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ORIGINAL ARTICLE

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Influences on mammals frequency of use of small bridges and culverts along the Qinghai–Tibet railway, China

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Abstract Understanding the use of small bridges and culverts by wildlife to cross the Qinghai–Tibet railway will aid in the design of wildlife crossing structures for similar transportation infrastructure. From 2014 to 2016, 36 infrared cameras were placed inside 14 small bridges and 11 culverts along the Qinghai–Tibet railway to determine the structures' effectiveness as wildlife passages. Thirteen species of mammals were found to use the small bridges and culverts to cross the railway. The crossing rates for all mammals were significantly higher for small bridges than for culverts. Tibetan antelope (*Pantholops hodgsonii*), Tibetan gazelle (*Procapra picticaudata*), kiang (*Equus kiang*), and wild yak (*Bos mutus*) preferred small bridges over culverts to cross the railway. In contrast, mountain weasel (*Mustela altaica*) and Asian badger (*Meles leucurus*) preferred culverts to cross the railway. The crossing rates of all mammals, particularly Tibetan gazelle and woolly hare, were positively influenced by structure width. Structure height had a positive influence on wild yak, but structure length had a negative influence on kiang. The distance to the highway had a positive influence on the crossing rates of all mammals, particularly wild yak and woolly hare. Human use of the structures had no influence on the crossings of most mammals except for common wolf. We suggest that road design schemes include large and open crossing structures to benefit most species with limitations on human activities near wildlife passages.

Keywords Highway · Underpass · Wildlife crossing structure · Road ecology · Tibetan plateau

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Introduction

The total length of paved and unpaved roads worldwide currently exceeds 64 million km (Van der Ree et al. 2015). Approximately one-fifth of the land in the United States is estimated to be directly affected ecologically by the development of the nation's public road system (Forman 2000). In 2003, road ecology emerged formally as an applied science in the United States. The field developed rapidly across North America, Europe, South America, and Australia (Forman et al. 2003; Van der Ree et al. 2015). In the last decade, road ecology has increased significantly in importance in Asia (Wang et al. 2015a). Road construction in developing Asian countries, including China and India, is currently progressing rapidly. These countries require the coexistence of rich biodiversity and their large human populations. The challenge they face is how to balance their need to construct roads for economic development with the need to conserve biodiversity (Kong et al. 2013; Wang et al. 2015a; Zhang et al. 2015). The Chinese national highway system not only benefits local economic development but also contributes to a larger national strategy of safety and social stability. By the end of 2015, the total length of roads in China had reached 4.57 million km (China Transportation News 2015). China currently has more than 120,000 km of expressway, much more than any other country. However, little research has focused on the impacts of roads on wildlife in China (Kong et al. 2013; Wang et al. 2015b).

The Tibetan plateau is one of the most important biodiversity hot spots in the world. It is home to many endemic and endangered fauna and flora (Sun et al. 2012). Moreover, the Tibetan plateau is one of the global centers for the original evolution of mountainous fauna, with relatively fewer species and large populations (Wu and Wang 2006). Two transportation lines, the Qinghai–Tibet highway and railway, currently run parallel to each other across the plateau. The highway has already been found to impede the migration of Tibetan antelope (*Pantholops hodgsonii*), the keystone species of the Tibetan plateau (Qiu and Feng 2004; Yang and Xia 2008; Buho et al. 2011). Meanwhile, some members of this species are killed by cars along the highway, especially during the migration season (Lian et al. 2011). Ungulates stay various distances away from the highway because of its traffic flow, chemical pollution, noise, and visual disturbance (Wang et al. 2014a). Furthermore, the construction of the railway has further narrowed the migration passage for the Tibetan antelope (Qiu and Feng 2004). According to the Chinese National Highway Network Planning (2013–2030), a Qinghai–Tibet expressway will be built in the near future. This expressway is the key section of the Beijing–Tibet expressway (G6) (Wang et al. 2014a). The expressway replacement will most likely increase the transportation system's barrier effect on Tibetan antelope and other species (Wang et al. 2014a). Therefore, it is critically urgent to include mitigative measures as part of the development of the Qinghai–Tibet expressway to protect wildlife on the Tibetan plateau.

