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Review

Effects of roads on animals and mitigation measures in Asia

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ABSTRACT

Asia, the world's largest continent, boasts extensive road networks and rich biodiversity. However, the significant threats that roads pose to Asian ecosystems remain largely unaddressed. This study aims to provide a broad overview and insights into the research status regarding the effects of roads on animals and the implementation of mitigation measures in Asia through a comprehensive literature review, thereby filling a critical gap in global road ecology research. Following a systematic literature search and the establishment of inclusion and exclusion criteria, we included 589 publications, encompassing 36 Asian countries, while an additional 12 countries had no relevant publications included. From the included studies, we identified seven types of effects of roads on animals in Asia: road mortality, barriers to movement, road avoidance, various behavioral and physiological responses, habitat effects, illegal hunting, and road attraction. We compiled all documented roadkill data from pertinent research, resulting in approximately 208,291 roadkill records, including 1048 species, with 148 species classified as above Least Concern (LC) by the International Union for Conservation of Nature (IUCN). Asia has also implemented various mitigation measures. At least 155 species utilized wildlife crossing structures, with 39 species classified as above LC. Despite a considerable body of research in this field, there exists a notable imbalance in the geographical distribution of research across Asian countries and among the species that are the focus of research and mitigation. We propose several recommendations for future research directions in Asia, with many of these also relevant to future studies globally.

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1. Introduction

Asia is the world's largest continent, characterized by extensive road networks and rich biodiversity. Asia's total land area spans 44 million square kilometers, accounting for 29.4 % of the total global land mass, and comprising 48 countries (Sinomaps, 2022). Asia has a massive-scale and rapidly expanding road network. For instance, India and China each have a total road length exceeding 5 million kilometers (Sur et al., 2022; Ministry of Transport of the People's Republic of China, 2024), respectively ranking second and third in the world, following the United States. Meanwhile, Asia harbors numerous biodiversity hotspots (e.g., Indo-Burma, Sundaland, Japan, Himalaya), accounting for nearly one-third of the total 36 biodiversity hotspots globally (Conservation International, 2025); and plays critical roles in the conservation of biodiversity, carbon sequestration through its vast forest reserves, and the mediation of global climate conditions. While many of these ecosystem services and benefits are at risk from roads and other linear infrastructure, the threats posed by these anthropogenic factors in Asia have not been adequately addressed. Specially, in consideration of the urgent requirements outlined by the Kunming-Montreal Global Biodiversity Framework (Xu and Wang, 2023) and within the context of the Belt and Road Initiative in Asia, it is imperative to assess the impacts of road infrastructure on wildlife, and to implement appropriate wildlife protection measures, aimed at safeguarding ecological connectivity and conserving biodiversity during the development of transport networks.

Road ecology, formally recognized as an ecological sub-discipline at the beginning of this century, examines the effects of roads on the ecological environment (Forman et al., 2003). Over the past decades, road ecology research has experienced rapid global expansion, extending from developed continents (North America, Europe, Oceania) to developing regions (South America, Africa, Asia). The interaction between roads and animals constitutes a fundamental theme in the field of road ecology. Roads represent the most extensive infrastructure built by humans and have profound effects on animals (Forman et al., 2003; van der Ree et al., 2015; Rosell et al., 2023; Grilo et al., 2025). There has been a significant research trend of conducting literature reviews regarding the effects of roads on animals categorized by taxa (e.g., mammals: Benítez-López et al., 2010; birds: Benítez-López et al., 2010; Kociolek et al., 2011; reptiles: Andrews et al., 2008; amphibians: Andrews et al., 2008; Beebee, 2013; insects: Muñoz et al., 2015; bats: Fensome and Mathews, 2016; primates: Galea and Humle, 2022). However, existing global reviews in this domain seldom involve undeveloped regions, such as Asia; and although individual global reviews involve Asia to some extent, they are only focused on specific issues. For instance, Galea and Humle (2022) conducted a global review concerning the impacts of transportation and service corridors on primates, in which nearly half of the included studies took place in Asia. Quintana et al. (2022) reviewed road impacts on 36 apex predator species, and found that eight of the ten species with the highest risk from roads occurred in Asia. Notably, Collinson et al. (2019) performed a pertinent review on Africa, while Pinto et al. (2020) conducted a relevant review on Latin America. The development of road ecology in Asia has also been rapid. For instance, following other continents, Asia established its own transportation ecology conference (the 1st Asia Transportation Ecology Forum) in 2021 (Maierdiyali et al., 2022). Although Asia has accumulated a wealth of research on the impacts of roads on wildlife, there remains a lack of comprehensive literature reviews at the continental scale. Consequently, it is essential to elucidate the overall research status concerning the effects of roads on animals in Asia. This understanding is crucial for bridging the gaps in the global road ecology landscape.

Through a comprehensive literature review, we aim to provide a broad overview and insights into the status of research concerning the effects of roads on animals and the implementation of mitigation measures in Asia, thereby addressing a significant gap in the global field of road ecology. This endeavor not only offers essential guidance for future road ecology research in Asia, but also contributes to the global advancement of road ecology science and practice elsewhere.

2. Materials and methods

2.1. Literature search

The literature reviewed in this study was collected in two stages. First, between May and July 2023, we conducted a literature search using Scopus and the Web of Science. The time range for the literature search was up to the end of 2022. To search as much literature as possible, a top-down strategy using broad keywords was adopted. The keywords were divided into three groups, with a total of 2400 combinations ($50 \times 8 \times 6$): (1) the names of the 48 countries and one region in Asia, plus "Asia"; (2) eight words to describe taxa: wildlife, animal, vertebrate, mammal, bird, reptile, amphibian, insect; and (3) six words to describe the infrastructure: road, highway, motorway, expressway, vehicle, traffic. The raw numbers of the search results for each keyword combination are provided in Appendix S1. To further collect Chinese literature, a search was also conducted on a Chinese database (CQVIP) using Chinese keywords: "动物" (i.e., animal) + "公路"/"道路" (i.e., highway/road).

