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Population dynamics of blue sheep *Pseudois nayaur* in Ningxia Helan Mountain National Nature Reserve, China

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Abstract. Long-term studies of population dynamics are important for conservation biology and wildlife management. We conducted 2790 line transects and observed 12516 blue sheep *Pseudois nayaur* from 2004 to 2009 in the Ningxia Helan Mountain National Nature Reserve of China, and found that the blue sheep population size fluctuated from 12375 in 2004 to 8188 in 2006 then 13344 in 2009, but did not ascend or decline continuously. Population size was positively correlated with the number of rainy days during the previous year. We divided the reserve into high, middle and low density areas according to average sheep encounter rates, and found that in different density areas blue sheep had different population dynamics, sex ratios and group sizes. Ratios between females and males, females and juveniles, and adults and juveniles were not different across six years in all three density areas. Group sizes increased with population size. We deduce that the blue sheep population will not increase or decrease constantly in the reserve, and that managers should manage varying density areas differently to maximize the conservation of blue sheep.

Key words: line transect, encounter rates, density area, rainy days

Introduction

Long-term studies of population dynamics are important to understand life-histories, population ecology, wildlife management and conservation biology (Caughley 1977, Tuljapurkar & Caswell 1997). Because the population size of many species of large herbivores can be a useful indicator for their conservation (Gaillard et al. 1998), wildlife managers and conservation biologists often try to measure wildlife population dynamics to evaluate management protocols (Liu et al. 2008). However, long-term and large-scale surveys are not an easy task due to budgetary and human resource constraints (Gusset & Burgener 2005) and as a result little work has been done to monitor the long-term population dynamics of large herbivores in China.

As an endemic species in the Tibetan Plateau and its surrounding mountainous regions (Liu et al. 2008), blue sheep *Pseudois nayaur* are distributed in large areas of China, Bhutan, India, Myanmar, Nepal, Pakistan and Tajikistan, but the population trend is unknown, and are categorized as a Least Concern species by the IUCN Red List (Schaller 1998, Hilton-Taylor 2011). Blue sheep also listed as a second grade nationally protected animal in China (Hu 2007), and in the Helan Mountain, over 100000 livestock emigrated from this region since 1997 (Wang et al. 2005), that released the competition with livestock, blue sheep population size increased from 1470-1770 in 1983 to 5325-9510 in 1997, and then 12178 in 2003 (Liu et al. 2007).

Helan Mountain lies within the blue sheep distribution area and is located between the Yinchuan and Alashan

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Plateaus in northern China. Surrounded by farmland, cities and deserts, Helan Mountain is isolated from other distribution areas of blue sheep (Wang et al. 1999, Luo et al. 2010). Blue sheep population dynamics in this area is shaped by birthrate and mortality rate, not by immigration and emigration (Liu et al. 2007). Population dynamics of blue sheep may not be influenced by predators and competitors because predators such as the wolf *Canis lupus* and leopard *Panthera pardus* have become extinct (Wang & Schaller 1996), and blue sheep are dominant to the only other large herbivore in the region, red deer *Cervus elaphus* (Luo et al. 2010). Furthermore, no studies have reported disease and parasitic effects on blue sheep population dynamics, and because vegetation is sparse on Helan Mountain (Di 1986), effective observation and estimation of blue sheep populations is possible (Liu et al. 2008). For these reasons we are able to focus on fewer potential factors influencing blue sheep population dynamics in this special region.

Blue sheep is a key species in the Ningxia Helan Mountain National Nature Reserve and research has been conducted within this reserve on population size (Liu et al. 2007, 2008), group size (Liu et al. 2009) and in developing a life table (Liang & Wang 2000, Wang et al. 2005). Blue sheep are not distributed evenly across the reserve (Liu et al. 2007) and it is known that ungulates population density often affects population dynamics (Bonenfant et al. 2009). As have been monitoring this species since 2004, we want to know whether the population was still in expansion or have reached a plateau, oscillating around the carrying capacity of the reserve. There is spatial heterogeneity in water resources, forest cover and levels of anthropogenic disturbances across the reserve (Di 1986), so some spatial heterogeneity related to blue sheep density and demography is also expected (Liu et al. 2007). It is helpful for developing management to understand the variability of local dynamics and density of blue sheep in the reserve. Population size of large herbivore inhabiting arid or semiarid areas is significantly affected by meteorological factors (Illius & O'Connor 1999), and with several confounding factors were ruled off (no migration, no predators, few competition, no parasite), Helan Mountain is a quasi-experimental place to assess climatic effects.