Transportation authorities worldwide are increasingly constructing wildlife crossing structures to mitigate the negative impacts of transportation infrastructure on wildlife (Forman et al. 2003; Glista et al. 2009). To facilitate wildlife movement, mainly for the long-distance migration of Tibetan antelope, and decrease the barrier effects on all wildlife on the Tibetan plateau, 33 wildlife crossing structures were located along the Qinghai–Tibet railway. These structures range in width from 213 to 11,705 m. Collectively, these structures form the largest installation of wildlife crossing structures located along a railway in the world (Wu and Wang 2006). While extensive monitoring of wildlife use of wildlife crossing structures has been ongoing in Europe, North America, and Australia for many years, it is relatively new in Asia (Van der Ree et al. 2007; Taylor and Goldingay 2010). Ongoing monitoring studies along linear infrastructure on the Tibetan plateau focus primarily on large-sized structures (width > 100 m, 33 wildlife crossing structures) and the Tibetan antelope (Li et al. 2008; Yang and Xia 2008). No attention had been paid to other species of wildlife and their use of small bridges (width ≤ 20 m) and culverts (Wang et al. 2014a). The potential advantages of small bridges and culverts (i.e., their inexpensive and convenient construction) underscore the need to understand how endemic species interact with these structures to maximize the utility of future wildlife crossing structures on the expressway (Wang et al. 2014a). This study investigated 25 small bridges and culverts and not the 33 large structures referred to above.

The aims of this study were as follows: (1) to investigate which wildlife species use small bridges and culverts to cross the Qinghai–Tibet railway and determine their crossing rates and (2) to assess the factors related to the crossing rate of mammals.

Methods

Study area

The Qinghai–Tibet railway was built between 2001 and 2006. The railway runs parallel to the Qinghai–Tibet highway (G109), which was constructed in the 1950s. The existing two-lane highway is 10 m wide and accommodates traffic volumes smaller than 5000 vehicles/day during peak periods. The 5–m–wide railway carries fewer than 30 trains/day. We focused on the Wudaoliang section in the Kunlun Mountain Pass where the highway and railway are located less than 2.5 km apart. The 107–km–long section lies between the southern Sanjiangyuan Nature Reserve and the northern Kekexili Nature Reserve (Fig. 1). It is a key area of concern regarding critical wildlife habitat connectivity, especially given the migration route of Tibetan antelope, which is within this section (Wang et al. 2017a). The elevations involved range from 4200 to 6860 m above sea level. Dry, cold, and long winters, strong winds, and high levels of solar radiation characterize the local climate. The mean annual temperature is − 8°C with an extreme recorded low temperature of − 46°C. The main vegetation type is alpine grassland and meadow, which is entirely devoid of trees and shrubs (Li et al. 2010). Approximately 69% of the total precipitation (262 mm) falls during the short summer season (June–August). Wild ungulates in the area include Tibetan antelopes, Tibetan gazelles (*Procapra picticaudata*), kiangs (*Equus kiang*), and wild yaks (*Bos mutus*) (Zheng 1994). The most significant mammalian predator of the Tibetan antelope is the common wolf (*Canis lupus*). Large raptors, including upland buzzards (*Buteo hemilasius*), cinereous vultures (*Aegypius monachus*), and lammergeiers (*Gypaetus barbatus*) are frequent scavengers of dead antelopes and other carrion (Lian et al. 2007). This area is almost free of human disturbance, except for occasional maintenance workers along the highway and railway in the daytime. The land cover is similar over the railway and highway. The habitat along the roadside within our research area is very homogeneous, with sparse grass and occasional temporary pools resulting from rainfall. Wildlife monitoring on the Tibetan plateau is challenging because the area is characterized by a harsh climate, high elevation, low oxygen levels, low wildlife population densities, and expansive landscapes.

