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Impacts of linear transport infrastructure on terrestrial vertebrate species and conservation in China

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ABSTRACT

Two strategic documents issued by the Chinese Central Government projected that, by the mid-21st century, the linear transport infrastructure (LTI) network of China will rank at the forefront of ecological and sustainable transport networks globally. With this goal, it is urgent to summarize existing research, benchmark international research levels, and propose development directions and strategies for terrestrial vertebrate species protection around LTI in China. In this study, we searched for peer-reviewed papers before 2020 in both Chinese and international databases. A total of 170 academic articles were collected. Most focused on roads, but some focused on railways, of which the Qinghai-Tibet Railway occupied half. The most researched taxa were mammals, including the Tibetan antelope (*Pantholops hodgsonii*), Siberian tiger (*Panthera tigris*), and Asian elephant (*Elephas maximus*), the number of bird research papers was less than half that of mammal research papers, and fewer amphibian and reptile studies. The impact of LTI on wildlife was classified to habitat effects, roadkill, behavioral influences, and barrier effects. Wildlife preservation efforts included wildlife and habitat surveys, route selection, subgrade and pavement design, and the design and monitoring of wildlife crossing structures. Studies were concentrated in five zoogeographical regions, i.e., the Qinghai-Tibet, South China, Central China, Northeast China, and Southwest China regions. Conservation suggestions, knowledge gaps, and future research directions for China were identified through comparisons with the state of international research. These focal priorities will help guide the development of road ecology in China. Multi-disciplinary, cross-departmental, and national level research is necessary. Based on this review, a national data integration platform should be established and efforts to cooperate with international research teams to mitigate the adverse effects of LTI should be made.

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1. Introduction

The biodiversity of China is one of greatest in the world. China has 673 mammal, 1372 bird, 408 amphibian, and 461 reptile species, representing about 12 %, 13 %, 4 %, and 4.5 % of their respective groups worldwide, among which 150 mammal, 77 bird, 272 amphibian, and 143 reptile species are endemic to China (Jiang et al., 2016). However, the biodiversity of China is also one of the most threatened in the world (Liu et al., 2003). Some of the most critical threats facing the natural ecosystems of China are habitat loss and fragmentation caused by linear transport infrastructure (LTI) (Zang et al., 2016).

By the end of 2018, more than 5,280,700 km of highways had been built in China, with 117,000 km national expressways and 40,000 km high-speed railways (Ministry of Transport of China, 2022). Based on current plans, the lengths of high-speed railways and expressway will reach 70,000 km and 160,000 km by 2035, respectively (Xinhua News Agency, 2021). Thus, it is necessary to study the effects of LTI on biodiversity.

Biodiversity loss is a global problem commonly linked to habitat degradation and fragmentation (Laurance, 2018; Hilty et al., 2020). LTI is a primary driving force behind habitat degradation and fragmentation (Ibisch et al., 2016). Global road networks have reached over 29 million km and have fragmented the terrestrial ecosystems into around 600,000 patches, more than half of which are under 1 km^2, which poses serious challenges to ecosystem integrity and wildlife (Ibisch et al., 2016). Road networks are ubiquitous, 83 % of US land areas is < 1 km from roads and 50 % of Europe land areas is < 1.5 km from roads (Riitters et al., 2003; Torres et al., 2016). LTI has had some positive effects, such as creating habitats and promoting movement in certain animals; however, its negative impacts are much greater (Forman et al., 2003; Van der Ree et al., 2015). Besides habitat loss, degradation, and fragmentation, LTI can result in roadkill, barrier effects, population endangerment, and extinction. China is still in the preliminary stages of researching how wildlife are affected by and interact with LTI (Chen et al., 2017). With the initiation of major national construction projects, such as Qinghai-Tibet Railway, Simao-Xiaomengyang Expressway, and Beijing-Xinjiang Expressway, the protection of rare and endangered species like the Tibetan antelope (*Pantholops hodgsonii)*, Asian elephant (*Elephas maximus*), and Giant panda (*Ailuropoda melanoleuca*) has attracted global attention (Wang et al., 2019a).

In 2019 and 2021, the Chinese central government issued two strategic documents regarding national transportation planning, entitled “Strategy on High-Level Transport Development” and “Layout of Comprehensive National Transport Network”, that prioritize the protection of wildlife in the design and construction of LTI (Xinhua News Agency, 2021). The documents project that, by the mid-21st century, the LTI network of China will rank at the forefront of ecological and sustainable transport networks worldwide.

As the largest infrastructure project in the world, China’s Belt and Road Initiative (BRI) will cross terrestrial and marine biodiversity hotspots which contain over 4138 animal species, which means that studies on the impacts of LTI on wildlife and effective countermeasures are urgently needed (Lechner et al., 2018; Hugher, 2019). In January 2022, guidelines on ecological protection of foreign infrastructure construction and investment was issued by the Chinese government, which indicated that Chinese enterprises should adopt international standards or much stricter standards to protect ecological environments during infrastructure construction, which includes roads and railways (Ministry of Ecology and Environment of China, 2022).

To best identify the priorities of research going forward, it is necessary to first summarize the existing research, benchmark international research levels, and propose future development directions and strategies for wildlife protection regarding LTI in China. Therefore, in this paper, we summarized the research on the impacts of LTI on terrestrial vertebrate species and the existing protection measures in China, then identified research gaps through comparisons with developed western countries, and finally we identified the most promising developmental directions for China.

