard ecology from micro-level to macro-level within the extent of Qilian Mountain National Park and contribute to the management and conservation planning and practice of the national park. In this study: systematic camera trapping surveys, combined with spatial explicit capture-recapture analysis were used, to estimate snow leopard density at the study site (chapter 2); multiple algorithms of Species Distribution Models (SDMs) were applied, to predict the snow leopard habitat at national nature reserve level (chapter 3); snow leopard habitat patches with good quality and corridors connecting those patches in Yanchiwan National Nature Reserve were identified (chapter 4); the snow leopard distribution, habitat patches and linkage analysis were upgraded from nature reserve level to national park level, and finished the snow leopard landscape-level ecological analysis for the first time in China (chapter 5); and finally, suggestions on management and conservation planning of Yanchiwan National Nature Reserve and Qilian Mountain National Park were provided, based on the results obtained from this research (chapter 2-5).

As the final section of the thesis, this chapter summarized the findings of this study in Yanchiwan National Nature Reserve, Qilian Mountain National Park and areas around, as the first case of snow leopard ecological study in national park level landscape in China. The discussion then took a wider view on the opportunities and suggestions on the further step studies in the area. Finally, the application to conservation and management of this study was discussed.

6.1 Limitations of this study and opportunities for future research

6.1.1 Limitations of this study

Whilst this thesis has provided important new insights on snow leopard ecology from micro to macro scale in Qilian Mountain National Park, and will perform as important scientific basis of management and conservation planning and practice in QMNP and surrounding areas, there are some limitations to this research.

Density of wild and domestic prey could be a key covariate in the models of snow leopard density estimation (Sharma et al., 2021). The best way at present to acquire reliable density information about wild and domestic prey could be conducting systematic wild prey density estimation survey (like using double-observer method), and having livestock census and grazing range survey. The prey survey area extent should be big enough to cover the buffer of the study area (so called "mask" in SECR). Due to the multiple reasons including survey planning, time and resource limitation et al, no such wild and domestic prey density survey could be conducted. In such a case, prey information from camera trapping was extracted and used in the snow leopard density estimation models as covariates. Although this was not the most ideal and precise prey covariates, it's the best use of the prey data we have. It is recommended to the QSNP management authority that prey and livestock surveys are carried out with urgency. Likely impacts of possible over grazing as well as effects of fencing should be taken into account in ongoing management planning.

The lack of key layers of human activities and disturbances at large scale were a further limitation here. Snow leopard distribution, key patches and linkage paths were identified in chapter 3 and 4. Layers of fence and village grazing areas in Yanchiwan National Nature Reserve were produced and used in the analysis. With such important background information, generalized linear model identified the potential negative impact of fence on snow leopard distribution, and two most important but also highly vulnerable area for snow leopard linkage were identified with success. Outputs of the impact of human disturbance on snow leopard ecology would be critical for managers to make targeted and adaptive management and conservation plans and practices (Alexander et al., 2015; Johansson et al., 2015; Karimov et al., 2018). It's not achievable without the key layers of human activities and disturbances. In the case of QMNP, efforts were made to get the layers of fence, grazing, mining and other human-included disturbance in the extent of QMNP and surround areas, but had no success. Therefore, the study and discussion on snow leopards in QMNP were restricted within the aspects of topography, climate and landcover with landscape and class levels.

Our knowledge on snow leopard movement and dispersal ability is still very limited, especially those ecological features could be remarkably different from place to place (Grönberg, 2011; Johansson et al., 2015; McCarthy et al., 2005, 2010; Poyarkov et al., 2020). In this study (chapter 3-5), due to the lack of information on movement and dispersal ability of snow leopards in QMNP, multiple plausible thresholds were used to simulate different scenarios. Although the multiple scenarios simulation and analysis increased the workload and the output produced were less targeted, this could be the best way so far to explore snow leopard ecology in the stage with some key information missing. However, the consistency of the results here offers some reassurances.

Based on the data collected from 2013 to 2018 across the QMNP extent, we got good results of models on distribution, movement, key patches and linkages. The performances of models will be further improved with larger snow leopard presence location sample size. With the ongoing progress of systematic snow leopard survey in QMNP, presence information of snow leopards has been flowing into the database. The quantity and spatial distribution of species presence locations has been improved a lot. We have reasons and confidence to expect further studies with much larger dataset and produce results with better model performance and precision.