Use of small bridges and culverts

From August to December in 2014, and between June 2015 and June 2016, we used 36 infrared cameras (Ltl 6310 wide angle; Shenzhen, China) to monitor wildlife crossing at 14 small bridges (width, 3.5–23 m; height, 2–5.7 m; length, 5 m) and 11 culverts (width, 1.5–3 m; height, 2–3 m; length, 8–30 m) (Table 1). The operation time varied between cameras because of inclement

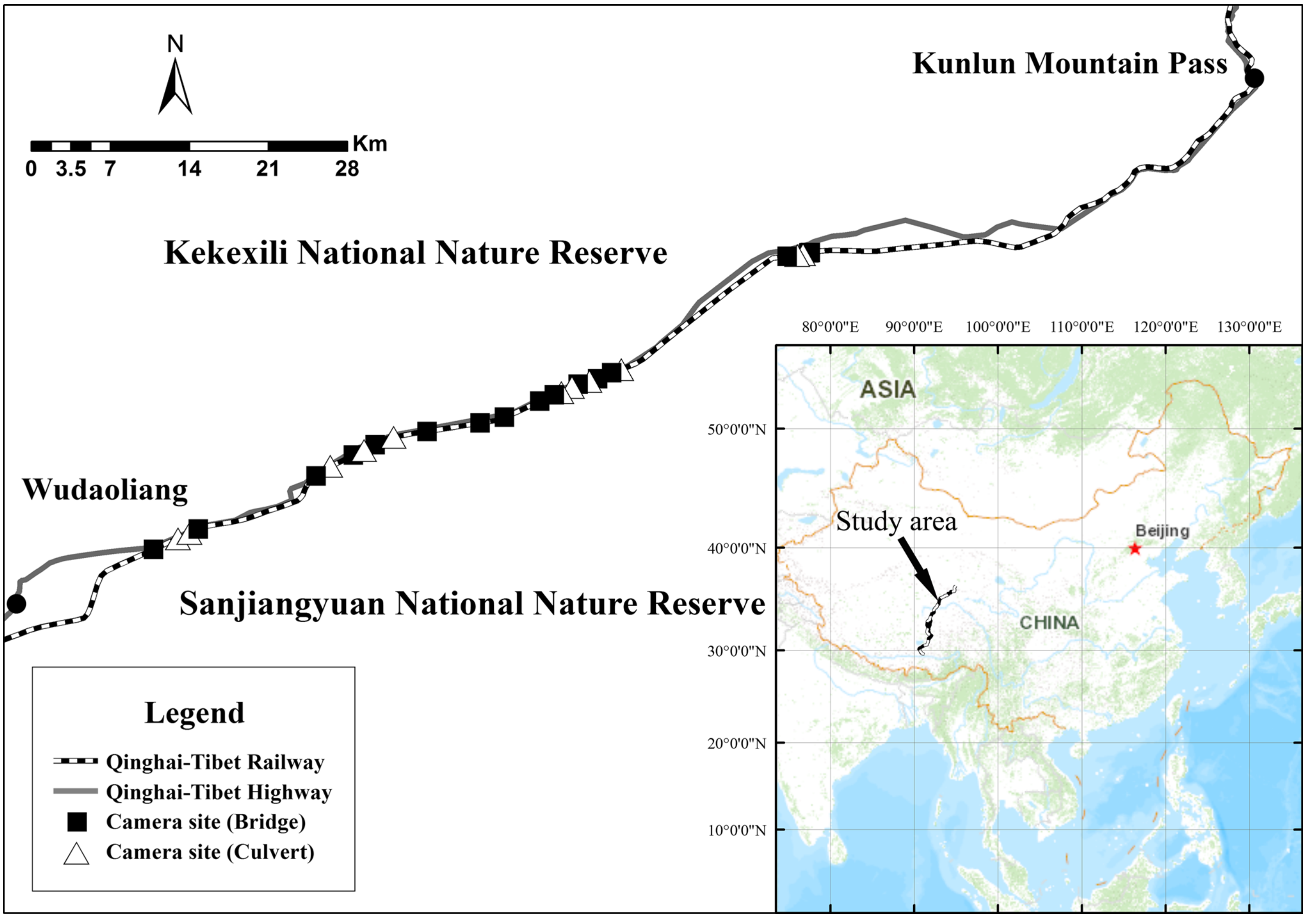

Fig. 1 Sketch map of the research section of the Qinghai–Tibet highway and railway, and the camera locations

