Landscape Ecol (2020) 35:69–81
https://doi.org/10.1007/s10980-019-00930-8

RESEARCH ARTICLE

Quantifying the effects of road width on roadside vegetation and soil conditions in forests

Ting Zhou · Xiaoying Luo · Yuping Hou · Yanci Xiang · Shaolin Peng

Received: 3 August 2019 / Accepted: 28 October 2019 / Published online: 27 November 2019

Abstract

Context The majority of ecological studies of roads have focused on their deleterious effects, and these preconceptions have hampered a full evaluation of the ecological functions of roads. As an integrated indicator, road width represents comprehensive effects, including anthropogenic and natural disturbances.

Objectives We try to explore the different effects produced by various road widths by considering changes in forest vegetation and soil.

Methods We selected six study forests spanning from Shandong Province in the north to Guangdong Province in the south of China, and we assessed the influences of wide and narrow roads on plant species diversity, biomass, and soil properties along transects running from the forest edges and adjacent forest interior. We used a "shape-dependent model" to explain the factors that determine the magnitude of road effects on forests.

Results Three variables measured in this study changed significantly with increasing distance from the road to the forest interior along wide roads: tree biomass, herbaceous plant biomass, and soil pH. However, no measurable biological or environmental effects were found from narrow roads. The different shapes of glades in a forest may be one reason for the various effects caused by roads of different widths.

Conclusions Forest roads of different widths may have quite different ecological effects. While wider roads with large glades tend to have substantial negative impacts, small-enough roads may cause little disturbance to the forest. This suggests that not all forest roads should be perceived as the same, and narrow roads may be compatible with forest conservation.

Keywords Road · Width · Forest conservation · Shape-dependent · Plant, soil

---

T. Zhou (✉) · S. Peng (✉)
State Key Laboratory of Biocontrol, School of Life Sciences, Sun Yat-sen University, Guangzhou 510275, China
e-mail: zhout32@mail.sysu.edu.cn

S. Peng
e-mail: lsspsl@mail.sysu.edu.cn

X. Luo
College of Tourism and Geography, Shaoguan University, Shaoguan 512000, China

Y. Hou
School of Life Sciences, Ludong University, Yantai 264025, China

Y. Xiang
School of Architecture and Art Design, Hunan University of Science and Technology, Xiangtan 411201, China

Introduction

Road construction is almost completely restricted or forbidden in forest conservation and management, especially in nature reserves, although the function of roads is self-explanatory. Over the last few decades, interest in the study of the ecological characteristics of the edges associated with roads has increased (Marcantonio et al. 2013). Seven categories of effects of roads on terrestrial and aquatic ecosystems have been reviewed: increased mortality from road construction, from collision with vehicles, modification of animal behavior, alteration of the physical environment, alteration of the chemical environment, spread of exotic species, and increased alteration of habitats by humans (Trombulak and Frissell 2000). Numerous negative effects of forest roads on the remaining forest have been reported, and the road construction is considered the primary cause of habitat fragmentation (Watts et al. 2007). Roads dissect previously large patches into smaller ones, and they create forest edge habitat along both sides of the road (Reed et al. 1996). This can lead to a change in community composition because species that depend on particular interior habitat conditions would be removed (Avon et al. 2010). Thus, retention of the remaining roadless or near-roadless portions of the landscape and restoring some roads are critical for maintaining habitat integrity (Trombulak and Frissell 2000). Areas without roads or little traffic (“roadless and low-traffic areas”) provide many benefits for biodiversity and human societies. Furthermore, the few remaining roadless and low-traffic areas in Europe should be an important focus of conservation efforts (Selva et al. 2011). Since the 1970s, conservation science has successfully informed the public and administrative concerns regarding roadless area protection, including the transformation of public policy discourse regarding roadless area management and the protection of the remaining roadless areas in natural forests (Turner 2006). Generally, to protect the integrity of forests, fewer roads should be built.

At the same time, many studies have shown that different road types will have different biological–environmental effects. For example, the road texture (surface) has an effect on species composition within the community (Godefroid and Koedam 2004). The type of trail and the use of trails by tourists interact with habitat characteristics may alter the activities of mammals in close proximity to these disturbed areas (Zhou et al. 2013). In particular, roadside effects were found to be greater and more pervasive than trailside effects (Wolf and Croft 2014), and transects adjacent to less used, unpaved trails were far less affected than roads (Zhou et al. 2013). Vegetation diversities in glades, rides and roads are different in plantation forests: in rides, the most important plantation feature in determining plant diversity is ride width, while increasing edge-to-area ratio corresponds to a decrease in β-diversity within glades (Smith et al. 2007). An in-depth or greater understanding of road effects can help manage the impacts of roads (Delgado et al. 2007; Kunert et al. 2015).