2. Materials and methods

2.1. Literature review

We retrieved peer-reviewed papers from both Chinese and international databases, including China National Knowledge Infrastructure (CNKI), Springer, Elsevier, Wiley-Blackwell, and the Web of Science. The search deadline was 2020. We specifically searched for the following words in keywords and titles: (“Road” OR “Highway” OR “Expressway” OR ”Railway”) AND (“Wildlife” OR “Vertebrate” OR “Mammal” OR “Bird” OR “Amphibian” OR “Reptile”) AND (“道路”或者“公路”或者“高速公路”或者“铁路”和“野生动物”或者“脊椎动物”或者“兽类”或者“鸟类”或者“两栖类”或者“爬行类”). We only searched for research conducted in areas located within in China, including China mainland, Taiwan, Hongkong, and Macau. In addition, we checked the references of all peer-reviewed papers to add any papers that might have been missed during our search, especially for certain species.

2.2. Impact of linear transport infrastructure on terrestrial vertebrate species

After reviewing the existing research in China, the impacts of LTI on wildlife were analyzed in terms of habitat, roadkill, behavioral activity, and barrier effects. Wildlife preservation efforts included: wildlife and habitat surveys, route selection, subgrade and pavement design, and design and monitoring of wildlife crossing structures (WCS). According to China’s zoogeographical regionalization based on terrestrial vertebrates, China can be divided into 7 regions: Northeast China, North China, Neimenggu-Xinjiang, Qinghai-Tibet, South China, Central China, and Southwest China (He and Gao, 2018). In this paper, we described the impacts of LTI on vertebrates and related preservation approaches in terms of zoogeographical regions.

3. Results

3.1. Research and preservation efforts on the effects of LTI on terrestrial vertebrate species

A total of 170 papers were retrieved, including 54 papers in English and 116 papers in Chinese. The earliest paper was published in 2003, the annual number of papers published in Chinese was significantly higher than that of English papers, except in 2011 (Fig. 1; Appendix-1). Overall, published research on the effects of LTI on animals has been increasing since 2003.

In terms of China's zoogeographical regions, the published papers focused on the Qinghai-Tibet region most (43), followed by South China (26), Central China (24), Northeast China (19), Southwest China (18), and finally North China with the least (4) (Fig. 2; Appendix-2).

In terms of LTI focus, 139 of the papers focused on roads, 41 papers focused on railways, and 17 papers considered both roads and railways. Among the 41 studies involving the railways, the Qinghai-Tibet Railway made up more than half (23 articles).

The research taxa included mammals, birds, reptiles, and amphibians. There were 126 papers related to mammals, which included endangered and rare species such as the Tibetan antelope, Siberian tiger (*Panthera tigris*), and Asian elephant. There were 56 bird papers and fewer amphibian and reptile papers, 37 and 30, respectively.

3.2. Impacts of linear transport infrastructure on terrestrial vertebrate species

3.2.1. Habitat effect

Chinese road networks have caused extensive loss and fragmentation of ecosystems, and around 18.37 % of the national land area is affected by LTI. The area affected by substandard roads (rural roads with traffic volume < 100 vehicle/day) was largest (Li et al., 2004). LTI and urbanization has led to landscape fragmentation, and some eastern Chinese provinces and bio-geographic zones have become highly fragmented, while the landscape integrity of western provinces and bio-geographic zones are relatively well preserved (Li et al., 2010). In Xishuangbanna in Yunnan Province of South China, landscape connectivity levels decreased after road construction and species with lower dispersal abilities were more affected by the subsequent habitat fragmentation (Liu et al., 2014).

Many publications have evaluated the impacts of road networks on habitats of rare and endangered species, including the Asian elephant, snow leopard (*Panthera uncia*), Amur leopard (*Panthera pardus orientalis*), Amur tiger (or Siberian tiger), North Chinese leopard (*Panthera pardus japonensis*), Cabot's tragopan (*Tragopan caboti*), Przewalski's gazelle (*Procapra przewalskii*), black snub-nosed monkey (*Rhinopithecus bieti*), crested ibis (*Nipponia nippon*), sable (*Martes zibellina*), and giant panda (*Ailuropoda melanoleuca*) (Zhang et al., 2015; Kang et al., 2015, 2020; Liu et al., 2017; Zheng, 2018; Jiang et al., 2014; Li et al., 2014; Celine et al., 2015; Xing et al.,