weather, human disturbances, camera software and hardware problems, and battery life (68–320 days). Typically, two cameras were located at the entrance and the exit of each culvert, and a camera was set inside each small bridge. All cameras were attached on the exclusion fencing that was placed along all small bridges and culverts. We placed cameras at a height of approximately 0.5 m and oriented them parallel with the ground. Following Wang et al. (2014b), all operational parameters of each camera were standardized (i.e., camera mode, camera; image size, 5 M; capture number, 3; interval, 10–60 s; time and sensor level, normal). For each bridge and culvert, we measured and recorded the structural variables of length, width, height, openness index (OI = width × height/length) (Mata et al. 2008; Clevenger and Huijser 2011), structure type (culvert or bridge), the distance between the structure and the highway, and the presence of humans as detected by the cameras (Table 1). During setting and maintaining the infrared cameras, we also checked the tracks and traces of any wildlife species that approached and crossed those underpasses, as the soil on the ground was soft because of the abundant rain and snow on the plateau. Therefore, the footprints of wildlife were easily preserved and distinguished.

Data analysis

For each bridge and culvert, we recorded the number of independent photos (IPs). We defined IPs as photos of individuals of the same species taken more than 0.5 h apart (Samejima et al. 2012; Wang et al. 2014b).

We determined that wildlife crossings of the structure were successful when the photos of an animal were present at both ends of the culverts or at the center under the bridges. We calculated the crossing rate of each structure based on the following formula: crossing rate = (number of IPs/number of days monitored) × 100. We used the Mann–Whitney U test to compare the crossing rate between bridges and culverts.

We used multivariate linear regression to investigate the influence of independent variables (structure length, width, height, OI, human disturbance, and distance to highway) on the crossing rates of mammals. We applied a stepwise selection procedure to retain significant variables and their interactions ($P < 0.05$). All statistical analyses were conducted using SPSS software (IBM 2010).

Table 1 Factors of small bridges and culverts related to the crossing rates of wildlife crossing structures

Series number	Type	Length (m)	Width (m)	Height (m)	Openness index (width × height/length)	Human disturbance*	Distance to highway (m)
1	SB	5.0	23.0	3.6	16.6	73.5	1000
2	SB	5.0	9.0	5.2	9.4	11.8	1000
3	C	30.0	3.0	2.5	0.3	94.1	1000
4	C	25.0	3.0	2.5	0.3	76.2	1000
5	C	16.0	1.5	2.0	0.2	23.9	90
6	SB	5.0	6.0	5.7	6.8	125.0	130
7	SB	5.0	4.5	5.2	4.7	34.2	190
8	C	15.0	1.5	2.0	0.2	10.0	150
9	SB	5.0	6.0	4.0	4.8	68.0	100
10	C	16.0	1.5	2.0	0.2	13.2	150
11	C	13.0	1.5	2.0	0.2	15.0	150
12	SB	5.0	3.5	4.3	3.0	9.2	210
13	SB	5.0	11.0	3.5	7.7	20.0	270
14	SB	5.0	6.0	3.5	4.2	32.5	250
15	SB	5.0	6.0	3.5	4.2	115.1	200
16	C	13.0	1.5	2.0	0.2	22.2	150
17	SB	5.0	15.0	3.5	10.5	118.0	220
18	C	14.0	1.5	2.0	0.2	9.1	250
19	SB	5.0	9.0	3.5	6.3	173.3	330
20	C	13.0	1.5	2.0	0.2	16.1	115
21	SB	5.0	7.0	3.5	4.9	70.6	145
22	SB	5.0	13.2	5.1	13.5	41.4	110
23	C	8.0	3.0	3.0	1.1	33.8	160
24	C	12.0	1.5	2.0	0.3	28.5	137
25	SB	5.0	13.0	2.0	5.2	12.0	230