Second, for each piece of literature included in the review (see Section 2.2), we carefully checked its reference list to further collect relevant literature. This second stage of the literature search process yielded about one-third of all the literature included in this review.

2.2. Inclusion and exclusion criteria

Only literature written in English, or written in Chinese with English abstracts, was included. The following types of literature were not included: (1) those that were broad in nature, i.e., those that dealt with wildlife habitat selection or use, habitat suitability, or animal distribution, and in which roads (e.g., distance to road, road density) were just one of many general parameters investigated; (2) those that dealt with the impacts of roads on the environment, but that were only marginally related to the impacts on animals; and (3) those that dealt with human-wildlife conflicts or the distribution/conservation status of species, in which road mortalities were only a small consideration among many types of human-caused deaths or were only mentioned minimally. Furthermore, Master's and Doctoral theses, news sources, and individual relevant documents for which the full text could not be obtained were not included.

2.3. Literature classification, reading, and information extraction

Between July and September 2023, we classified all included publications based on the subject matter and collected additional literature by checking the reference list of each publication. Thereafter, we read and analyzed each publication more thoroughly and extracted predefined parameters, e.g., the literature source, publication year, country, species investigated, taxa, road characteristics, study method, time span, specific effect type, and main conclusions.

Additionally, during the review process, the classification of each publication was further refined and optimized, and the reference list of each publication was further examined for potential supplementary literature.

2.4. Literature synthesis

For the studies pertaining to roadkill, we conducted a comprehensive synthesis of the literature from multiple perspectives. In particular, we made efforts to compile roadkill data from Asia. Specifically, we extracted, screened, and consolidated all documented roadkill records. In the process of compiling this data, we meticulously examined and eliminated potential duplications across studies, considering factors such as study area, time span, species, and database. For other categories of impact, we synthesized the research themes, and endeavored to draw some general patterns. For the studies concerning mitigation measures, we also synthesized the literature from multiple perspectives.

3. Results

3.1. Temporal and spatial distribution of publications

In total, 589 publications (Appendix S2) encompassing 36 countries were included, among which 398 were written in English and 191 were written in Chinese. The vast majority of the publications were journal articles ($n = 543$, 92 %), with the remaining comprising 22 conference papers, 16 reports, and 8 books/book chapters. The earliest publication included was from 1984, with only 13 publications dated between 1984 and 2002. The remaining 576 publications were published between 2003 and 2022. The number of publications increased rapidly after 2010, with the largest number published in 2020 ($n = 54$) (Fig. 1). India had the largest number of English publications ($n = 103$), followed by China ($n = 102$), South Korea ($n = 37$), Malaysia ($n = 37$), and Japan ($n = 29$) (Fig. 2). Twelve countries, primarily located in Western Asia, did not have any studies included. It should be noted that 18 publications were related to more than one country. For these publications, we identified the countries involved and added them to the total number of publications of each country.

3.2. Overall research status in Asia

From all the included publications, we identified nine categories of subject matter, including seven types of effects of Asian roads on animals (i.e., road mortality, barriers to movement, road avoidance, various behavioral and physiological responses, habitat effects, illegal hunting, and road attraction, Fig. 3), mitigation measures, and review articles. It should be noted that 96 publications contained more than one of these nine categories.

3.2.1. Road mortality

Among the various effects of roads on animals, roadkill has been studied the most. We identified 166 publications (28 %) related to roadkill.

A total of 103 studies obtained original roadkill data by conducting formal field surveys, and the roadkill surveys spanned from two days to twelve years. Eleven studies described opportunistic observations. Forty-one studies mainly used secondary roadkill data for analysis. The secondary data were obtained from a diverse array of sources, such as various databases maintained by relevant government departments,

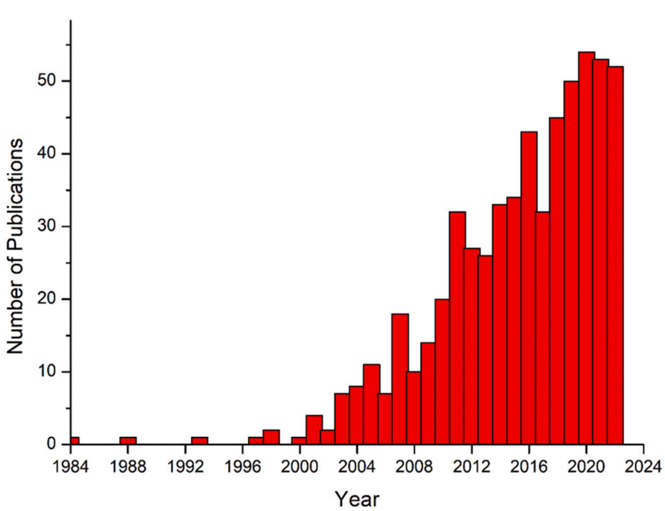

Fig. 1. The temporal distribution of all publications.

non-governmental organizations, citizen science, media, and interviews. Considering all the original and secondary documented roadkill data from these studies, there were approximately 208,291 roadkill records from 1965 to 2022 (Appendix S3). These records included 1048 species (212 mammals, 241 birds, 290 reptiles, 124 amphibians, 181 invertebrates; Fig. 4, Appendix S4), of which 148 were above Least Concern according to the International Union for Conservation of Nature (IUCN) Red List of Threatened Species (40 Near Threatened, 46 Vulnerable, 52 Endangered, 10 Critically Endangered) (IUCN, 2024).