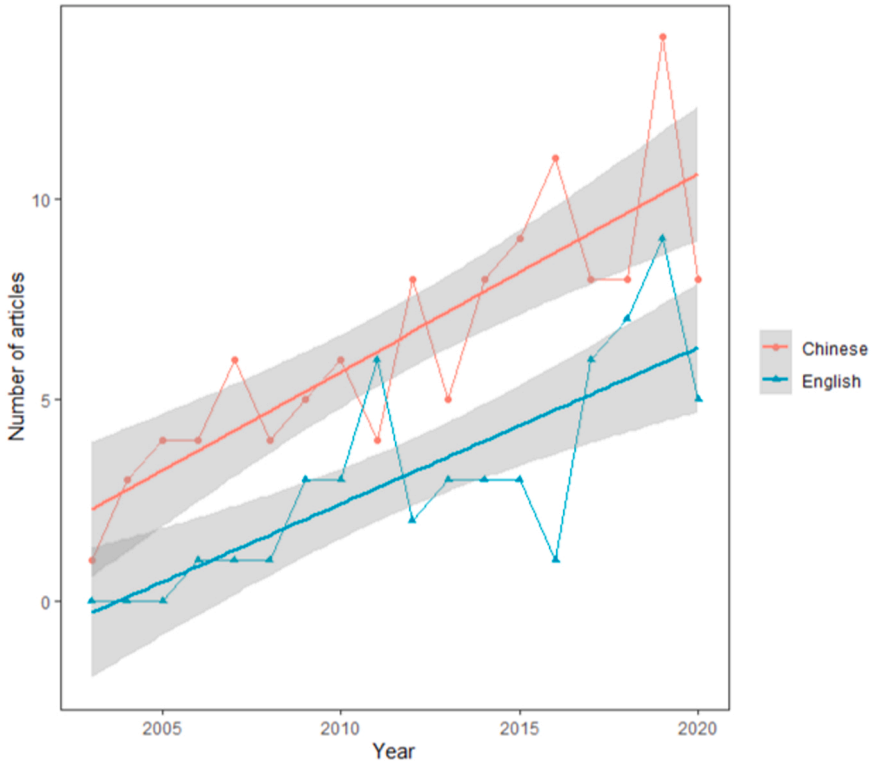

Fig. 1. Number of publications on research in China by year.

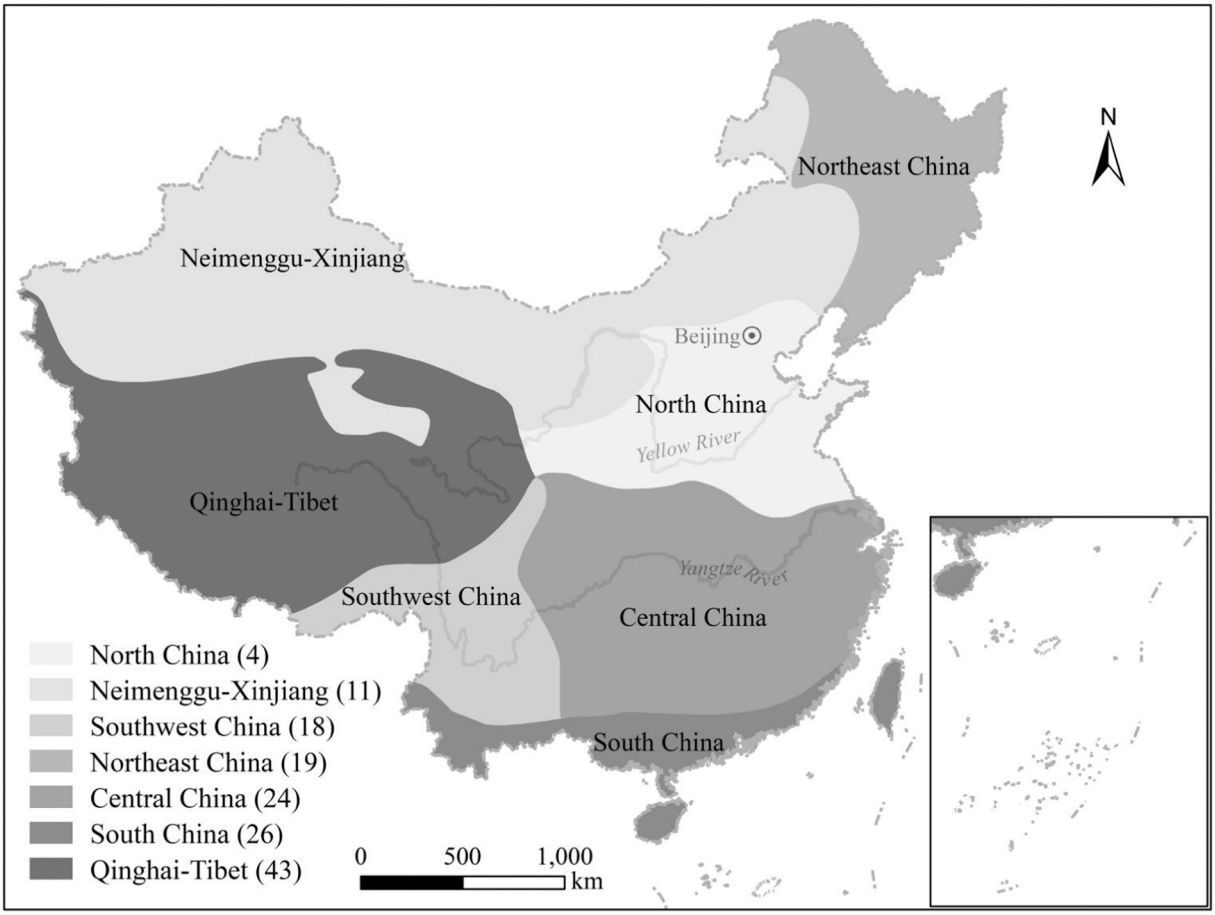

Fig. 2. Map showing zoogeographical regions in China and number of associated publications.

2019; Yang et al., 2012; Xiao et al., 2019). From these studies it could be seen that the snow leopard, Cabot's tragopan, and Przewalski's gazelle are seriously affected by habitat fragmentation (Zhang et al., 2015).

3.2.2. Roadkill

Studies on roadkill in China have generally been concentrated in three areas, Changbai Mountain in Northeast China, Ruogai wetland in Qinghai-Tibet, and Taiwan in South China. In addition, several studies were scattered in Yunnan, Xinjiang, and other locations.