SB small bridge, *C* culvert; *Human disturbance = (number of IPs/number of days monitored) × 100, *IPs* independent photos

Results

Crossing rate of small bridges and culverts

It was difficult to distinguish between Tibetan fox (*Vulpes ferrilata*) and corsac fox (*V. corsac*) based on only pictures, especially with photos taken at night. Therefore, we grouped the two species together as "fox." In some photos, the species of wildlife were difficult to distinguish when only a portion of the animal was recorded or the wild animal was moving too quickly to be recorded. In these cases, the photos were omitted from the analysis.

Within 2452 monitoring days, we acquired 4237 IPs of mammals and 1447 IPs of humans. Thirteen species of mammals were detected using small bridges and culverts to cross the railway; several of those species are either protected in China or listed as threatened/endangered on the IUCN Red List (IUCN 2017), such as Tibetan antelope (Fig. 2), kiang (Fig. S1), wild yak (Fig. S2), Tibetan gazelle (Fig. S3), and Eurasian lynx (*Lynx lynx*, Fig. 3; Table 2). The crossing rates across all structures was highest (705.4) for woolly hare (*Lepus oiostolus*), followed by Tibetan gazelle (479.1), fox (449.8), kiang (304.6), common wolf (278.3, Fig. S4), and Tibetan antelope (126.7). Low crossing rates were observed for other species, including mountain weasel (*Mustela altaica*, 11.1), wild yak (5.8), Eurasian lynx (5.4), Asian badger (*Meles leucurus*, 4.8), Himalayan marmot (*Marmota himalayana*, 2.7), and beech marten (*Martes foina*, 0.8) (Table. S1). Common wolf and fox used all 25 crossing structures, and Tibetan gazelle, Tibetan antelope, kiang, and woolly hare used more than half of the crossing structures. Wild yak never crossed the culverts and only used four small bridges. Kiang used all small bridges but only one culvert to cross the railway. Lynx used nine structures, i.e., four small bridges and five culverts (Table S1).

The crossing rate per structure for small bridges (190.81 ± 25.48) was significantly higher than that for culverts (90.27 ± 22.48) for all mammals (Mann–Whitney $U = 28.000$, $Z = -2.961$, $P = 0.003$). Four ungulates (Tibetan antelope, Tibetan gazelle, kiang, and wild yak) were found to prefer small bridges over culverts to cross the railway (Tibetan antelope, Mann–Whitney $U = 1.000$, $Z = -3.280$, $P = 0.001$; Tibetan gazelle, Mann–Whitney $U = 1.000$, $Z = -3.808$, $P = 0.000$; kiang, mainly crossed small bridges except for one culvert; wild yak: exclusively used small bridges). In contrast, mountain weasel and Asian badger preferred culverts to cross the railway (both species mainly used culverts and seldom used small bridges). No preference was found between small bridges and culverts among other species (woolly hare, Mann–Whitney $U = 17.000$, $Z = -1.535$, $P = 0.125$; fox, Mann–Whitney $U = 83.000$, $Z = -0.247$, $P = 0.805$; common wolf, Mann–Whitney $U = 61.000$, $Z = -1.332$, $P = 0.183$; Eurasian lynx, Mann–Whitney $U = 7.000$, $Z = -1.149$, $P = 0.251$; Himalayan marmot, Mann–Whitney $U = 2.000$, $Z = -0.577$, $P = 0.564$) (Fig. 4).

Fig. 2 Tibetan antelope using a culvert located under the railway (Series Number 8)

Fig. 3 Eurasian lynxes using a culvert located under the railway (Series Number 23)

Factors related to the crossing rate of small bridges and culverts along the railway

Six species-specific models were developed (Table 3). The proportion of variance (R^2) explained by the models developed for each species had values ranging from 0.208 to 0.716. Some structural and road-related factors were important model components for wild yak, kiang, Tibetan gazelle, woolly hare, and common wolf, although their influence varied by species. Structure width was positively correlated with crossings for all mammals, especially Tibetan gazelle, and woolly hare. Structure height and length were the two most important predictors of wild yak and kiang crossings. Distance to highway helped explain the crossing rates for all mammals, particularly wild yak and woolly hare. Human disturbances influenced the crossing rates of common wolf.