We monitored the blue sheep in numbers of valleys in the Ningxia Helan Mountain National Nature Reserve from 2004 to 2009. According to the mean encounter rates of each valley, we categorized the reserve into high, middle and low density area. We estimated the population size in the reserve each year by Distance 6.0, set out to explore population dynamics and the variability of population structure in different parts of this important reserve, also their correlations with the number of rainy days during the previous year. We also assess blue sheep population status and provide suggestions on how to better manage this population.

Material and Methods

Study area

Our fieldwork was carried out from January 2004 to December 2009 in the Ningxia Hui autonomous region of China with approval from the Ningxia Forestry Department and Ningxia Helan Mountain National Nature Reserve (38°21′-39°22′ N, 105°44′-106°42′ E) (Fig. 1). The reserve covers 2062.5 km^2 of mountainous and rocky terrain at elevations of 1000-3556 m above sea level. The highest mean daily temperature occurs in July, ranging from 19.5-25.4 °C, and the lowest in January, ranging from –8.9 °C to –6.4 °C. Typical temperate arid and semi-arid upland vegetation types are dominated by *Stipa breviflora*, *Ajania fruticulosa*, *Prunus mongolica*, *Picea crassifolia*, *Pinus tabulaeformis*, *Salix cupularis*, *Caragana jubata* and *Arenaria* spp. (Di 1986).

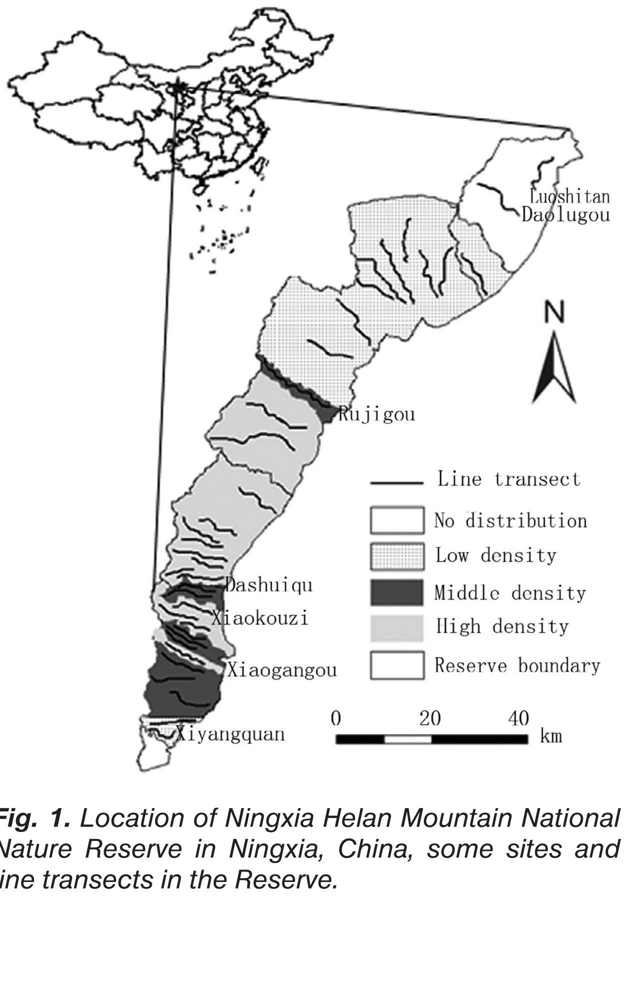

Fig. 1. *Location of Ningxia Helan Mountain National Nature Reserve in Ningxia, China, some sites and line transects in the Reserve.*