6.1.2 Opportunities for future research

As mentioned above, this research has been limited by the lack of snow leopard movement and dispersal information in QMNP. Before 2021, China had a blank page on snow leopard radio or satellite telemetry collaring. As the country with most snow leopard habitat and population, China should catch up on the studies with snow leopard collaring. From February to April, two snow leopard (one adult male and one adult female) individuals were successfully captured and satellite collared in YNNR by the joint team of Wildlife Institute of Beijing Forestry University, Yanchiwan National Nature Reserve Administration and Eco-Bridge Continental (EBC, a local wildlife conservation NGO) (communication with Wildlife Institute, Beijing Forest University). Two snow leopards were captured in Yemananshan Mountian and Northern part of Shulenanshan Mountain.

In March 2021, an adult male snow leopard was found appeared in a local herder's backyard which adjacent to a primary school in Xitan Village of Menyuan Country, Qinghai Province. This individual was then be captured, collared and released by the same team of Wildlife Institute of Beijing Forestry University and Eco-Bridge Continental. The following tracks after the release indicated snow leopards have been in good conditions with collars (personal communication with EBC). The success of snow leopard collaring in China opened a new window which allow us to have much wider view and much more possibilities on snow leopard research in China. Specific to this study and area of QMNP, the data from these three individuals will greatly increase the understanding on snow leopard movement and dispersal, which is critically important to increase the precision of the models improved.

This study was focused on macroecology, however, the snow leopard distribution, key patches and linkages identified in this study, can provide thoughts and ideas to discuss the spatial genetic diversity pattern in QMNP connectivity. Such knowledge can provide insights into a populations' genetic status, but it's particularly scarce for the snow leopard. Based on the faecal samples used in this study, the analysis on spatial genetic diversity pattern of snow leopards in the Gansu part of QMNP was conducted (Atzeni et al., 2021, submitted). Results from such research could be used to verify the supposed potential isolation between key patches of snow leopards. Currently the snow leopard spatial genetic diversity study only covered the Gansu part of QMNP, with the increasing faecal samples from bigger spatial extent, the further analysis would reveal the snow leopard genetic diversity patterns in QMNP, and results from this thesis would provide important reference in the discussion.

6.2 Applications to conservation and management

The major application of this study, was providing solid scientific foundation to help Nature Reserves, Qilian Mountain National Park, and surrounding areas to make targeted and adaptive conservation and management plans. In chapter 3 and 4, key habitat patches, linkage paths, and important areas for connections were identified. With such information, while conducting fence removing, grazing banning and other conservation and management projects, managers of nature reserve then could set up the priorities of operation areas to ensure the resource utilization efficiency and conservation effectiveness. Also, for the coming snow leopard survey and monitoring, results from this study would be very help in identify the study areas.

Results from this study will certainly benefit the conservation and management in QMNP. As a newly established national park, a lot of conservation and management projects had been planned in general. For example, according to the "Overall Planning of Qilian Mountain National Park (Draft for comments)" (National Forestry and Grassland Administration of China (National Park Administration of China), 2019), in total 3,000 wildlife corridors will be built as a part of the wildlife corridor connection project. The effect of the project cannot be ensured without good decisions on the locations of corridors, and this study demonstrates how to make the corridor location decisions.

The available spatial layers for railways, and different levels of highways were overlapped with the species distribution model, key patches and linkage paths produced from this study, in the extent of QMNP and surrounding areas (fig. 6.1). Three key areas (Area A, B and C) of snow leopard linkage within the QMNP were preliminary identified according to the intersection between the snow leopard linkage paths with railway and highway. In Area A, the existence of the Tiejingshan Iron Deposit, railway and provincial highway, could possibly increase the risk of isolate the largest and most important snow leopard habitat patch, high-quality patch 1, into two parts from the middle. Patch 5 and 10 were important for connectivity (chapter 5), however, linkage between the two patches is intersected by a provincial highway in key Area B. Within Area C, connections between the "tail" of the park in the east and the main part in the middle are also at risk of being cut off by national highway and railway.