In the Changbai Mountain area, from 2008 to 2012, 3475 vertebrates (belonging to 59 species) were killed by traffic on 80 km road, with a roadkill rate that averaged 61.6 individuals per 100 km, of which amphibians had the highest mortality (2996 individuals) (Wang et al., 2013a,b). Of mammal roadkill, 69.4% occurred on roads with load of 1–40 vehicles/h, and the highest roadkill happened on roads with loads of 30–40 vehicles/h (Piao et al., 2012). Bird roadkill was associated with bird flying height and positively correlated with roadside abundances (Piao et al., 2016).

In the Ruoige wetland, many amphibians were killed by road traffic, with the highest mortality occurring in April (Zhang et al., 2018). The roadkill hot-spots occurred close to breeding waters and road mortality was significantly associated with traffic volume at night (Zhang et al., 2018). The proportion of wetland within 1000–2000 m of highways was strongly associated with the road mortality of three amphibian species (Dai and Wang, 2011).

Taiwan has one of the largest roadkill databases based on citizen science in the world, the Taiwan Roadkill Observation Network (TaiRON) (Hsu et al., 2018; Yue et al., 2018). Based on the TaiRON data, one study quantified taxonomic, seasonal, and temporal trends in roadkill, and revealed that snakes were the most common animals killed by road traffic (35 %), and 26 % of snake roadkill were protected species (Chyn et al., 2019). In Taiwan, risks of roadkill for venomous, semiaquatic and aquatic snakes, turtles were highest in montane regions, coastal lowlands, southwestern coast, and central areas, respectively (Chyn et al., 2019). Roadkill projection models integrating this data performed well across ecological levels and spatial scales, which can be applied anywhere with sufficient roadkill and environmental data and is scalable to address the ecological question of interest (Lin et al., 2019).

A scattering of studies were conducted across other parts of China. For instance, 5 Przewalski's horses (*Equus ferus*) were killed by traffic along the G216 over 3 months in the Kalamaili National Nature Reserve of Xinjiang (Zhang et al., 2008). Asian elephants crossed

the Sixiao expressway 44 times over 7 months after the expressway started operating, leading to 2 accidents (Pan et al., 2009).

3.2.3. Impacts of linear transport infrastructure on animal behavior and activity

LTI affects wildlife behavior and activity rhythms. Road traffic has been shown to affect bird behaviors, for instance, the retreat behavior of thrushes was affected by traffic noise (Liu et al., 2018). In the Three Parallel Rivers of the Yunnan Protected Areas of Southwest China, there were significant correlations between noise at the road shoulder up to 100 m from the roadside, speed and size of vehicles, and behavioral reactions of birds (Wang et al., 2012). The behavioral reactions of the black-necked crane were correlated with vertical distance from highways (Wang et al., 2011). In Hainan Province of South China, the nesting of scaly-breasted munias in trees lining an arterial road was identified as a potential anti-predation strategy (Zhou et al., 2020). The behavior of black-faced spoonbills in the Taipa-Coloane Wetland Reserve in Macao did not appear to be affected by traffic noise (Zhang et al., 2012). In the Qinghai-Tibet region, both alert and flush distances significantly decreased with increasing human disturbance, and larger species had longer alert times and flush distances along the Qinghai-Tibet railway (Ge et al., 2011).

Road traffic has also been shown to affect mammal behavior. In the Shennongjia National Nature Reserve of Hubei Province in Central China, the diurnal activities of the tufted deer and goral changed significantly with proximity to tourist roads; while tourist roads had no effects on sika deer or boar (Li et al., 2015). Roads had negative effects on seed-dispersal function of rodents, which could ultimately cause profound changes in the structure of plant communities (Chen et al., 2019a, 2019b). In the Qinghai-Tibet region, highways around Qinghai Lake caused the abnormal variation in the diurnal activity of Przewalski's gazelle, which tended to keep away from the highway when the traffic flow was high (Li et al., 2009). By comparing differences in behavioral time budgets before and after the operation of Qinghai-Tibet railway, it was seen that male Tibetan antelopes were initially affected by the Qinghai-Tibet railway, but gradually adapted to its presence (Miao et al., 2020).

Roads also affected amphibian behavior. In the Northeast China region, for example, Chinese brown frogs (*Rana chensinensis*) demonstrated a clear tendency to cross culverts, while the Asiatic toad (*Bufo gargarizans*) tended to avoid culvert passages, and both species tended to cross culverts more frequently if they connected water bodies or had higher vegetation cover at the entrance (Lan et al., 2020).

3.2.4. Barrier effect

Following habitat loss and degradation LTI can act as barriers to wildlife movement, causing fragmentation, in addition to directly causing roadkill and altering animal behavior. Barrier effects can be assessed by field investigations involving infrared cameras, GPS telemetry collars, DNA analyses, and GIS. The barrier effects of LTI have been observed in a variety of rare and endangered species, including snow leopard, Siberian tiger, Siberian leopard, North Chinese leopard, black-necked crane (*Grus nigricollis*), Tibetan antelope, and Asian elephant, among others. The consequences of the barrier effects include reduced number of movement corridors, increased migration time/route distance, intensified human and animal conflict, restricted breeding pools, formation of road-effect zones, etc.