Table 1. *Encounter rates ± SD, the length and the number of line transects in each valley from 2004 to 2009, and density groups categorized of each valley. A blank indicates no survey or insufficient data. Numbers in brackets are the line transects surveyed in this valley in this year.*

Valleys	Length (km)	Encounter rates (Means ± SD)							Density groups
		2004	2005	2006	2007	2008	2009	Total	
Luoshitan	8.87		0.00 ± 0.00(32)	0.00 ± 0.00(15)	0.00 ± 0.00(12)	0.00 ± 0.00(28)	0.00 ± 0.00(38)	0.00 ± 0.00(125)	No
Daolugou	7.68		0.00 ± 0.00(24)	0.00 ± 0.00(31)	0.04 ± 0.14(13)	0.00 ± 0.00(23)	0.00 ± 0.00(34)	0.00 ± 0.05(125)	No
Dafenggou	5.31		0.00(1)		0.00 ± 0.00(3)	0.03 ± 0.11(11)	0.03 ± 0.11(12)	0.03 ± 0.10(27)	Low
Chaohu	5.82		0.09 ± 0.10(4)		0.14 ± 0.17(6)	0.00 ± 0.00(3)	0.00 ± 0.00(13)	0.05 ± 0.10(26)	Low
Dawukou	9.22		0.20 ± 0.56(16)	0.04 ± 0.11(21)	0.01 ± 0.03(18)	0.05 ± 0.14(18)	0.04 ± 0.18(31)	0.06 ± 0.25(104)	Low
Hongguozi	4.56			0.10 ± 0.50(33)	0.14 ± 0.29(14)	0.06 ± 0.17(25)	0.11 ± 0.32(28)	0.10 ± 0.36(100)	Low
Guidegou	5.76		0.17 ± 0.32(23)	0.20 ± 0.25(13)	0.00 ± 0.00(4)	0.00 ± 0.00(13)	0.00 ± 0.00(8)	0.11 ± 0.24(61)	Low
Wangquangou	6.31		0.16 ± 0.61(15)	0.25 ± 0.59(7)	0.36 ± 0.67(10)	0.05 ± 0.17(14)	0.30 ± 0.41(8)	0.20 ± 0.51(54)	Low
Yangchigou	7.42		0.23 ± 0.53(13)	0.16 ± 0.32(15)	0.35 ± 0.35(13)	0.25 ± 0.33(14)	0.45 ± 0.78(9)	0.27 ± 0.46(64)	Low
Baijigou	6.89		0.18 ± 0.41(18)	0.00 ± 0.00(8)	0.05 ± 0.15(8)	0.19 ± 0.15(10)	0.70 ± 0.67(15)	0.27 ± 0.48(59)	Low
Xiyangquan	3.88	0.00 ± 0.00(1)	0.80 ± 1.08(10)	0.43 ± 1.33(12)	0.06 ± 0.17(9)	0.21 ± 0.34(6)	0.00 ± 0.00(2)	0.37 ± 0.94(40)	Low
Shanzuimiao	4.10	0.12 ± 0.34(8)	0.21 ± 0.36(7)	0.24 ± 0.34(2)	1.03 ± 3.00(9)	0.34 ± 1.04(18)	0.30 ± 0.46(4)	0.41 ± 1.44(48)	Low
Rujigou	8.78			0.44 ± 0.92(15)	0.16 ± 0.36(18)	0.07 ± 0.16(20)	0.93 ± 0.84(24)	0.43 ± 0.73(77)	Low
Xiaowangquangou	5.87		0.34(1)	0.36 ± 0.40(9)	0.27 ± 0.23(12)	1.08 ± 1.21(3)	0.58 ± 0.54(17)	0.47 ± 0.53(42)	Low
Gangou	3.89	0.75 ± 1.46(13)	0.79 ± 0.93(15)	0.36 ± 0.72(29)	0.45 ± 0.80(27)	0.47 ± 1.55(17)	0.50 ± 1.11(22)	0.51 ± 1.06(123)	Middle
Dushugou	3.79	0.15 ± 0.30(7)	0.09 ± 0.19(9)	0.00(1)	0.69 ± 0.65(8)	2.04 ± 2.70(4)	0.53 ± 0.76(9)	0.53 ± 1.07(38)	Middle
Gaokouzigou	4.26	0.67 ± 0.78(6)	0.59 ± 0.83(2)	0.23 ± 0.47(4)	0.47 ± 0.68(5)	0.50 ± 0.42(7)	0.79 ± 1.09(8)	0.57 ± 0.73(32)	Middle