The above example is only a limited application in overall conservation and management planning. According to the "Overall Planning of Qilian Mountain National Park (Draft for comments)" (National Forestry and Grassland Administration of China (National Park Administration of China), 2019), the following conservation and management activities will be conducted: 1) promoting the prohibition of grazing with an area of 3,640 km^2, including 2,640 km^2 in Gansu and 1,000 km^2 in Qinghai. Promote the seasonal rotational grazing with an area of 2,740 km^2, including 1.940 km^2 in Gansu and 800 km^2 in Qinghai. 2) Conduct 200 km^2 habitat restoration for snow leopards and other wildlife, including 100 km^2 in Gansu and 100 km^2 in Qinghai. 3) Carry out the wildlife corridor connection project, remove grassland and forest farm fence 7,000 km (5,000 km in Gansu and 2,000 km in Qinghai), and build 3,000 wildlife corridors within the QMNP. Although some of the key layers (grazing area, depredated habitat range, distribution of fences, etc.) were unavailable for this study, the output from this study would be important reference when making the conservation and management plan.

Finally, from the analysis, Zhongwunongshan Mountain-another potential important large area snow leopard high-quality patch (patch 2 in chapter 5) located in Delingha, Qinghai Province, was identified. This area may play the role of bridge or step stones for the snow leopard population communication between the national park and the main part of Qinghai-Tibet Plateau. No systematic snow leopard survey and conservation had been conducted in the region. The results of this thesis can be used to highlight and promote the need for surveys and conservation effort in Zhongwunongshan Mountain.

Based on the results of this study, the following conservation and management recommendation were provided for the management bureaus of Yanchiwan National Nature Reserves, Qilian Mountain National Park, and State Forestry and Grassland Administration:

a) Identify the priority areas for measures related to reduction of grazing extent and intensity, and removal of fences. High quality patches with key ecological functions (for example, patch 1 as population source, and patch 7 as a stepping stone - see table 4.2 and figure 4.5) are priority areas for the species when reducing grazing extent and intensity. Similarly, area A and B (figure 4.8), which were identified as key areas for population connectivity are potentially seriously affected by fences, and should be prioritized regions for fence removing activities.
b) Within Qilian Mountain National Park, patch 1 (figure 5.12) was the largest high quality area for snow leopard, which may play the role as the snow leopard population source to "pump

out” individuals to other patches around. Therefore, this patch should be the core area with utmost importance for the national park. Strick management should be implemented in that region to ensure the survival of snow leopard in this area and the park.

c) Patch 5 and 10 in QMNP represent significant importance for snow leopard movements and patch connectivity (table 5.6, figure 5.12), but the highway between them may set a serious barrier for the linkage. Similarly, area C (figure 6.1) also potentially showed strong negative impact on connections produced by highways and railways. Those areas are suggested as the important regions to be considered for the proposed wildlife corridor construction project in the QMNP.

   The remarkable large high quality path 2 (figure 5.12) and the patch 4 and patch 9 nearby, were identified from this study. They are located outside the QMNP, and may play the role of bridging or stepping stones for the snow leopard population connectivity between the national park and the main part of Qinghai-Tibet Plateau. At present, those areas are under no strict management, and no snow leopard survey have been conducted there. These areas merit priority attention for future surveys and other conservation activities. Systematic surveys using the same methods as this study will provide essential information of snow leopard there, upgraded conservation and/or management measures can be applied if there are evidences reveal the importance in snow leopard survival and conservation of the region.

6.3 Conclusion

As the first case of snow leopard ecological study in national park level landscape in China, this study focus on the study spatial extent from micro level to macro level, covered micro study site (400 km^2) to Yanchiwan National Nature Reserve, and finally extent to Qilian Mountain National Park and areas around. This thesis estimated the snow leopard density in the core habitat area, and discussed the impact of prey and geographic covariates on density estimation models. Snow leopard distribution, resistance surfaces, key patches, activity surfaces, and linkage paths were analyzed based on the dataset of snow leopard presence from multiple methods and different years. Results from the thesis increased the knowledge about snow leopard ecology at multiple spatial scales, and will provide important reference for the ongoing conservation and management planning and practices in Qilian Mountain National Park.