As a result, roads do not have completely negative effects. Previous research showed that road segments had no significant effects on plant species diversity since unnecessary cut and fill operations were avoided in the studied road (Tehrani et al. 2015), and the width of the road was narrow. Plant species richness and diversity are highest in the plots closer to the hiking trails (Queiroz et al. 2014). Some species benefited from increased light intensities on abandoned logging roads, and others benefited from low densities of competing vegetation on roads with compacted soils in a tropical Bolivian forest (Nabe-Nielsen et al. 2007). These items, together with the ability of the ecosystem to repair itself, can mitigate the negative effects of roads (Tehrani et al. 2015). In fact, the size of a road can affect many other elements, including anthropogenic and natural disturbances. Roads of different dimensions represent open patches of different sizes in the forest community, with concomitant effects on species associations (Thornton et al. 2011) and the extent of forest fragmentation. Habitat loss, degradation and fragmentation are also related to road size (Forman 2006). Therefore, the road size can affect the influence roads have on forest ecosystems to a certain extent.

The majority of ecological studies of roads have focused on their deleterious effects, and these preconceptions have hampered a full evaluation of the ecological functions of roads (Zeng et al. 2011). In fact, we often observe more tall trees and herbaceous cover near forest paths, and some animals forage, migrate, and participate in other activities along roadsides. Roads seem to have some positive effects because in closed forest ecosystems, light availability is a major constraint on tree growth and survival, and the idea that canopy gaps contribute to the maintenance of tree species diversity has a long history in forest ecology (Gravel et al. 2010). Roads can also be seen as canopy gaps in some sense. Appropriate disturbances typically cause changes in the local microclimate by opening up space in the canopy, resulting in heterogeneous habitat, and heterogeneous resources allow species with different niche requirements to meet their habitat requirements, which leads to higher species diversity (Bartels and Chen 2010). The intensity of the effect of spatial heterogeneity is associated with patch size. The response of a species to the patch variable is affected by the patch size (Thornton et al. 2011). Based on these theories, we proposed a hypothesis: road with different width would produce different characteristics of biological effects, environmental effects and longitudinal effects. To verify this hypothesis, we evaluate vegetation and soil properties across gradients from roadsides to forest interiors. Along transects perpendicular to roads in six forest nature reserves spanning from Shandong Province in the north to Guangdong Province in the south of China, we measured vegetation types, stand characteristics, and soil physicochemical characteristics.

Methods

Study area

We selected six samples distributed from north to south China (Fig. 1), Kunyushan (KYS) Nature Reserve in Shandong Province (121° 37′–121° 51′ E, 37° 12′–37° 18′ N), Hengshan (HS) Nature Reserve in Hunan Province (112° 34′–112° 44′ E, 27° 10′–27° 20′ N), and Danxiashan (DXS) Nature Reserve (113° 36′′′–113° 47′ E, 24° 51′–25° 04′ N), Dinghushan (DHS) Nature Reserve (112° 30′–112° 33′ E, 23° 09′–23° 11′ N), Heishiding (HSD) Nature Reserve (111° 49′–111° 55′ E, 23° 25′–23° 29′ N), and Baiyunshan (BYS) (113° 16′–113° 19′ E, 23° 09′–23° 13′ N) in Guangdong Province, China. KYS is a warm temperate deciduous broad-leaved forest, HS is a mid-subtropical evergreen broad-leaved forest, DXS, DHS, HSD and BYS are lower subtropical evergreen broad-leaved forests. BYS is a national grade-AAAA scenic area located in the city of Guangzhou, and the others are nature reserves that conserve zonal vegetation. The studied roads had two widths (narrow = 2 m and wide = 6–8 m), which were used for different purposes. Roads of the two widths are commonly present, and the 6–8 m wide roads are utilized for transportation infrastructure while the 2 m wide roads are utilized as walking roads or access paths through the forests.