Discussion

The protective value of small bridges and culverts

We found that all small bridges and culverts were used by mammals. This indicates that small bridges and culverts, even if not originally designed for the movement of wildlife, can facilitate wildlife movement across the transportation infrastructure and can be important parts of regional conservation strategies (Ng et al. 2004; Mata et al. 2008; Mateus et al. 2011; Borda-de-Água et al. 2017).

We found that at least five Chinese nationally protected species and four species of international conservation concern used the small bridges and culverts. Tibetan antelope used 10 small bridges and six culverts, as well as other large crossing structures not included in

Table 2 Species of mammals that used small bridges and culverts along the railway

English name	Scientific name	Chinese protective class	IUCN
Tibetan antelope	*Pantholops hodgsonii*	I	NT
Kiang	*Equus kiang*	I	LC
Wild yak	*Bos mutus*	I	VU
Tibetan gazelle	*Procapra picticaudata*	II	NT
Eurasian lynx	*Lynx lynx*	II	LC
Corsac fox	*Vulpes corsac*	China RL-EN	LC
Beech marten	*Martes foina*	China RL-EN	LC
Mountain weasel	*Mustela altaica*	China RL-NT	NT
Asian badger	*Meles leucurus*	China RL-NT	LC
Common wolf	*Canis lupus*	China RL-VU	LC
Tibetan fox	*Vulpes ferrilata*	China RL-VU	LC
Woolly hare	*Lepus oiostolus*	China RL-LC	LC
Himalayan marmot	*Marmota himalayana*	China RL-LC	LC

IUCN International Union for Conservation of Nature and Natural Resource, *RL* Red List, *I* First class protection in China, *II* Second class protection in China, *EN* endangered, *NT* near threatened, *VU* vulnerable, *LC* least concern

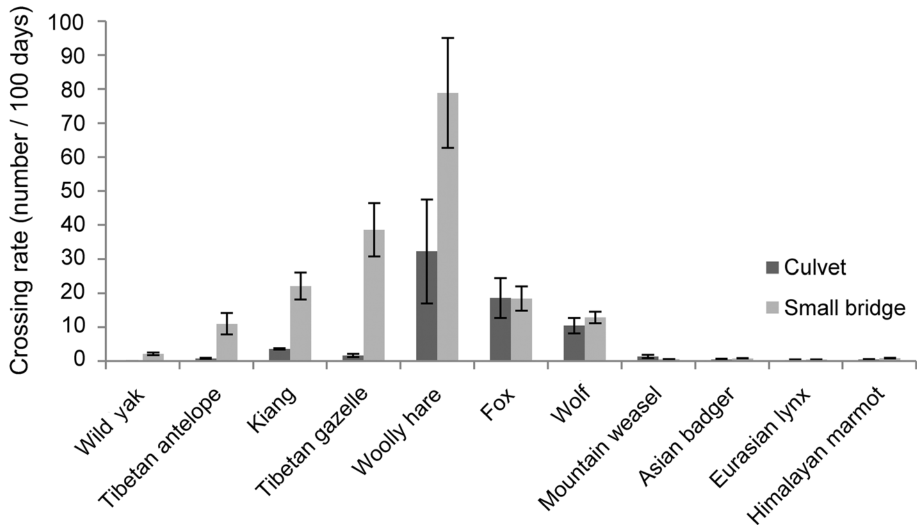

Fig. 4 Crossing rates [mean ± standard error (SE)] of wildlife in different types of structure

Table 3 Variables retained in the stepwise regression model, coefficients (*B*), standard error (SE), significances, *P* value (*t*-test) and deviance explained (R^2)