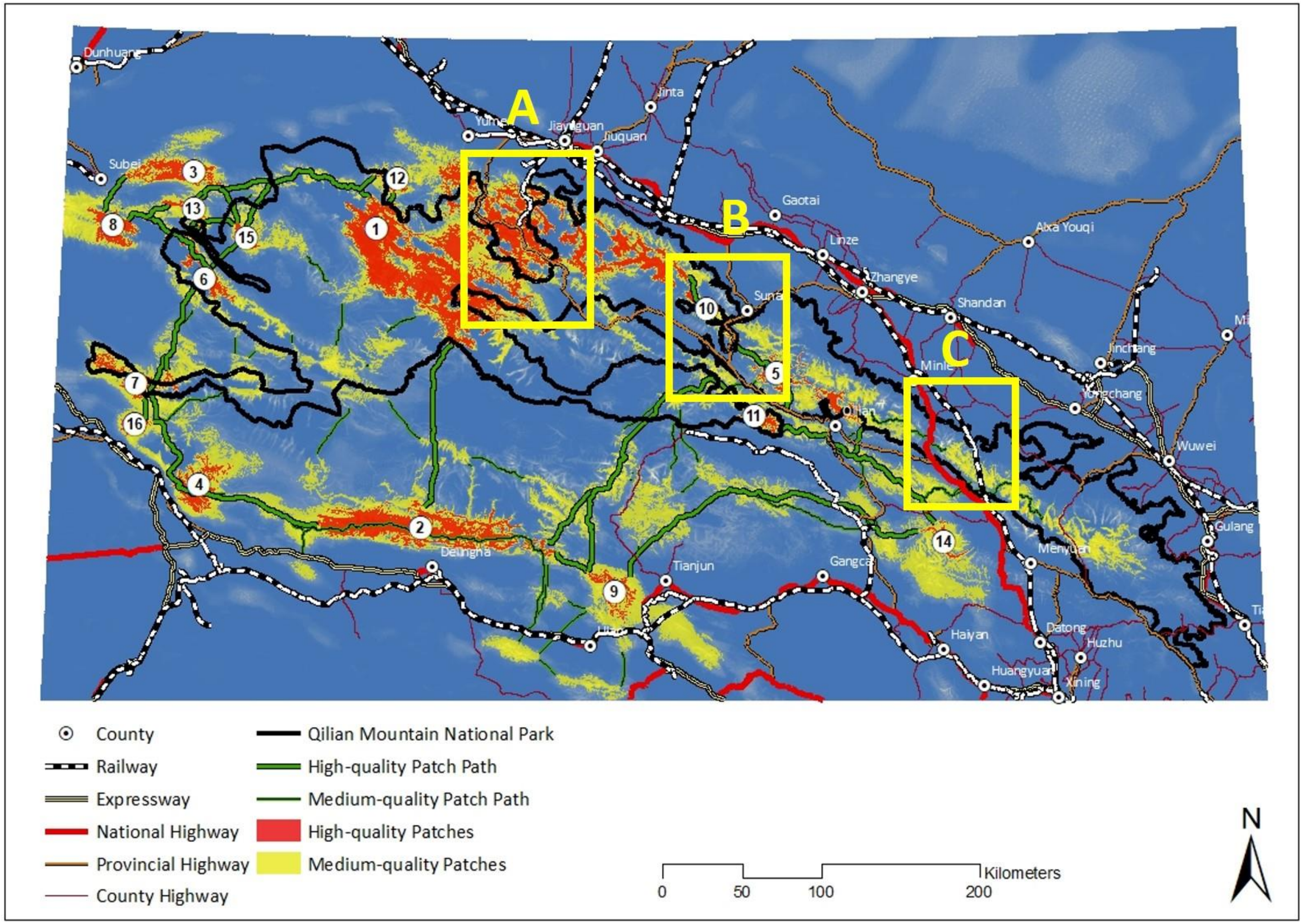

Figure 6.1 Key areas with potential high vulnerability from railways and multiple levels of roads in QMNP and surrounding areas (in frames).

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