The main focus of many roadkill studies was the identification of the spatiotemporal characteristics or factors related to roadkill, and 90 studies used statistical methods for analysis. It is worth mentioning that individual studies developed new models, such as hybrid consensus modeling (HCM), a novel model to identify roadkill hotspots based on the combination of kernel density estimation and maximum entropy (Karanasios et al., 2021), and a novel spatiotemporal roadkill distribution model (Lin et al., 2019). Many factors associated with roadkill were quantitatively explored in these studies, and we classified them into four main categories (Table 1).

Species-specific life history traits, such as foraging, thermoregulation, nesting, flight patterns, dispersal, and seasonal migration or activity for mating, reproduction, breeding, and hibernating, were generally used to qualitatively explain roadkill. For example, common factors increasing the risk of roadkill for birds contained searching for food such as seeds, grains, grits, and dead animals on or along roads, nesting alongside roads, and low flight height when crossing roads (Piao et al., 2016; Siva and Neelanarayanan, 2020; Sur et al., 2022). Butterflies were prone to roadkill when migrating across roads during the breeding period (Vadivalagan et al., 2012; Saraf and Jadesh, 2017). The life-history and morphological traits of reptiles and amphibians, including foraging or thermoregulation on roads, seasonal migration for breeding or hibernation, body size, low movement speed, and slow reaction to vehicles, made them vulnerable to roadkill (Baskaran and Boominathan, 2010; Tok et al., 2011; Chyn et al., 2019; Shin et al., 2022; Wang et al., 2022).

Roadkill can have serious impacts on the viability of wildlife populations. Roadkill was the main cause of human-caused mortality for the Persian leopard (*Panthera pardus saxicolor*, Naderi et al., 2018) and brown bear (*Ursus arctos*, Nayeri et al., 2022) in Iran. One study estimated that at least 5 % of the otter (*Lutra lutra*) population in Israel died on roads each year between 2000 and 2004 (Guter et al., 2005). The significant gender bias of land crab (*Sesarma haematoche*) roadkill in coastal areas of Korea was predicted to potentially result in local population decline (Ryu and Kim, 2020). Roadkill had a medium impact on the golden langur (*Trachypithecus geei*) population in Bhutan (Thinley et al., 2020), as well as the Jilin clawed salamander (*Onychodactylus zhangyapingi*) and Siberian wood frog (*Rana amurensis*) populations in China's Changbai Mountain Nature Reserve (Wang et al., 2021). Some studies predicted that the leopard (*Panthera pardus*) in Rajaji National Park and the Hariwar Conservation area of North India might be extinct in 50 years if the observed roadkill level persists (Grilo et al., 2021), and that roadkill incidents would reduce the adult tiger (*Panthera tigris*) population by 39 % over 20 years in Nepal's Chitwan National Park (Carter et al., 2022).

Animal-vehicle collisions (AVCs) also have serious consequences for human safety; eight studies reported on human fatalities and injuries caused by AVCs. Additionally, roadkill data can also be used to compile large-scale density index maps of wildlife (Tatewaki and Koike, 2018).

3.2.2. Barriers to movement

We identified 68 publications (12 %) that dealt with barriers to movement. In these studies, mammals were the primary focus ($n = 55$), followed by birds ($n = 4$), amphibians ($n = 3$), reptiles ($n = 1$), and invertebrates ($n = 1$).

Barrier effects depend on species characteristics, road and traffic characteristics, and surrounding landscapes and human disturbance. For