In the Qinghai-Tibet region, the Qinghai-Tibet highway and railway delayed the migration of Tibetan antelope, which potentially led to increased mortality of offspring and increased spread of disease (Buho et al., 2011). Delays may also be species specific, the time taken by Tibetan antelope to cross the road (156 s) was higher than the Tibetan gazelle (*Procapra picticaudata*) (28 s) and kiang (*Equus kiang*) (18 s) (Yin et al., 2006, 2007). The WCS across the Qinghai-Tibet railway was built at a non-optimal location that requires an 86 km detour off the optimal migration route (Xu et al., 2019). The Qinghai-Tibet highway and railway also have barrier effects on mammals which restrict genetic exchange, leading to genetic differentiation (Zhou et al., 2006; Yu et al., 2017).

In the Central China region, the gene flow among giant panda populations was blocked by the G108 in Sichuan province (Zhu et al., 2011). In the South China region, the Sixiao Expressway reduced the number of Asian elephant crossing corridors from 28 to 23 and the Kunman expressway blocked some of the herd's migration corridors (Pan et al., 2009). Asian elephants were also affected by barriers due to road traffic, and 82 % of human-elephant conflicts occurred along roads (Huang et al., 2019). In the Northeast China region, roads had negative effects on the distributions of Siberian tigers and their prey (Li et al., 2017).

Highways have been shown to act as relatively significant barriers towards ungulates such as kiang, Tibetan gazelle, and red deer (*Cervus canadensis*), among others (Zhou, 2014; Wang et al., 2020). The main factors that determine the degree of the barrier effects were: highway grade (Zhang et al., 2016; Feng et al., 2013), traffic volume (Yin et al., 2006; Zhang et al., 2016), location of WCS (Buho et al., 2011; Xu et al., 2019), distance between LTI (Wang et al., 2017a), etc. In addition, artificial disturbances along the roadside, including road construction and land use changes, can affect wildlife movement.

The 'road-effect zone' is defined as the area of the adjacent landscape into which the ecological effects of roads and traffic extend (Forman and Deblinger, 2000). Identifying the road-effect zone is important to better understand the conflicts between LTI and wildlife (Forman and Alexander, 1998). Road-effect zones vary considerably among different wildlife species, and can range from 50 to 5000 m in China. However, road-effect studies have mainly focused on mammals and birds, with very few studies on amphibians and reptiles (Appendix-3).

Some wildlife are highly adaptable or tolerant to barrier effects. For example, Mongolian five-toed jerboas displayed edge attraction along roads in the Mt. Kalamaili Nature Reserve (Ji et al., 2017) and the Gonghe-YuShu expressway has had trivial effects on lynx (*Lynx lynx*) (Wang et al., 2020). Along the Qinghai-Tibet railway, Tibetan antelope gradually became adapted to the WCS and retention time before crossing the WCS was reduced over time (Bu et al., 2013). The secondary highway in Changbai mountain area had no obvious impact on large and medium-sized animals, and the Siberian weasel (*Mustela sibirica*) even preferred to move close to the roadside (Wang et al., 2010, 2016).

3.3. Wildlife conservation and linear transport infrastructure

3.3.1. Wildlife and habitat survey

The distributions of wildlife, habitats, migration, or movement corridors along LTI are fundamental to proposals of various protection measures (Li et al., 2010). In the Central China region, when selecting the optimal giant panda corridors, key indicators such as habitat features, topography, construction cost, and feasibility were considered. Two optimal positions for a giant panda corridor were identified along the 306 km provincial highway in Sichuan Province (Gong et al., 2014). Using line and belt transect methods, surface water surveys, sign-tracking investigations, MaxEnt models, Linkage Mapper models, etc., hot-spots and movement corridors of wildlife were identified (Wu et al., 2020; Guan et al., 2020; Zhang et al., 2019; Wang et al., 2014; Zheng et al., 2017; Lian et al., 2012a, 2012b; Liang et al., 2016; Wu et al., 2020). This provided guidance for optimizing the locations of WCS. Similarly, in Xishuangbanna in the South China region, seven potential corridors were identified that linked different nature reserves, which should be considered stepping-stones for elephant movement and genetic communication (Liu et al., 2017).

3.3.2. Route selection

From the perspective of route selection, avoiding wildlife habitat is always the best solution, and Chinese engineers do endeavor to avoid wildlife habitats when designing routes (Chen et al., 2017). For example, newly built highways should avoid black-necked crane habitats by at least 135 m (Wang et al., 2011), new expressways should avoid existing highways and railways by at least 1500 m to mitigate disturbance to ungulates on the Tibetan plateau (Wang et al., 2017a). The new concept of "habitat cost" was proposed to quantify the impacts of road construction on wildlife habitats to ensure that the requirements of the habitat are considered during