Sampling design and data collection

To explore the effects of roads in forest systems, a series of sample plots were placed at different distances from the road edge. Our design was based on the assumption that the most dramatic edge effects occur within 5 m of the road, according to our previous studies (Zhou et al. 2009), and other impacts attenuate within similar distances. Previous literature on the spatial extents of roadside effects indicated trends that were effects at either short distances of up to 15 m or long distances of > 50 m, as reviewed by Wolf and Croft (2014). For example, the pattern of plant species richness rapidly stabilized towards the interior (10 m) (Arevalo et al. 2008). Differences in species composition at forest edges and the interior penetrate approximately only 5 m into the forest (McDonald and Urban 2006). The vegetation and microclimate change abruptly within the first 5–10 m of the forest-road edges (Garcia et al. 2007), and the reduction in temperature near forest edges extended up to 20 m inside the forest (Ewers and Banks-Leite 2013). Based on these studies, we selected areas 25 m away from roads as plots.

We selected roads with two width categories: the wide group varied from 6 to 8 m across, and the narrow group was 2 m wide. We created a set of five transects corresponding to five different distances from an edge (0–5, 5–10, 10–15, 15–20, and 20–25 m). Transects were 10 × 5 m and ran parallel to the road, with the long side of the plot perpendicular to the road (Fig. 2). Data were collected from three replicate sites of each road type in each forest.

To characterize the environmental conditions at the study sites, we collected data on vegetation and soil. In each transect, we recorded the height and diameter in breast height (DBH) of the trees (higher than 1.3 m). In addition, we recorded the types of herbaceous plants and recorded the aboveground herbaceous biomass. We calculated the Shannon–Wiener diversity index, richness, and biomass of all trees and herbaceous