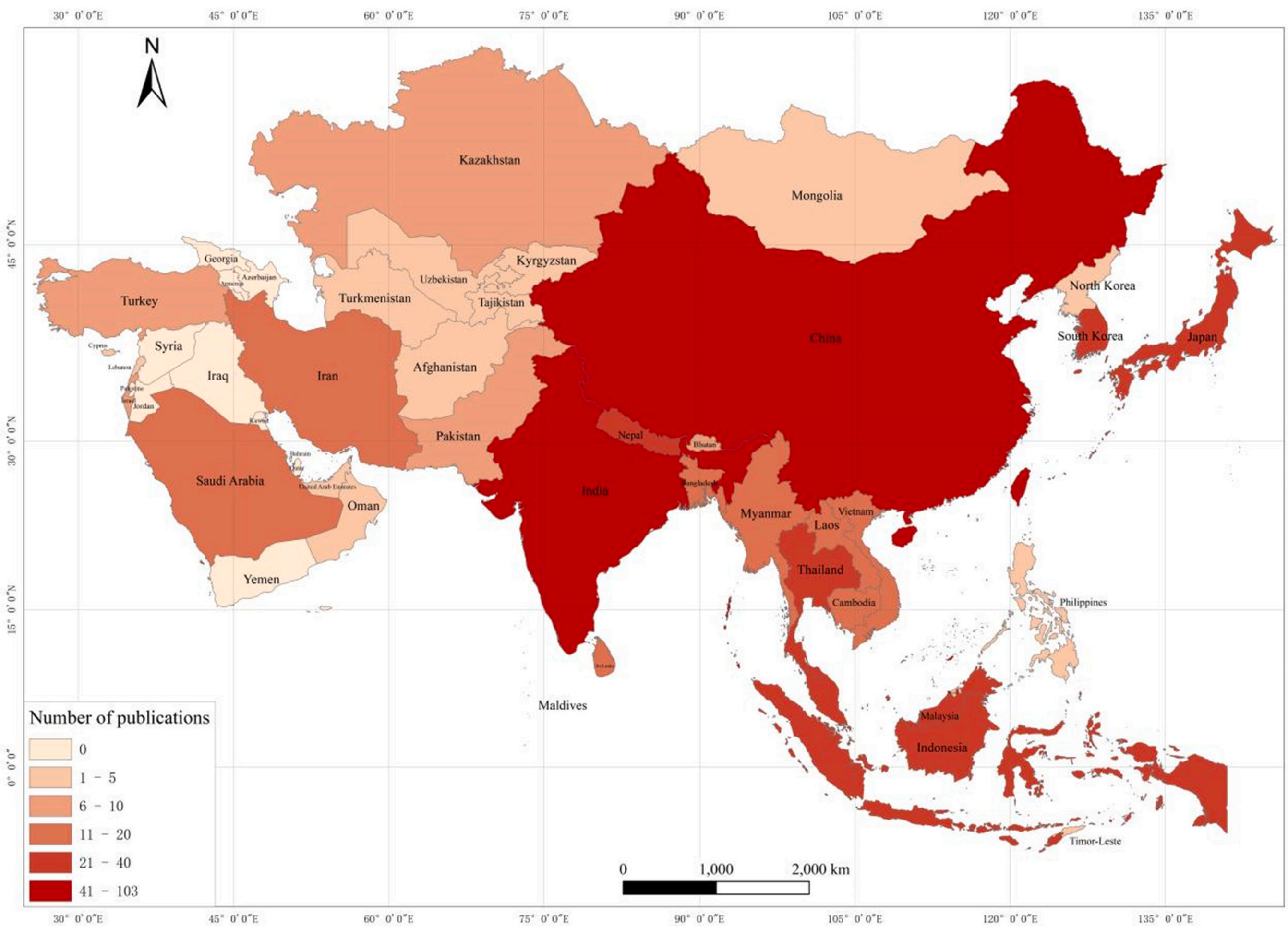

Fig. 2. The country distribution of English publications between 1984 and 2022.

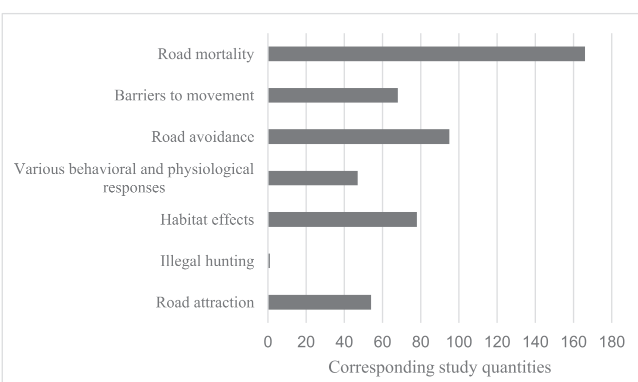

Fig. 3. Seven types of effects of Asian roads on animals.

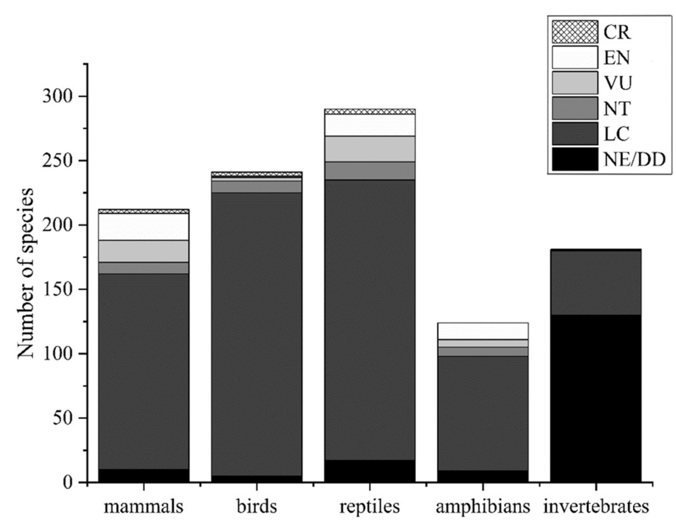

Fig. 4. The class and protection level of animal roadkill in Asia (CR–Critically Endangered, EN–Endangered, VU–Vulnerable, NT–Near Threatened, LC–Least Concern, NE/DD–Not Evaluated/Data Deficient).

some small animals impacted by barrier effects, the physical presence of the road itself was considered an obstacle. In China's Mt. Kalamaili Nature Reserve, the paved road acted as a barrier for great gerbils (*Rhombomys opimus*, Ji et al., 2017). In Nopporo Forest Park in western Hokkaido, Japan, even narrow unpaved roads acted as barriers against the movement of carabid beetles, and both the increase in the road width and the presence of road surface pavement had negative impacts on their road crossing rates (Yamada et al., 2010). In a tropical forest in northern Vietnam, two understory bird species, namely the puff-throated babbler (*Pellorneum ruficeps*) and buff-breasted babbler (*Pellorneum tickelli*), were reluctant to cross narrow forest roads (Thinh et al., 2012). For some large animals impacted by barrier effects, traffic intensity was found to play an important role. In Peninsular Malaysia, the road had a strong barrier effect on the movement of Asian elephants (*Elephas maximus*)

Table 1
The factors associated with roadkill that have been quantitatively explored.

	Factors
Species-related	Taxonomic group, sex, adjacent population density, distance to roads, habitat range, elevational distribution, body width, body length, body mass, forearm length, wingspan, echolocation call type, frequency of maximum energy in echolocation calls, frequency of road crossing, traversing speed, traversing angle, the ability to dodge oncoming vehicles, and group size.
Road and traffic	Traffic volume, speed limit, vehicle type, vehicle length, vehicle width, road density, road type, road length, road width, road slope, road alignment (straight or curved), raised ground, number of traffic lanes, median barrier, roadside barrier (retaining wall, guard rail, fence), underpass, cutting, drainage, bridge, tunnel, exit, connectivity, and roadside vegetation (type, density, height, mowing).
Landscape and environment	Latitude, elevation, agricultural land (e.g., rice field, pasture, orchard), woody area (e.g., various forest types, shrubs), grassland, wetland or water body (stream, river, reservoir, sea), barren land, beach, ridge, dumping ground, protected area, residential area, building, recreational park, tourist site, mining, ranger station, overhead cable, roadside open area, temporal factors (year, season, month, festival, time of day), weather (rainfall, temperature, humidity), moon brightness, artificial light, and habitat assessment (habitat quality score, habitat fragmentation index, habitat richness, habitat heterogeneity, habitat suitability index).
Other human-related	Local human population, number of tourists, artificial feeding, visibility, drivers' reaction to animals on the road, bad driving behavior (inattention to the road ahead, speeding, overtaking, sudden lane change, failure to control the vehicle), hunting mode, and survey effort.