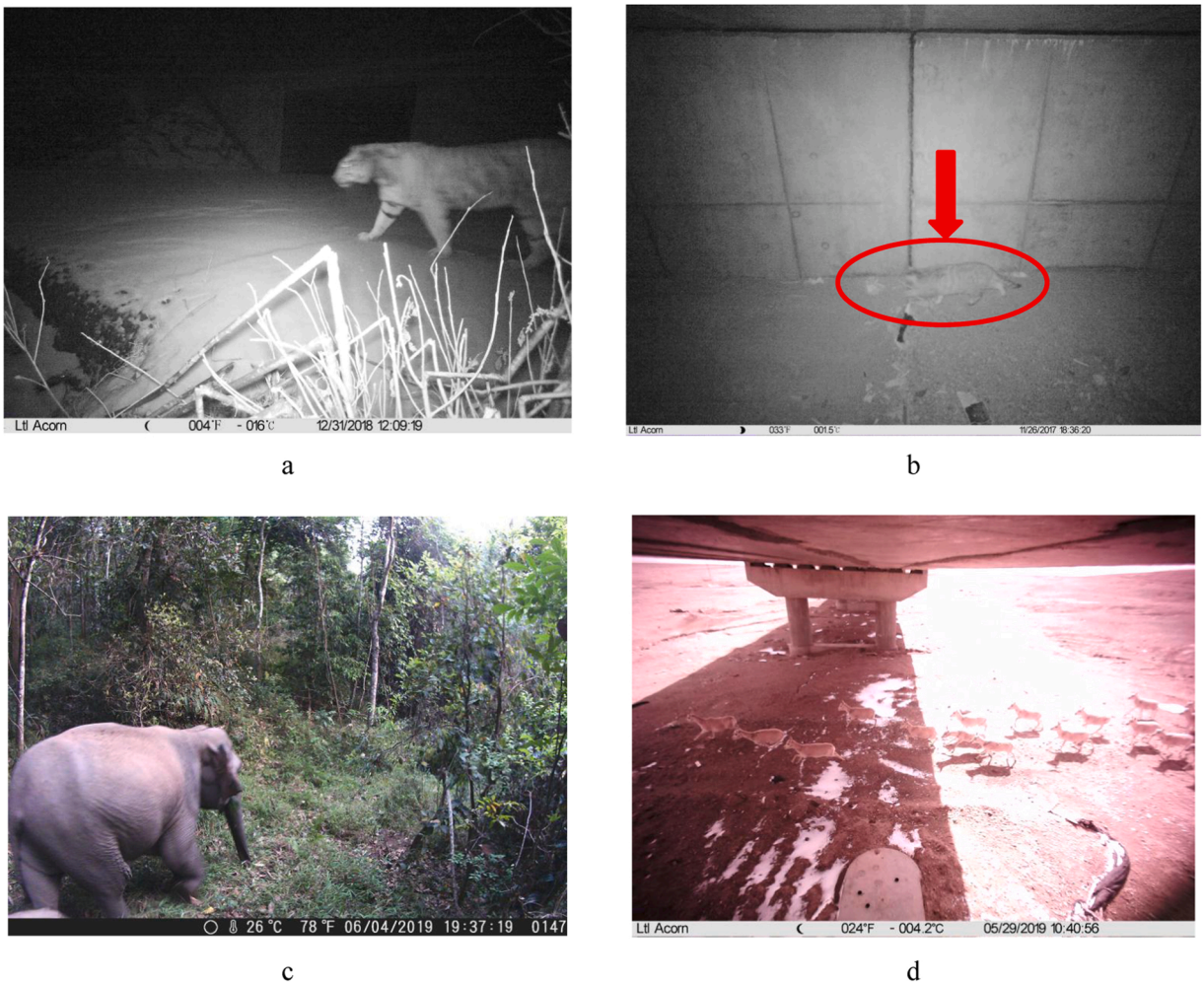

Fig. 3. Several typical monitoring pictures of wildlife crossing structure demonstration projects. a. Siberian Tiger approaching a culvert in Tiger and Leopard National Park, Northeast China; b. Pallas' cat using a culvert along G7 expressway, Neimenggu-Xinjiang region; c. Asian elephant using the habitat on top of the tunnel along Sixiao expressway, South China; d. Tibetan antelopes crossing under a bridge along Qinghai-Tibet highway, Qinghai-Tibet region.

route design and selection process (Gong et al., 2014).

3.3.3. Subgrade and pavement design

The impacts of LTI on wildlife can be reduced by optimizing the design of the subgrade and pavement, which can take many different forms. For example, in the Qinghai-Tibet region, minimizing pavement width has been shown to benefit amphibians in the Zoige wetland (Gu et al., 2011). Similarly, reducing the slope of highways facilitated safe crossing of the Qinghai-Tibet highway by Tibetan antelope (Wu et al., 2009). In the Central China region, noise reduction pavements are widely used to reduce the impact of road traffic noise on birds in the East Dongting Lake National Nature Reserve (Dong et al., 2008). In giant panda habitats, the bridge and tunnel ratios of highways can be increased to retain more habitat integrity (D. Wang et al., 2013). In the South China region, minimizing pavement widths and limiting vehicle speeds have reduced the impacts of traffic on movement of Francois's langur (*Trachypithecus francoisi*) (Dong et al., 2018). In addition, building roadside ditch walls with gradients $< 45^{\circ}$ effectively facilitated the escape of amphibians in XiKeng reservoir (Zhang et al., 2010) and Changbai Mountain area in Northeast China region (Wang et al., 2019b).

3.3.4. Design of wildlife crossing structures

Most WCSs are built for mammals, and relatively few for birds, amphibians, and reptiles (Appendix-4). Most WCSs are underpasses and few are overpasses (traffic tunnels) or canopy crossings. The design of WCS for mammals must consider location, type, density, size, attractive habitat, and auxiliary facilities (Zhang et al., 2019; Wang et al., 2018; Han, 2014). China has designed many WCS in different areas, including in the Qinghai-Tibet region (Wu et al., 2009), Changbai Mountain in Northeast China (Wang et al., 2017b), tropical forests in South China (Pan et al., 2009), dry and semi-arid areas in Neimenggu-Xinjiang (Zhang et al., 2019), among others. These WCSs facilitate the movement of animals and connect habitats for endemic and endangered species, including Asian elephants, giant panda, Tibetan antelope, etc.