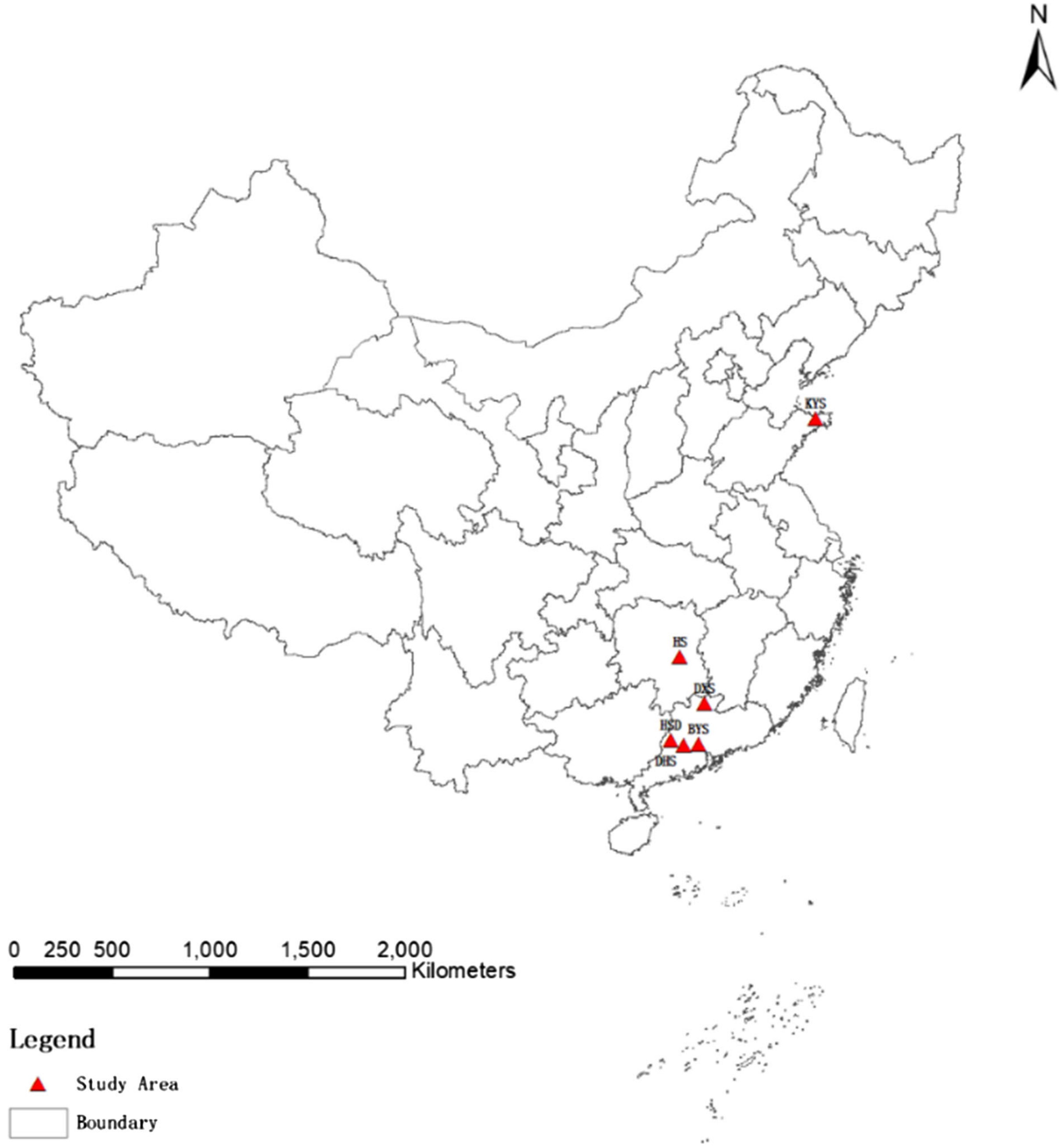

Fig. 1 Locational map of the six study forests (red triangle): Kunyushan (KYS) Nature Reserve in Shandong Province, Hengshan (HS) Nature Reserve in Hunan Province, and Danxiashan (DXS) Nature Reserve, Dinghushan (DHS) Nature Reserve, Heishiding (HSD) Nature Reserve, and Baiyunshan (BYS) in Guangdong Province, China

plants in each transect. Soil samples were collected at a depth of 0–5 cm from the surface at the three locations in each transect, and the subsamples were pooled to form a composite sample for each sampling location. We measured soil pH, moisture, available phosphorus, organic matter, and soil microbial biomass carbon. Soil water content, pH, and microbial biomass carbon were measured in fresh soil, and the remaining soil samples were air-dried in the shade in the laboratory.

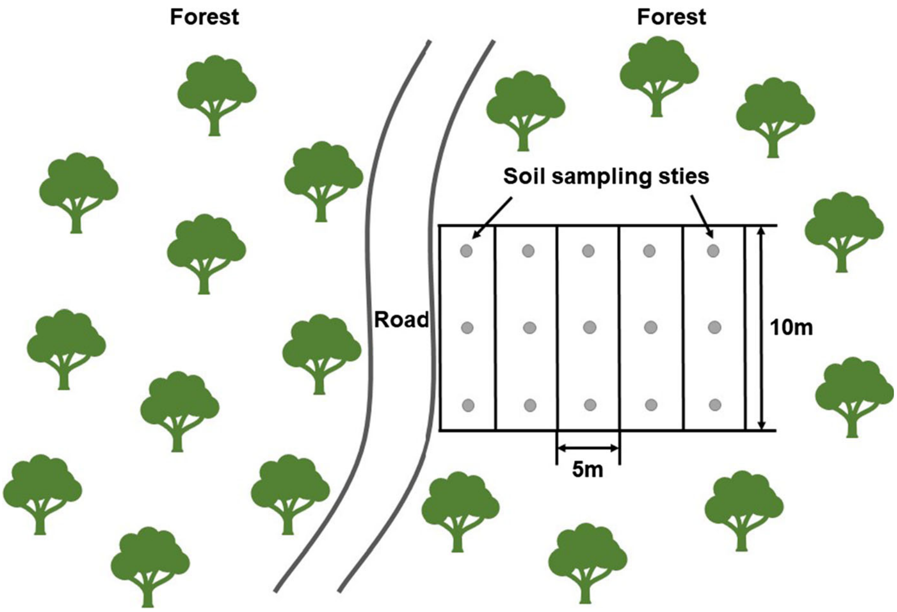

Fig. 2 Sample plots along the road. Diagram showing the sampling design used for the study of vegetation and soil compaction near forest paths

Data analysis

The parameters (vegetation biomass, Shannon–Wiener diversity index, richness, soil moisture, pH, microbial biomass carbon, total N, available P, and organic matter) were calculated and plotted against distance. All data were combined from all six mountain sites in a way that provided a more general view of how parameters vary with distance from roads using a Wilcoxon test. Statistical analyses were performed by SPSS 20.0, and data were analyzed using rank transformation analysis. This method first transformed the original variables into ranks, and then the newly generated ranks were analyzed by a one-way ANOVA. A Student–Newman–Keuls (SNK) multiple range test was used to make multiple comparisons (significance level of 0.05).