(reducing permeability by an average of 79.5 %), and most of their road crossing occurred at night when traffic density was lower (Wadey et al., 2018). In central India, a sub-adult male tiger (*Panthera tigris*) crossed roads more than six times faster than it moved normally, and crossed roads more often at night to avoid high traffic density (Hussain et al., 2022). In China's Hoh Xil Nature Reserve, the road crossing of the Tibetan antelope (*Pantholops hodgsonii*), Tibetan gazelle (*Procapra picticaudata*), and kiang (*Equus kiang*) was negatively affected by vehicle traffic (Yin et al., 2006).

An important consequence of the barrier effect of roads is reduced gene flow and reduced genetic diversity. Ten studies demonstrated that the gene flow of several species was affected by road barriers, e.g., the Asiatic black bear (*Ursus thibetanus*, Vaeokhaw et al., 2020), the jungle cat (*Felis chaus*, Thatte et al., 2020; Tyagi et al., 2022), the leopard (*Panthera pardus*, Thatte et al., 2020), the tiger (*Panthera tigris*, Thatte et al., 2018; Thatte et al., 2020), the giant panda (*Ailuropoda melanoleuca*, Zhu et al., 2011), the plateau pika (*Ochotona curzoniae*, Zhou et al., 2006), the Japanese brown frog (*Rana japonica*, Kobayashi et al., 2018), Boie's wart frog (*Fejervarya limnocharis*, Garcia et al., 2017), and the tree sparrow (*Passer montanus*, Zhang et al., 2013).

3.2.3. Road avoidance

We identified 95 publications (16 %) related to road avoidance, indicating that roads and traffic repel animals away from the vicinity of roads. Among these publications, mammals were the most frequently studied ($n = 66$), followed by birds ($n = 24$), invertebrates ($n = 13$), amphibians ($n = 5$), and reptiles ($n = 3$).

Different animals exhibit road avoidance behaviors for various reasons. For certain taxa, particularly smaller species, the factors influencing road avoidance were found to be closely linked to the environmental conditions that are critical for their life history. For instance, in subtropical evergreen forests on Okinawa Island, southwestern Japan, the avoidance behavior of collembolan species was affected by changes in the soil moisture content and litter density caused by the change of the vegetation structure in the vicinity of roads (Hasegawa et al., 2015). In Shangyu and Shenyang, China, the pollution generated by road and traffic changed the content of heavy metals in the soil surrounding roads, which subsequently affected the soil fauna community structure adjacent to roads (Han et al., 2009; Li et al., 2010a). Environmental humidity was found to be of great significance to the survival and reproduction of amphibians. For example, ornate rice frogs (*Microhyla ornate*) on China's Kinmen Island, a species that typically resided in shady and humid environments, avoided road edges (Lin, 2015). Some small mammals avoided roads mainly due to changes in vegetation and habitat structure and composition induced by road construction (Rhim et al., 2012). Certain larger mammals and birds avoided roads mainly due to direct disturbances caused by roads and traffic (Li et al., 2009; Gubbi et al., 2012; Bista et al., 2022), such as traffic noise (Zhang et al., 2012; Shieh et al., 2016; Dhananjani and Mahaulpatha, 2022).

Road avoidance means that a road creates an effect zone, the extent of which varies among different animal species, with some reaching several kilometers, e.g., those for moose (*Alces alces cameloides*, Jiang et al., 2009; Hu et al., 2013) and giant pandas (Zhao et al., 2017; He et al., 2019). Avoidance behavior impacted the duration of the activities of some animals, and even altered their circadian rhythms (Griffiths and van Schaik, 1993; Li et al., 2009; Habib et al., 2020; Watabe and Saito, 2021). Road avoidance was also found to exacerbate habitat fragmentation and indirectly give rise to habitat loss, especially for animals with a high degree of habitat specificity, such as moose (Hu et al., 2013), giant pandas (Zhao et al., 2017; He et al., 2019), red pandas (*Ailurus fulgens*, Bista et al., 2022), sambar deer (*Rusa unicolor swinhoii*, Yen et al., 2013), sables (*Martes zibellina*, Li et al., 2014), and Asian elephants (Sharma et al., 2020).

3.2.4. Various behavioral and physiological responses

A total of 47 publications (8 %) demonstrated that roads and traffic can exert a range of impacts on the behavior or physiological health of animals, e.g., affecting vigilance, foraging, resting, escape behavior, flight patterns, seed dispersal, breeding, acoustics behavior, group characteristics, or physiological functions. Among these studies, the majority were conducted on mammals ($n = 22$), followed by birds ($n = 12$), aquatic animals ($n = 9$), amphibians ($n = 3$), and insects ($n = 1$).