Datinggou	4.02	0.21 ± 0.40(6)	0.21 ± 0.56(7)	0.00 ± 0.00(3)	1.46 ± 4.02(15)	0.21 ± 0.51(6)	0.34 ± 0.79(22)	0.57 ± 2.11(59)	Middle
Qingyanggou	5.33	0.02 ± 0.06(10)	0.98 ± 1.89(13)	1.09 ± 1.27(18)	0.22 ± 0.47(11)	1.31 ± 1.36(8)	1.28 ± 1.56(6)	0.81 ± 1.32(66)	Middle
Yushugou	5.23	1.03 ± 1.43(5)	3.15 ± 4.46(2)	0.72 ± 2.03(8)	0.33 ± 0.45(4)	1.10 ± 1.84(4)	0.29 ± 0.40(8)	0.81 ± 1.67(31)	Middle
Xiaoshuiqu	3.25	2.31 ± 2.71(4)	1.59 ± 3.82(11)	0.43 ± 0.95(10)	0.53 ± 1.08(14)	0.65 ± 1.82(18)	0.79 ± 1.22(9)	0.87 ± 2.07(66)	Middle
Huangqikou	3.92	0.21 ± 0.54(24)	0.03 ± 0.12(23)	0.56 ± 1.25(26)	1.52 ± 2.76(35)	2.35 ± 4.33(23)	0.48 ± 0.84(24)	0.90 ± 2.32(155)	Middle
Suyukou	5.75		1.89 ± 2.31(19)	0.62 ± 0.96(29)	1.06 ± 1.46(26)	1.44 ± 4.52(23)	0.46 ± 0.64(35)	0.991 ± 2.27(132)	High
Xiaohelankou	4.27	1.76 ± 1.35(4)	1.05 ± 1.02(4)	0.35 ± 0.50(2)	1.20 ± 1.79(17)	1.01 ± 0.76(6)	0.95 ± 1.04(14)	1.10 ± 1.32(47)	High
Helankou	4.58	0.75 ± 0.67(11)	1.66 ± 2.26(16)	0.60 ± 1.61(17)	1.63 ± 1.77(31)	0.93 ± 1.24(15)	0.87 ± 0.87(21)	1.15 ± 1.58(111)	High
Xiaogangou	3.16	0.72 ± 0.57(7)	1.74 ± 3.66(6)	1.27 ± 2.78(9)	1.84 ± 2.90(6)	0.99 ± 2.18(8)	0.84 ± 1.32(6)	1.21 ± 2.33(42)	High
Xiaoshuigou	6.34		1.42 ± 2.34(12)	0.64 ± 0.94(14)	0.89 ± 1.42(22)	1.14 ± 1.85(17)	1.83 ± 2.07(31)	1.27 ± 1.83(96)	High
Dashuiqu	3.63	2.63 ± 4.99(17)	2.16 ± 3.42(13)	1.97 ± 3.83(14)	0.85 ± 2.31(35)	0.64 ± 0.96(15)	0.46 ± 0.72(24)	1.28 ± 2.94(118)	High
Zhufenggou	2.55	0.10 ± 0.18(8)	4.31 ± 1.11(2)	2.02 ± 1.54(7)	3.38 ± 5.40(8)	1.47 ± 0.81(8)	0.65 ± 0.62(9)	1.62 ± 2.68(42)	High
Dashuigou	8.78		0.91 ± 1.47(20)	1.26 ± 1.99(13)	1.34 ± 2.12(19)	1.16 ± 1.86(28)	3.02 ± 4.32(41)	1.79 ± 3.03(121)	High
Baisikou	3.52	2.60 ± 3.69(21)	2.57 ± 3.22(16)	2.62 ± 5.13(19)	1.70 ± 2.82(21)	1.94 ± 2.04(11)	1.33 ± 2.01(27)	2.07 ± 3.30(115)	High
Xifenggou	4.13		0.79 ± 1.15(23)	2.25 ± 2.34(20)	3.17 ± 3.77(21)	3.55 ± 4.84(30)	0.98 ± 1.13(27)	2.17 ± 3.28(121)	High
Chaqikou	4.36		0.27 ± 0.45(24)		2.91 ± 4.29(26)	3.29 ± 1.89(25)	3.16 ± 3.50(27)	2.45 ± 3.18(102)	High
Xiaokouzi	2.82	5.46 ± 6.13(10)	1.55 ± 2.41(14)	2.36 ± 2.24(14)	3.76 ± 3.66(18)	0.99 ± 2.12(19)	2.25 ± 1.80(26)	2.51 ± 3.23(101)	High
Zhengmuguan	3.47	4.26 ± 5.00(14)	3.60 ± 3.84(14)	1.56 ± 3.63(17)	0.95 ± 0.99(10)	1.44 ± 1.34(6)	3.46(1)	2.55 ± 3.74(62)	High
Dakouzi	2.55	1.53 ± 2.38(9)	5.49 ± 6.23(5)	1.86 ± 2.53(15)	4.06 ± 3.93(14)	4.71 ± 4.71(3)	2.41 ± 1.43(12)	2.91 ± 3.39(58)	High