The design of WCS for amphibians should consider location, attractive habitat (small-scale pond groups and migration corridors), utilities for protecting migration corridors (fences, structures for easy entry and exit, alert signs), and evaluations of efficiency (Wang et al., 2017c). The first amphibian crossing structure was established in the Northeast China region (Wang et al., 2017c).

The attractiveness of habitats can be determined based on vegetation, water bodies, terrain, and available micro-habitats. Attractive habitats can be used to entice wildlife across WCS and prevent wildlife from entering paved areas and being killed by vehicles. Attractive habitats are mainly designed for mammals and amphibians, such as the giant panda (D. Wang et al., 2013), Rhesus macaque (*Macaca mulatta*) (Zhou, 2014; Li et al., 2019), Chinese brown frog, Asiatic toad (Z.C. Wang et al., 2017), etc. Cases of attractive habitat design and implementation are rare in China, and consequently, effective evaluations are lacking.

Auxiliary facilities include alert signs (Zheng et al., 2017; Zhou, 2014; Li et al., 2019), speed reduction belts (Xing et al., 2019; Zhou, 2014; Zheng et al., 2017; Luo et al., 2015), noise reduction measures (Zheng et al., 2017; Wang et al., 2018; Dong et al., 2008), shading measures (Wang et al., 2018), bird roadkill prevention structures (Zhou, 2014; Zhao, 2019), traffic flow control (Piao et al., 2016; Gu et al., 2011), tourist behavior control structures (Wang et al., 2013a), road closures (Jiang et al., 2014), etc. As the costs of these measures are relatively low, they have been widely utilized on road crossings in nature reserves, however, there have been very few studies evaluating their effectiveness.

3.3.5. Monitoring wildlife crossing structures

At the time of this review, there were 19 active WCS demonstration projects in 7 zoogeographical regions, but only 8 projects were being monitored (Appendix-4; Fig. 3). At the monitored WCS projects, monitoring time ranged from 14 days to 5 years. The monitoring methods included infrared cameras, snow tracking methods, and on-site observation, among others. Often, rare and endangered species such as the Tibetan antelope, Siberian tiger, and crested ibis were monitored specifically.

In the Qinghai-Tibet region, thirty-three WCSs have been established along the Qinghai-Tibet railway. The Tibetan antelopes have adapted well to the WCS. The utilization rate of the WCS reached 100 % in 2007, and the lingering and detention times while crossing the WCS have become shorter (Li et al., 2008; Yang and Xia, 2008). Tibetan antelope, kiang, and Tibetan gazelle have become accustomed to using small bridges to cross railways (Zhang et al., 2009). Canine predators prefer small bridges and culverts, while herbivores prefer large and middle-sized bridges (Wang et al., 2020; Feng et al., 2013).

In the Central China region, WCS are used by takin (*Budorcas bedfordi*), Chinese serow (*Capricornis milneedwardsi*), Reeve's muntjac (*Muntiacus reevesi*), and wild boar (*Sus scrofa*). The takin and Chinese serow tend to choose stone-substrate WCS, Reeve's muntjac prefer soil-based WCS, and wild boar had no obvious preference based on WCS substrate (Zhang et al., 2016). The ratio between crossing over and under a railway bridge was about 7:3 for crested ibises, while egrets (*Ardea alba*) were more likely to cross the railway below the bridge (Hu et al., 2020).

In the South China region, twenty-five Asian elephant corridors are continuously monitored along the Simao-Xiaomengyang expressway where it passes through the Xishuangbanna National Nature Reserve. The corridor utilization rate was only 44 % at the beginning of expressway operation, but the utilization rate reached 72 % after 10 years of operation, and the elephants exhibited preference for the corridors that overlapped with their original migration routes (Pan et al., 2009; Guan et al., 2020).

In the Northeast China region, thirteen medium and large animal species have been observed to cross highways using tunnels, bridges, and culverts. The utilization rates of bridges and culverts were 88 % and 44.2 %, respectively. Vegetation type, human interference, and size of WCS all significantly impacted utilization (Wang et al., 2013a, 2017b). Siberian tiger tracks were found above the highway tunnel in Changbai Mountain, indicating that the highway tunnel was benefiting the tigers (Jiang et al., 2014).

In the Neimenggu-Xinjiang region, at least 5 species of mammals and 14 species of birds were actively using WCS along the Beijing-

Xinjiang expressway, including wildcat (*Felis silvestris*) and Pallas' cat (*Otocolobus manul*). Based on the utilization rates of mammals and birds, bridges were superior to culverts. Furthermore, water and vegetation played important roles in guiding the movement of wildlife through the WCS (Li et al., 2019).

4. Discussion

4.1. Lack of research on the impact of LTI on terrestrial vertebrate species

Although research on the impacts of LTI on wildlife has been carried out in different regions of China, compared to international efforts, large knowledge gaps still exist. 1) Although LTI has been shown to greatly impact rare and endangered species (Xiao et al., 2019), comprehensive studies on the impact of LTI on populations, behaviors, and movements of animals are lacking. 2) The impact of roadkill on wildlife cannot be assessed at the national level because existing roadkill data are only available in scattered datasets that cover short time periods and small areas. Global assessments of vulnerability of mammals to roadkill are needed to guide roadkill related research (Grilo et al., 2021). 3) DNA methods and GPS collars are scarcely used in China, thus the barrier effects of LTI on wildlife are generally not evaluated satisfactorily. 4) The dynamics and mechanisms of changes in animal behavior caused by LTI are rarely studied. 5) Few studies have systematically and comprehensively considered the habitat, roadkill, behavioral, and barrier effect impacts of LTI. Furthermore, the cumulative effects of LTI on wildlife populations are unclear.