For instance, when Tibetan antelope were close to roads, their vigilance and movement increased, while their foraging decreased (Lian et al., 2011; Ru et al., 2018, 2022). The alert distance and flight initiation distance of the Xinjiang ground jay (*Podoces biddulphi*), white-rumped snowfinch (*Montifringilla taczanowskii*), plain-backed snowfinch (*Montifringilla blanfordi*), and rufous-necked snowfinch (*Montifringilla ruficollis*) decreased significantly with the increase of the road effect (Ge et al., 2011; Xu et al., 2013). Roads limited seed dispersal service by rodents (Cui et al., 2018; Chen et al., 2019; Niu et al., 2021) and by dung beetles (Hosaka et al., 2014). Exposure to traffic noise increased exploration behavior and cortisol concentrations but decreased the resting metabolic rate of plateau pikas (*Ochotona curzoniae*, Qu et al., 2022), impaired certain physiological functions of the golden hamster (*Mesocricetus auratus*, Ma et al., 2016), and caused spotted doves (*Spilopelia chinensis*) to alter their acoustics behavior to reduce the masking effects of traffic noise (Shieh et al., 2016). Furthermore, the toxicity of road runoff had considerable adverse physiological effects on *Bufo viridis* (Dorchin and Shanas, 2010) and benthic animals (Watanabe et al., 2011; Hiki et al., 2019).

3.2.5. Habitat effects

A total of 78 publications (13 %) demonstrated that roads can impact habitats through habitat loss, habitat fragmentation, and loss of connectivity, as well as a reduction in habitat suitability or quality. These studies encompassed a range of scales, from macro-level analyses to assessments focused on specific species.

Several studies have documented habitat fragmentation in China on a national scale (Li et al., 2004, 2010b). Some rare species have been affected severely by road-induced fragmentation in China, e.g., the snow leopard (*Panthera uncia*), Cabot's tragopan (*Tragopan caboti*), and Przewalski's gazelle (*Procapra przewalskii*, Zhang et al., 2015). About 14 % of the habitat units for goitered gazelle (*Gazella subgutturosa*) and about 9 % of the habitat units for wild sheep (*Ovis orientalis*) were lost after freeway construction in Ghamishloo Wildlife Refuge in Iran (Makki et al., 2013). Roads were found to reduce the habitat suitability or quality for various species, e.g., sambar deer (Yen et al., 2013), Asian elephants (Liu et al., 2017), and giant pandas (Fan et al., 2011; Kang et al., 2020).

3.2.6. Illegal hunting

One study (Clements et al., 2014) illustrated that roads facilitate illegal hunting in Peninsular Malaysia, which can be considered an indirect effect that roads have on wildlife.

3.2.7. Road attraction

Roads and roadsides can also attract animals by providing them with advantages, and 54 publications (9 %) fell within this category of research. Mammals were the most frequently studied taxa ($n = 29$), followed by birds ($n = 16$), invertebrates ($n = 11$), amphibians ($n = 6$), and reptiles ($n = 4$).

In contrast to road avoidance, road attraction results in a higher density of certain species near roads as compared to farther away. The behaviors on or near roads include foraging, hunting, nesting, breeding, thermoregulation, and ease of movement. For instance, roads provided various food sources, such as roadside vegetation, road-killed animals, the presence of prey along roads, food offered by humans, litter dropped by humans, and grit for a wide range of animal species, from insects to large mammals, e.g., Asian elephants, yellow weasels (*Mustela sibirica*), Iriomote cats (*Prionailurus bengalensis iriomotensis*), dholes (*Cuon alpinus*), and several bird, ungulate, primate, frog, and insect species. Roadsides were also preferred nesting sites for some bird species mainly because there were fewer predators (Rao and Koli, 2017; Khamcha et al., 2018; Zhou et al., 2020).

3.2.8. Mitigation measures

We identified 95 publications (16 %) on wildlife protection associated with road infrastructure development.

Protection measures for wildlife along roads in Asia have been considered at all stages of road development. Wildlife crossing structures (WCSs) were studied the most, including underpasses ($n = 32$), overpasses ($n = 16$), and canopy crossings ($n = 11$). Additionally, 11 studies addressed the locations of WCSs. Sixteen studies focused on animal detection systems; these were primarily from Saudi Arabia and India and were related to house animals (e.g., camel and cow) and large-sized animals (e.g., Asian elephants). Some studies also centered on the design of other road facilities, such as driver warning signs, roadside ditches, and fences ($n = 9$), and route selection and optimization ($n = 4$).

The WCSs considered in these studies were used by 155 species, including 90 mammals (37 above LC), 21 birds, three reptiles (two above LC), two amphibians, and 39 invertebrates (Fig. 5, Appendix S5).

The most frequently used research method was camera trapping, which was employed in 24 studies. Following that, the investigation methods (e.g., the line transect method, pitfall traps, footprint traps, snow tracking, sign surveys, direct animal sightings) were used in an additional 17 studies. Twelve studies applied GIS and modeling techniques, such as habitat suitability assessments and the MaxEnt model. GPS collars were used in two studies, and unmanned aerial vehicle (UAV) remote sensing was utilized in one study. Interviews and questionnaires were employed in four studies. Notably, nine studies implemented field experiments, five of which conducted control and experimental samples, and two of which monitored before-and-after measurements. Less than half of the studies provided information on road and traffic conditions, such as the number of lanes, road surface type, speed limit, and traffic volume. Of the 40 studies with defined research periods, the majority (n = 32) were conducted within two years. Twenty-four studies had a duration of less than one year, including a few that lasted for only one to two months. Only three studies spanned over five years. Two studies, from South Korea and India, considered population-level factors. Cost-benefit analyses of mitigation measures have not been observed.

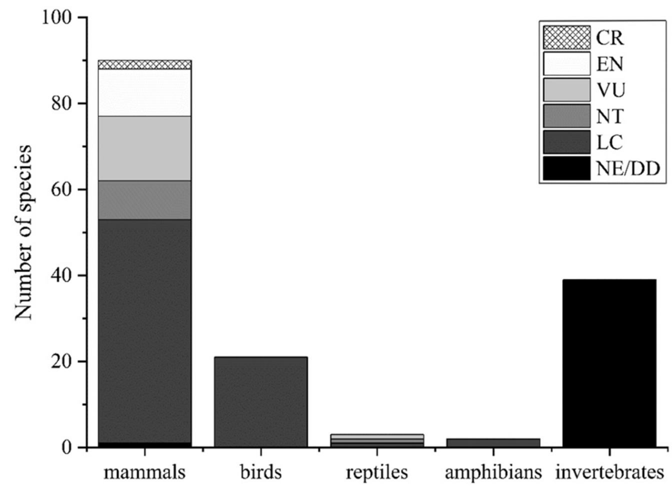

Fig. 5. The class and protection level of animals utilizing WCSs in Asia.