Individual parts of the reserve have different rainfall and vegetation cover (Di 1986). North of Rujigou has an annual rainfall of 180 mm, high desertification and no forest, and the presence of coal mines destroyed the scattered plants. The middle region between Rujigou and Dashuiqu has an annual rainfall above 400 mm, has a rich and good coverage of vegetation and has been protected with the assistance of Germany since 1995. South of Dashuiqu has an annual rainfall of 300 mm, forest in low elevation areas were destroyed by mining prior to 1999 and forests remained scattered at higher elevation.

Data collection

As one of the most effective methods for estimating animal densities, line transect surveys are often used to monitor wildlife populations over large areas (Newey et al. 2003, Focardi et al. 2005). Similar to Liu et al. (2008), line transects were designed according to the terrain at 36 valleys in the reserve. Two trained people familiar with the area and blue sheep conducted line transect surveys and walked from the entrance to the end of the valley observing both sides of the line transect. When blue sheep were encountered, juvenile (including both juveniles and yearlings of criterion in Gaillard et al. 2000), female and male adults were distinguished by the length of body, size of horn and colour of skin (Wang et al. 1998), and their numbers were recorded respectively. Distance between the sheep (or the centre of the group if it was a group) and the observer was recorded by a rangefinder, and sighting angle between sheep and the line transect was recorded by a compass. Each line transect survey was carried out during a morning of the first third of each month at a walking speed of 2-2.5 km/h. Numbers of line transects surveyed at each valley can be found in Table 1. To avoid repetition, each transect was only surveyed in one direction. Rainfall was recorded from 2000 to 2009 at the Shitanjing weather station located in the reserve.

Data analysis

We used encounter rates to evaluate population variation. Encounter rates were calculated by dividing the number of individuals encountered in each valley by the cumulative effort (total length of the line transect) for that valley each year. The reserve was divided into high, middle and low density areas according to mean sheep encounter rates at each valley. Using the line transect which had the most blue sheep encountered in each valley, Distance 6.0 (Thomas et al. 2009) was used to get the estimated number of the reserve each year, the method can be seen in Liu et al. (2008). Data of the mean group size and encounter rate in each valley were log-transformed to fit the normal distribution. Then the general linear models (univariate) with the Bonfferroni multi-comparisons were used to analyze differences of the encounter rate and the mean group size among years and density areas (low, middle and high). We used the Kruskal-Walis H test to determine differences in sex ratio between different density areas. A Chi-square test was used to test for differences of sex ratio in each density area, the ratio of female and juvenile blue sheep and estimated population size. The effect of rainfall on herbivore populations follows a time lag (Forchhammer et al. 1998, Dickman et al. 2001) and we used Spearman correlations to detect the link between population size and the number of days with rain events in the previous year, we used linear regression to look for relationships between encounter rates and group sizes. All statistical analyses were done in SPSS13.0 (SPSS Inc. Chicago, USA).