Species	Variables	*B*	SE	*P*-value	R^2
Wild yak	Constant	− 0.998	0.310	0.004	0.472
	Height	0.303	0.088	0.002	
	Distance to highway	0.001	0.000	0.022	
Kiang	Constant	24.891	4.813	0.000	0.308
	Length	− 1.297	0.405	0.004	
Tibetan gazelle	Constant	3.344	6.536	0.614	0.309
	Width	2.582	0.804	0.004	
Woolly hare	Constant	− 29.066	10.436	0.011	0.716
	Distance to highway	0.129	0.022	0.000	
	Width	2.822	1.241	0.033	
Common wolf	Constant	7.836	1.795	0.000	0.208
	Human disturbance	0.066	0.027	0.022	
All mammals	Constant	11.988	15.836	0.457	0.662
	Width	7.521	1.883	0.001	
	Distance to highway	0.119	0.033	0.001	

the current study but discussed in other studies (Yang and Xia 2008; Li et al. 2008). This indicates that this species can adapt to different types of crossing structures over time. Therefore, one can expect that the small bridges and culverts of the future expressway will probably be used by Tibetan antelope.

Within our study area, many large and medium-sized bridges have been constructed to protect the permafrost and provide crossing opportunities for wildlife on the Qinghai–Tibetan plateau (Wu and Wang 2006). Tibetan antelope have readily adapted to these underpasses, although they utilize only a few of the structures (Yang and Xia 2008). Ungulates can adjust themselves to adapt to those artificial passages if the size of passages is enough big (Wang et al. 2017b). In North America, large underpasses allow their use by a wide range of wildlife (Clevenger and Huijser 2011). Although we do not know the rate of use of large underpasses by other ungulates, it is likely they adapt to these structures relatively easily. We focused only on wildlife rates of use of small bridges and culverts because these smaller-sized structures are commonly neglected by ecologists and engineers in China. Our study will contribute to the advancement of road ecology research on the Tibetan plateau.

Two-thirds of China's land mass is covered with mountains. As a result, numerous small bridges and culverts have been constructed on linear transportation corridors to protect infrastructure from perpendicular water flow. These bridges and culverts are suspected to benefit wildlife movement. This study is the first to monitor wildlife's rate of use of small bridges and culverts by infrared cameras over a 3-year period in China. To advance road ecology in China, similar research should be conducted in other ecologically sensitive areas of the country.

Factors related to mammals' crossing rates

Structural attributes

In the absence of high levels of human activity, structural attributes best explain the performance indices for both large predator and large prey species (Clevenger and Waltho 2005). Previous research has indicated that the size of structures is important to wildlife and that ungulates prefer large and open wildlife crossing structures (Ng et al. 2004; Clevenger and Waltho 2005; Mata et al. 2008). We found that ungulates on the Tibetan plateau preferred structures that are short, wide, and high. Yaks were never detected in the culverts, while kiangs used all of the small bridges but only one culvert. This lack of crossings could be a clear sign of a strong barrier effect of culverts for wild yak and kiang. Kiangs were photographed near the entrances of other culverts, suggesting an interest in crossing but that the culverts were unsuitable. The one culvert the kiang successfully crossed is wider and taller than the other culverts. This indicates that the size of this culvert likely represents the smallest size (length, 8 m; width, 3 m; height, 3 m) suitable for kiang. Tibetan antelope currently primarily use the Wubei or Kekexili bridge underpasses (width > 200 m, height > 6 m) to cross the railway and scarcely use other underpasses (Yin et al. 2006; Xia et al. 2007). The crossing rate of Tibetan antelope at small bridges and culverts is relatively low (126.69), although the crossing rate at small bridges is higher than that at culverts. Pronghorn, a seasonally migratory ungulate species similar to Tibetan antelope, which live in open habitats and rely on vision to detect and avoid predators, prefer using overpass crossing structures to underpass crossing structures along US Highway 191 in western Wyoming (Sawyer et al. 2016). Therefore, it is conceivable that Tibetan antelope will likely use overpasses to cross highways or railways in the Tibetan plateau if these structures can be built as overpasses in the future.