3.2.9. Review articles

A total of 72 review articles (12 %) were found, among which 34 were written in English and 38 were written in Chinese, and can be roughly divided into three categories: (1) reviews on certain effects of roads on wildlife in a certain country, e.g., roadkill in South Korea (Hong et al., 2022); (2) globally relevant reviews, in which Asia occupied an important share, e.g., the effects of roads on primates worldwide (Galea and Humle, 2022); and (3) reviews, commentaries, or guidelines authored by Asian scholars regarding certain effects or mitigation measures, drawing from some domestic or international literature.

4. Discussion

Asia's extensive road network intersects with its rich biodiversity. Through the identification of seven distinct types of ecological impacts, it becomes evident that roads in Asia exert widespread and profound effects on wildlife.

Over 1000 species have been killed on Asian roads, ranging from the largest mammal, the Asian elephant, to various small insects. Among the Asian road-killed species, there are 867 terrestrial vertebrate species, which is nearly 30 % more than that found in Latin America (Pinto et al., 2020). The higher roadkill diversity in Asia may reflect differences in road density, biodiversity baselines, or research effort. Research on other types of effects in Asia, although predominantly focused on mammals, is noteworthy in that each category of effect encompasses multiple taxa, ranging from vertebrates to invertebrates, which reflects the breadth of research related to Asia, and indicates that any given taxon may be subject to various complex ecological effects imposed by roads, necessitating ongoing research to deepen understanding. The categories of effects we identified are derived from the outcomes of impacts on animals. For instance, we did not categorize noise, pollution, and similar factors as distinct categories of effect, as seen in some related review studies (e.g., Kociolek et al., 2011; Muñoz et al., 2015). Instead, we consider these to be influencing factors, while the outcomes of these influences are manifested in the animals' behaviors and physiological responses. Furthermore, in the presentation of results, we also emphasize summarizing general patterns or analytical perspectives by synthesizing the relevant literature, in order to provide broader research insights. For instance, we categorized the factors associated with roadkill that have been quantitatively examined in relevant studies into four major categories, encompassing a wide range of specific factors, offering a useful framework for guiding factor selection in future roadkill research.

Compared to other continents, research regarding interactions between roads and animals in Asia started relatively late. For instance, many studies had been conducted in Europe and North America prior to the 21st century, enabling Forman et al. (2003) to write their seminal *Road Ecology* textbook. The geographical distribution of road ecology research is also still very uneven among Asian countries, especially between East and West Asia. Studies are primarily concentrated in a few countries, while many countries have either not begun road ecology research at all or have only produced a limited number of publications to date.

While many roadkill studies have been produced in Asia, their quality varies, particularly in terms of data collection protocols and analytical depth. The influencing factors of roadkill demand broader and more thorough investigation. Moreover, only a few roadkill studies evaluated population-level impacts. We put forward the following suggestions for future roadkill research in Asia, and many of which also apply globally. First, the establishment of roadkill databases is of critical importance. Citizen science is an efficient way to collect roadkill data in a flexible manner across wide areas (Shin et al., 2022). The roadkill database developed through citizen science in the Taiwan region is an exemplary model (Hsu et al., 2018; Chyn et al., 2019). Nevertheless, data from citizen science are often collected opportunistically, and there are likely many kinds of biases that should be avoided or taken into account when analyzing the data (Chyn et al., 2019). Therefore, it is better to systematically collect roadkill data with consistent search and reporting effort, preferably with a minimum set of parameters and established protocols. An example of this is the Korea Road-kill Observation System (KROS) launched by the South Korean government in 2018 to integrate roadkill data on a national scale (Kim et al., 2019). Second, while many factors associated with roadkill have been explored worldwide, most studies have only taken a few explanatory factors into account (Pagany, 2020). More importantly, because the relationships between explanatory factors are often quite complex, more sophisticated models (e.g., structural equation modeling) should be employed or developed to help understand the importance and interrelatedness of the individual factors. Third, emphasis should be placed on conducting population-level studies to evaluate the threat of roadkill to the viability of local populations (Grilo et al., 2021; Moore et al., 2023).

In addition to roadkill, studies on other impact categories still involve a limited range of species, with a predominant focus on mammals. It is imperative to broaden the scope of road ecology research to highlight various types of effects, include a larger number of countries, and take into account a more diverse range of species. This can serve as the foundation for evaluating the cumulative effects of roads on wildlife on a large scale, which can also facilitate the integration of the mitigation hierarchy into the strategic planning process of transportation networks and ultimately avoid potential negative impacts on biodiversity.

While some flagship species have received significant attention and study, many other endemic and endangered species require further research. For instance, the Asian elephant has not only been extensively researched in the context of road development by relevant Asian countries, but has also garnered global interest, promoting the IUCN Asian Elephant Working Group to establish and publish two guidelines (Ament et al., 2021; Dodd et al., 2024). In the future, it is imperative that the protection of individual species is transcended and that a broader range of species and ecosystem concerns is integrated throughout the entire road development process.