Results

An annual average of 12516 sheep was recorded across 2790 line transects from 2004 to 2009 (Tables 1, 2). Except for one group of four blue sheep found in 2007, we did not encounter any blue sheep in Daolugou, Luoshitan and south of Xiyangquan (Table 1), so we

Table 2. *Observed number, estimated density and population size of blue sheep from line transect surveys, 95 % confidence interval of density and abundance, coefficient of variation [CV (%)] and AIC in Ningxia Helan Mountain National Nature Reserve from 2004 to 2009 (Distance 6.0, Model: Half-normal + cosine).*

Year	Observed number	Density (sheep/km^2)	Estimated number	95 % confidence interval for density	95 % confidence interval for abundance	CV (%)	AIC
2004	982	6.00	12375	2.75～13.08	5672～26978	40.4	300.59
2005	1697	5.10	10519	2.63～9.87	5424～20357	34.1	529.30
2006	1561	3.97	8188	2.51～6.27	5177～12932	23.4	581.09
2007	2715	4.42	9116	2.05～9.56	4228～19718	40.1	503.46
2008	2305	5.51	11364	3.35～9.06	6909～18686	25.5	510.07
2009	3252	6.47	13344	3.77～11.08	7776～22853	27.6	466.92

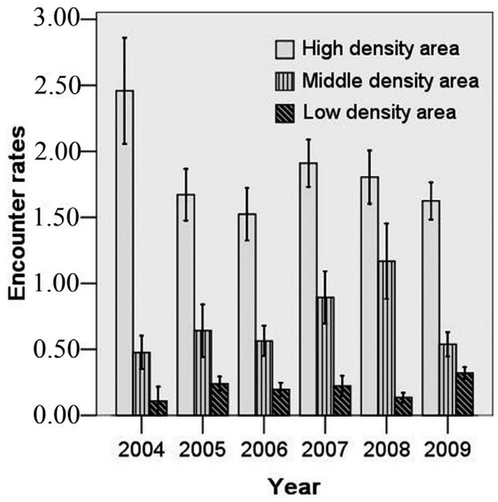

Fig. 2. *Variation in blue sheep encounter rates from 2004 to 2009 in Ningxia Helan Mountain National Nature Reserve (mean ± SE).*

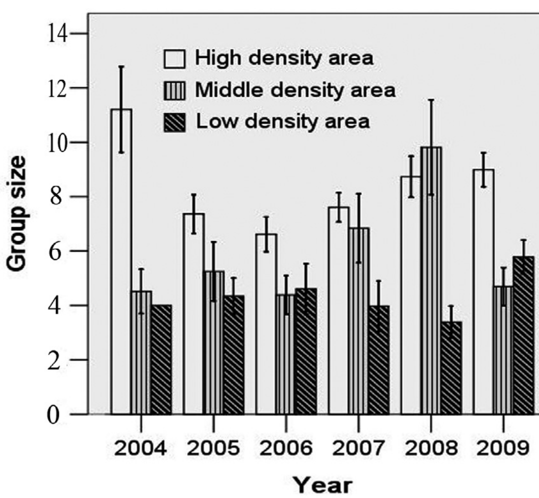

Fig. 3. *Blue sheep group size variation in Ningxia Helan Mountain National Nature Reserve from 2004 to 2009 (mean ± SE).*