4.2. Efficiency of wildlife preservation measures in LTI are largely unknown

Though there are studies on the wildlife protection measures surrounding LTI in China, they are scattered across various provinces and are generally more geared toward qualitative analyses rather than quantitative. There are several specific protection methods that need to be further researched and reassessed. 1) Routes are selected to avoid crossing nature reserves according to legal requirements, but wildlife are often active outside their reserves because suitable habitats may be located outside of the reserves; so it is insufficient to only consider reserves. Furthermore, route selection does not fully consider wildlife habitat connectivity in terms of road network layout. Based on the latest international work, the unimpeded movement of species and the flow of natural processes are vital to sustaining biodiversity. Ecological connectivity is endorsed by the Convention on Migratory Species, and is a hot topic in road ecology research (Hilty et al., 2020). 2) Few studies have focused on the design of WCS for amphibians and reptiles and case studies of canopy crossings and overpasses are lacking. 3) At present, efforts to monitor WCS have been insufficient, with too few monitoring samples/sites, short monitoring times, few monitored species, and a lack of studies at the genetic level. Long-term monitoring is widely conducted in North America and Europe (Clevenger et al., 2009; Bhardwaj et al., 2020) and is vital to scientific evaluations of the effectiveness of WCS (Clevenger and Huijser, 2011). 4) With the development of natural protection systems in China, there is a lack of comprehensive research regarding wildlife conservation surrounding LTI (Wang et al., 2019a). These knowledge gaps make it difficult to enact specific conservation strategies based on specific conservation needs. 5) There is no published standard code for wildlife protection regarding LTI at the national level in China. Road ecology related guidelines have been published in many countries worldwide, and China should study successful experiences and compile its own standard code to guide LTI construction going forward.

4.3. Future research direction

China should carry out comprehensive, multi-disciplinary, cross-departmental research at the national level. This can be achieved by establishing a unified national data integration platform and actively integrating it into international research platforms.

4.3.1. Fundamental research

New technologies such as DNA barcoding and GPS collars can facilitate the systematic exploration of the impacts of LTI on wildlife at both macro and micro levels. These technologies enable the robust evaluation of habitat fragmentation, the characterization of typical wildlife movement and identification of wildlife corridors and movement bottlenecks, the description of road-effect zones and their dynamics. In addition, using citizen science to collect roadkill data and construct a national roadkill monitoring platform should be an important developmental direction. The knowledge provided by these technologies will help us comprehensively evaluate the impact of LTI on wildlife at different scales.

4.3.2. Preservation measures

At the route selection and road network level, road network density and spatial structures should be designed around habitat connectivity. At the highway design level, new technologies (e.g., GPS collars) should be used to identify wildlife movement corridors to guild site selection for WCS. Special research is required regarding WCS, especially amphibian and reptile WCS, canopy crossings, and overpasses. Nationwide continuous monitoring programs of WCS should be established to ensure long-term studies with large sample sizes and multiple species. Furthermore, other engineered measures designed to protect wildlife (drainage ditches, fence, etc.) and attractive habitats should be continuously monitored to determine their effectiveness. Furthermore, gene-level evaluations are required to further improve scientific assessments of WCS and ensure they comprehensively characterize the state of animal populations affected by roads.

4.3.3. Project demonstration

Most existing WCS were designed to be multi-functional, and specialized WCS are rare. As China starts to construct canopy crossings and overpasses, as well as underpasses, it is necessary to build prototype projects of different types of WCS so that their effectiveness can be evaluated and optimized. This will allow different types of WCS to be applied strategically to optimize their effectiveness and address the needs of natural populations of various scales and compositions.

4.3.4. Standard specification

At present, the existing standards and norms regarding wildlife preservation requirements for LTI are set in principle, but specific technical requirements and parameter specifications are lacking. Referring to China's zoogeographical regionalization based on terrestrial vertebrates, a variety of WCS designs along with monitoring guides should be established in each region, and the design parameters should be clarified with designs that are specialized for regional needs. These efforts will help guide customized wildlife protection efforts around LTI in each unique region. Finally, standardized specifications for WCS design and monitoring at the national level can be established to ensure that programs nationwide are comparable.

5. Conclusion

Although road ecology is relatively new in China, more and more research is being conducted. Synchronously, many kilometers of green LTIs will soon be constructed in China. Recently, the Second United Nations Global Sustainable Transport Conference was held in Beijing, and the Chinese government issued the "Report on Sustainable Transport in China", wherein road ecology was an important focus. Road ecology will be an important research sector in China as its LTI rapidly expands. In this paper, we provide conservation suggestions and directions for future research to best develop road ecology research in China. Furthermore, these suggestions and directions, if followed, will contribute to the development of environmental-friendly LTI along BRI corridors in the future.

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CRediT authorship contribution statement

Conceptualization, Y.W.; Methodology, Y.W. and J.Q.; Project administration, Y.W. and Y.P.; Resources, Y.W. and Y.H.; Writing – original draft, Y.W., J.Q. and Y.H.; Writing – review & editing, Y.W., J.Q., Y.P. and Y.H. All authors have read and agreed to the published version of the manuscript. All authors have read and agreed to the published version of the manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.gecco.2022.e02207.

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Further reading

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