The studies on mitigation measures in Asia have mainly centered on WCSs, with mammals as the primary target species. While Asian birds, reptiles, amphibians, and invertebrates are greatly impacted by roads, the design and monitoring of mitigation measures for these groups are scarce. Additionally, studies on road network layouts and route selection to safeguard wildlife during road planning are limited, even though such avoidance measures are essential and should be considered before other mitigation measures. Infrared cameras and field investigations are frequently employed to monitor mitigation measures in Asia, whereas other advanced techniques, such as GPS collars, are seldom utilized. The assessments of the mitigation measures in Asia also often lack robust scientific methods and frequently have the following limitations: (1) the duration is too short to document seasonal or annual patterns of impacts; (2) BACI (Before-After-Control-Impact) designs and benchmark comparisons are essential for the scientific evaluation of WCS effectiveness; however, they are infrequently utilized in studies; (3) studies that adopt population variables are very rare; (4) information and variables related to road traffic, which are essential for understanding wildlife-road interactions, are often overlooked. (5) The economic evaluation of mitigation measures is crucial; however, cost-benefit analyses of mitigation measures are not only rare in Asia but are also relatively scarce worldwide (Ascensão et al., 2021).

Based on the identified research gaps in Asia and insights gained from other continents (e.g., Global: Denneboom et al., 2021; Soanes et al., 2024; Europe: Rosell et al., 2023; Latin America: Pinto et al., 2020; Africa: Collinson et al., 2019), the following recommendations are proposed to guide future mitigation research and practices in Asia. First, strategic environmental studies concerning road network layouts at the strategic planning level, and which incorporate the mitigation hierarchy and assess cumulative effects, should be conducted prior to the selection of a specific route and the design of any mitigation measures. Second, Asia should improve the systematic and scientific design and assessment of WCSs, particularly in relation to: (1) BACI research designs should be used to guide assessments for WCSs. (2) Monitoring should encompass a duration of at least 2 to 3 years prior to the commencement of construction, continue throughout the construction phase until its completion, and extend for a period of 3 to 10 years, or even up to 15 years, during the operational phase. The specific duration will depend on the research questions being addressed and the metrics being evaluated (Rosell et al., 2023). (3) The design of WCSs should integrate a comprehensive array of road-related factors (e.g., structures, materials, density, shape, ditches, slopes, warning signs, speed bumps, noise barriers, traffic volume, speed limits, and animal detection systems); furthermore, it is essential to adhere to species-specific best practices and evaluate the impact of these designs on the population viability of target species (Denneboom et al., 2021; Soanes et al., 2024). (4) GPS collars have proven to be valuable tools for locating WCSs, and their broader application in Asia is recommended (Dodd et al., 2024). (5) Cost-benefit analyses for WCSs should be carried out. (6) Standards and regulations pertaining to WCSs as well as other mitigation measures across all Asian countries should be published to enhance wildlife protection during the road development process. To date, several organizations and countries have established such standards, such as the Asian Development Bank (ADB, 2019), the Convention on Migratory Species (Wingard et al., 2014), the IUCN (Dodd et al., 2024), China (GB/T 43646-2024, 2024), and India (WII, 2016).

This study has limitations and areas for further exploration in the future. First, we only included literature written in English, or in Chinese with English abstracts. Reviewing literature written in other languages is beyond our current capabilities. Second, the research subject of this study is roads, akin to the predominant emphasis observed in the majority of road ecology research. However, although on a much smaller scale than roads, other linear infrastructures, such as railways and fences, may also significantly impact biodiversity, warranting dedicated review studies in the future. Third, this study seeks to provide a broad overview and insights into the research status regarding the effects of roads on animals and the implementation of mitigation measures in Asia. We recommend that future studies build upon this research by selecting one or more impact categories to conduct more in-depth investigations into specific issues, such as Medrano-Vizcaíno et al. (2022) and Moore et al. (2023).

5. Conclusion

This study provides a groundbreaking comprehensive review of road ecology research in Asia. Over the past two decades of rapid development, road ecology in Asia has made significant strides and amassed a substantial body of research. However, there exists a notable imbalance in the geographical distribution of research across Asian countries and among the species that are the focus of research and mitigation. The studies examining the effects of roads on animals in Asia encompass a broad range of topics, from which we identified and categorized seven types of effects. Furthermore, we undertook efforts to compile roadkill data in Asia, which may significantly contribute to the global science and practice of road ecology. This endeavor, for instance, provides a crucial foundation for future large-scale roadkill research at the intercontinental level.

Asia should draw lessons from other continents to circumvent previous errors in road development. With the swift advancement of road ecology, Asia has the opportunity to integrate successful strategies from other regions into its road development processes. Furthermore, principles and practices of road ecology customized for Asian contexts can be developed, thereby contributing to the global advancement of road ecology.

CRediT authorship contribution statement

Haotong Su: Writing – review & editing, Writing – original draft, Software, Resources, Methodology. **Yun Wang:** Writing – review & editing, Writing – original draft, Supervision, Software, Resources, Funding acquisition, Data curation. **Qilin Li:** Writing – original draft, Methodology, Formal analysis, Conceptualization. **Yangang Yang:** Methodology, Formal analysis. **Abudusaimaiti Maierdiyali:** Methodology, Formal analysis. **Shuangcheng Tao:** Resources, Project administration. **Yaping Kong:** Resources, Project administration. **Jiding Chen:** Resources, Project administration. **Jiapeng Qu:** Writing – review & editing, Methodology, Formal analysis. **Yongshun Han:** Writing – review & editing. **Aili Kang:** Writing – review & editing. **Shu Chen:** Writing – review & editing. **Yoichi Sonoda:** Writing – review & editing. **Wendy Collinson-Jonker:** Writing – review & editing. **Jed S. Merrow:** Writing – review & editing. **Marcel P. Huijser:** Writing – review & editing. **Lazaros Georgiadis:** Writing – review & editing. **Rodney van der Ree:** Writing – review & editing.

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.

Data availability

Data can be located in the Appendix.

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Appendix A. Supplementary data

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