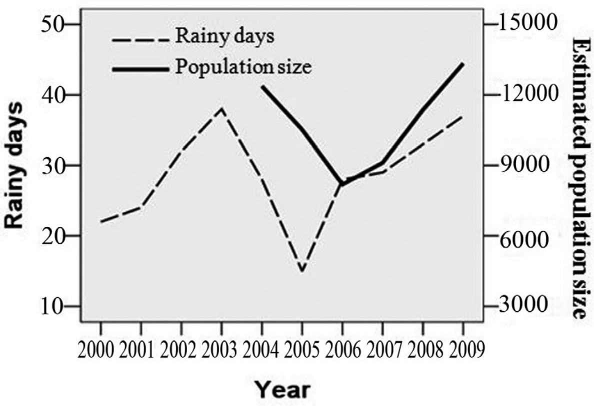

Fig. 4. *Number of rainy days from 2000 to 2009 and estimated population size from 2004 to 2009 in Ningxia Helan Mountain National Nature Reserve.*

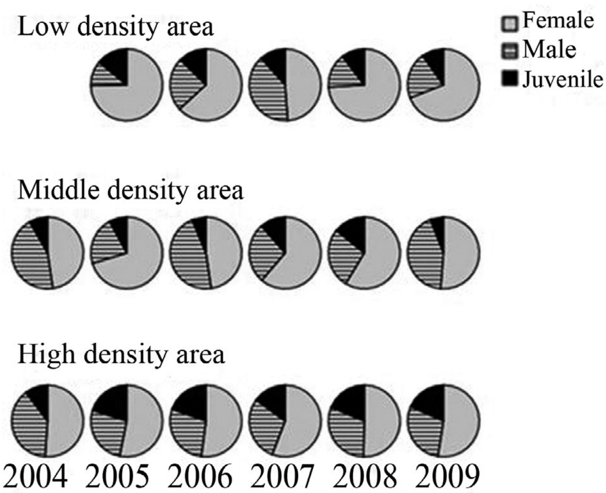

Fig. 5. *Sex ratio variation of blue sheep in different density areas of Ningxia Helan Mountain National Nature Reserve from 2004 to 2009. Note: limited by manpower, we had no effective sex ratio survey in low density area in 2004.*

classified these regions as not having blue sheep (Fig. 1), and ignored them in analyses. The encounter rate was 0.99 sheep per km line transect across the whole reserve. We categorized the valleys where the mean encounter rate was above 0.99 sheep/km as a high density area, areas lower than 0.50 sheep/km as a low density area, and areas with an encounter rate of 0.50-0.99 sheep/km as a middle density area (Table 1, Fig. 1).

The encounter rate was mainly affected by the difference of areas (F = 55.96, P < 0.001), not varied among years (F = 0.21, P = 0.96), and had no interactive effects between the two factors (F = 0.77, P = 0.66) (Fig. 2). Group size was not different among years (F = 0.48, P = 0.79) and had no interactive effects between year and area (F = 0.71, P = 0.71), but varied among density areas (F = 10.75, P < 0.001). Multiple comparisons showed that group size was larger in high density area (Mean ± SD: 8.48 ± 5.55) than that in middle density area (6.12 ± 5.25) and low density area (4.60 ± 3.64) (P < 0.05), but had no difference was found between low and middle density area (P > 0.05) (Fig. 3). Estimated population size fluctuated from 12375 in 2004 to 8188 in 2006, then to 13344 in 2009 (χ^2 = 972.21, df = 5, P < 0.001) (Table 2). We found a correlation between population size and rainy days in the preceding year (r = 0.93, P = 0.008) (Fig. 4), and the group size and encounter rates (linear regression model: Y = 0.80 + 0.36 encounter rate, r_{adj}^2 = 0.46, F = 138.28, P < 0.001).

Over six consecutive years, ratios between females and males, females and juveniles, and adults and juveniles did not differ in each density area, either ratios between females and males between density areas ($P > 0.05$), but the numbers by females and juveniles, and adults and juveniles were significantly different for three density areas ($P < 0.05$). Adult females comprised 50.32-55.89 % of the population in the high density area ($\chi^2 = 0.41$, $df = 5$, $P = 0.99$), 47.62-70.30 % in the middle density area ($\chi^2 = 6.98$, $df = 5$, $P = 0.22$), and 48.84-74.65 % in the low density area ($\chi^2 = 7.98$, $df = 4$, $P = 0.09$). Juveniles comprised 9.73-17.65 % of all animals over the six years ($\chi^2 = 2.67$, $df = 5$, $P = 0.75$) (Fig. 5).