In contrast, mountain weasel and Asian badger prefer to use culverts to cross the railway. Similar behavior is also found in Siberian weasel (Wang et al. 2017b). Larger carnivores, specifically bobcats and coyotes, traverse passages of a wide variety of sizes, from the largest spanning bridge underpasses to the smaller pipe culverts (Ng et al. 2004). We found a similar trend for lynx because they used nine crossing structures ranging in length from 5 to 30 m, in width from 1.5 to 23 m, and in height from 2 to 5.2 m.

Distance to the highway

We found that the distance between the crossing structures of the railway and highway was positively correlated with the crossing rates of all mammals, particularly wild yak and woolly hare. Tibetan antelope currently primarily use the Kekexili underpass during migration (Wu and Wang 2006; Xia et al. 2007; Li et al. 2008). The distance between the Kekexili underpass and the highway is approximately 1.5 km. Rolling landforms can mitigate the visual disturbance caused by the highway and reduce animal anxiety (Yin et al. 2006). Both factors benefit the migration of Tibetan antelope (Lian et al. 2012). Consequently, it is easy to understand why Tibetan antelope are used to using crossing structures located far away from the highway. The avoidance distance of wild yak (999 m $\pm$ 304) is the greatest distance to the highway among the four ungulates. This appears to be a result of the trade-off made between searching for food resources and risk-avoidance behavior regarding the highway and its traffic (Lian et al. 2011).

Human disturbance

Most research indicates that human disturbance significantly negatively impacts the rate of wildlife use of crossing structures (Clevenger and Waltho 2005; Grilo et al. 2008; Glista et al. 2009). During the Qinghai–Tibet railway construction period (2003–2004), human activity was the most serious factor affecting the efficiency of all crossing structures along the railway (Xia et al. 2007). Increasing human presence associated with railways and highways may be the main threat to Tibetan antelope and may be greater than the threat from the infrastructure itself (Xia et al. 2007). However, we did not observe this situation in our research area. Moreover, human disturbance positively influenced the rate of common wolf use of structures. We believe that two reasons were primarily responsible for this finding. First, no residences and/or houses were found in our research area, and only railway maintenance workers used the small bridges and culverts periodically during daylight hours. Consequently, the human disturbance was relatively limited. Second, while the construction of the Qinghai–Tibet railway was finished in 2007, our research was conducted from 2014 to 2016; therefore, we believe that various species of wildlife have adjusted their behavior to adapt to the artificial disturbances caused by the railway and highway. In North America, wildlife can modify their behavior to adapt to the transportation infrastructure (Clevenger and Huijser 2011). With the operation of the Qinghai–Tibet railway, Tibetan antelope have become accustomed to using the underpass structures associated with the railway (Yang and Xia 2008). The avoidance distance of Tibetan gazelle to the highway is less than 200 m, and Tibetan antelope and Tibetan gazelle appear relatively undisturbed by the traffic (Lian et al. 2011, 2012). Tibetan antelope often approach close to the highway and do not appear to be afraid of motor vehicles and the highway (personal communications). Furthermore, we found that Tibetan antelope used more large-sized underpasses, such as the Qingshuihe underpass, to cross the railway during their migration periods (authors' unpublished data). We also found that Tibetan antelope used 10 small bridges and six culverts to cross the railway. Therefore, the present low intensity of human disturbance has not significantly impacted the crossing rate of all small bridges and culverts. However, in the long run, it is anticipated that human disturbances will increase with the construction of new transportation infrastructure. Consequently, it is necessary to limit human activities near wildlife passages in the future, especially during the migration periods of the Tibetan antelope.

Conclusions

We found that all small bridges and culverts were used by mammals. Ungulates on the Tibetan plateau preferred structures that are short, wide, and tall. Culverts had a strong barrier effect for wild yak and kiang. We suggest that road design schemes include wider crossing structures to benefit the most species. Human activities near wildlife passages should be limited in the future.

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