Discussion

Rainfall is the main factor influencing herbivore population sizes in arid and semi-arid areas (Cairns & Grigg 1993) because it provides free water and increases available food (Kotler et al. 1998, Dickman et al. 2001). Rainfall in the middle part of the reserve is double that in the northern part, and also significantly higher than that in the south. All high blue sheep density areas were found in the middle part of the reserve except Xiaokouzi and the near regions (Fig. 1), which is outside this area and has good plant cover and continuously flowing water. The smallest density of blue sheep was found in the north, where a lack of rainfall and plants and extreme human destruction related to mining (Di 1986) are important factors causing the low density of sheep in this region. Rainfall in the southern part of the reserve was less than that in the middle part, but more than that in the north. Thus, the density of blue sheep in the south was less than that in the middle, but more than that in the north (Fig. 1).

Although population size increased substantially from the 1980s to 2003 (Liu et al. 2007), and varied among years, encounter rates and population size do not appear to grow or decline continuously (Fig. 2, Table 2). As vegetation biomass is determined by rainfall (Wellard 1987), rainfall is the major factor affecting fluctuations in populations in arid areas (Dickman et al. 2001). The effect of the number of days with rain events in the preceding year on population size showed a consistent relationship over our study. This finding is similar to the time lag effect of rainfall found in dasyurid marsupials in arid central Australia (Dickman et al. 2001). Due to the reserve's poor capability to hold water, the number of rainy days had also a major influence on the growth of vegetation (Suhadi 2009), and blue sheep population size. Rainy events were more frequent in 2003 than in any other year (Fig. 3) and likely produced more food for herbivores (Caughley & Lawton 1981, Cairns & Grigg 1993). Given that herbivore populations are closely modulated by food availability in arid areas (Robertson 1987), it was no surprise that the encounter rate of blue sheep was highest in the year following this peak in rainfall, 2004 (Fig. 2, Table 2). As the number or rain events decreased and the availability of food lessened, severe weather had additional impacts on the high density population (Skogland 1985). For example, in 2004 the mortality rate of juveniles in the reserve increased as did senescence (Wang et al. 2005). Population size and encounter rates declined in 2005, and reached their lowest in 2006 as the number of days with rain events declined in 2004 and 2005 (Figs. 2, 4, Table 2).

To avoid selection pressure arising from predation and intraspecific competition, large herbivores form larger groups in more open habitat (Gerard & Loisel 1995). Due to the severity of mountains in this area, less prey pressure and less open area (Schaller 1977, Wang & Schaller 1996), blue sheep appear to maintain small group sizes within the reserve (Liu et al. 2009). Group size in the reserve (7.36 ± 9.38) was less than that found on the Tso Lhamo plateau (17.3 ± 14.2 (Chanchani et al. 2010)), and group sizes differed across the reserve (Fig. 3). Abundant rainfall in 2003 not only triggered population expansion in 2004, but also increased group size, of which groups in high density areas had the largest group size (Fig. 3). Wirtz & Lörscher (1983) found that antelope group size is positively correlated with population size, group size of blue sheep also increases with increasing of population density in the reserve.

Similar to ungulates with a female biased sex ratio (Karanth & Sunquist 1992), blue sheep in the reserve were predominantly females from 2004 to 2009 (Fig. 5). This bias towards females resulted in a consistent proportion of juvenile blue sheep over the six years (Fig. 5), little more than the mortality of blue sheep in the reserve (Liang & Wang 2000, Wang et al. 2005). Our study shows that the population dynamics of blue sheep vary across the reserve and suggests that managers adopt different strategies in areas sustaining different densities of blue sheep in order to increase population size. For example, we recommend monitoring infectious diseases and parasites in high density areas, the restoration of forests in middle density areas, and preventing human activity from harming vegetation in low density areas. Further suggestions are to improve fire management strategies and to prohibit illegal hunting across the whole reserve.

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