Clarification of shape-dependent effects

We hypothesized that shape-dependent effects are the mechanisms of different effects caused by roads with different widths, so we designed an experiment to clarify this relationship. We selected roads with widths of 2 m and 6 m, and a glade with a width of 30 m. These sites can be defined as three shapes with the same area, including long-narrow (2 m/width * 150 m/length), rectangle (6 m/width * 50 m/length) and similar square (30 m/width * 10 m/length). In particular, we selected the similar square site to represent extreme shape conditions. We surveyed the temperature and moisture at several sample sites on these roads, as shown in the figures. We collected five samples along the road from the road middle (S1), road transition (S2), road edge (S3) and forest interior (S4 and S5) (Fig. 3).

We calculated the temperature and moisture differences between the glade and forest interior in the three shapes, as follows:

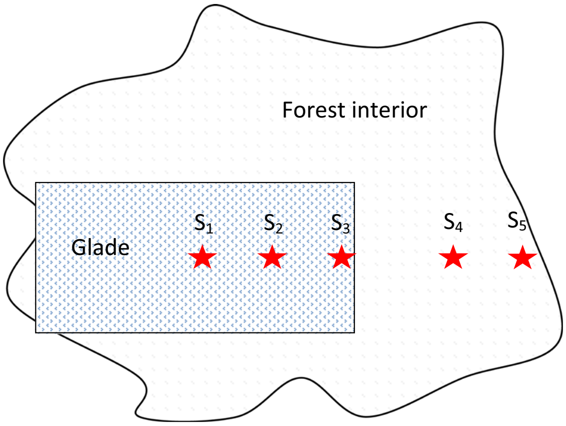

Fig. 3 The sketch of sample plots for testing the shape-dependent model. Five samples (red pentagram) were collected to survey the temperature and moisture along the road from the road middle (S1), road transition (S2), road edge (S3) and forest interior (S4 and S5)

$$\Delta \mathrm{M} = S_1 - (S_4 + S_5)/2 \quad \Delta \mathrm{T} = S_2 - (S_4 + S_5)/2$$
$$\Delta \mathrm{E} = S_3 - (S_4 + S_5)/2$$

where ΔM indicates the difference between the glade or road middle (M) and the forest interior, ΔT indicates the difference between the glade or road transition (T) area and the forest interior, and ΔE indicates the difference between the glade or road edge (E) and the forest interior. The variations of ΔM, ΔT and ΔE among the different shapes were calculated to reflect the differences caused by glades with different shapes.

Results

Vegetation properties in different transects from the roads to the forest interiors

The biomass of tree and herbaceous was highest in the transect within 5 m adjacent to the wide roads (Fig. 4), but there was no significant difference between the four transects within 5 to 25 m of the road. For the narrow roads, the vegetation biomass within 5 m along the road edges was higher than the four transects within 5 to 25 m of the road, but no significant difference was found.

In relation to vegetation biodiversity and richness, no significant differences were observed between the edges and forest interiors of wide or narrow roads (Figs. 5, 6). However, we noticed that plant diversity increased from forest edge to interiors along wide roads, while diversity decreased from forest edge to interiors along narrow roads (Fig. 5). No consistent trends were found with regard to plant richness, except that plant richness decreased from forest edge to interiors along narrow road (Fig. 6).

The soil moisture increased from the forest edges to the forest interiors along both wide and narrow roads without significant differences. The soil pH at the edge sites was significantly less acidic than that at the interior sites along the wide road, while no significant differences were found for the narrow road (Fig. 7).

Soil total N, organic matter and microbial biomass carbon tended to increase from the road edge to the forest interior, without significant differences along the wide road, while no effects of distance from the road on soil available P were found (Fig. 8). Moreover, these factors did not change along narrow roads.

Analysis of shape-dependent effects

The different shapes of glades in a forest may be one reason for the various effects caused by roads with different widths. At all locations (middle, transition area or edge) within the glade, the differences in air temperature and moisture were associated with glade shape (similar square, rectangle, or long-narrow). There were similar trends in the middle of the glade, in the transition zone between glade and forest, and at the edge of the forest. The temperature and moisture differences between the middle of a similar square glade and the forest interior were largest, followed by the rectangular glade and then the long-narrow glade

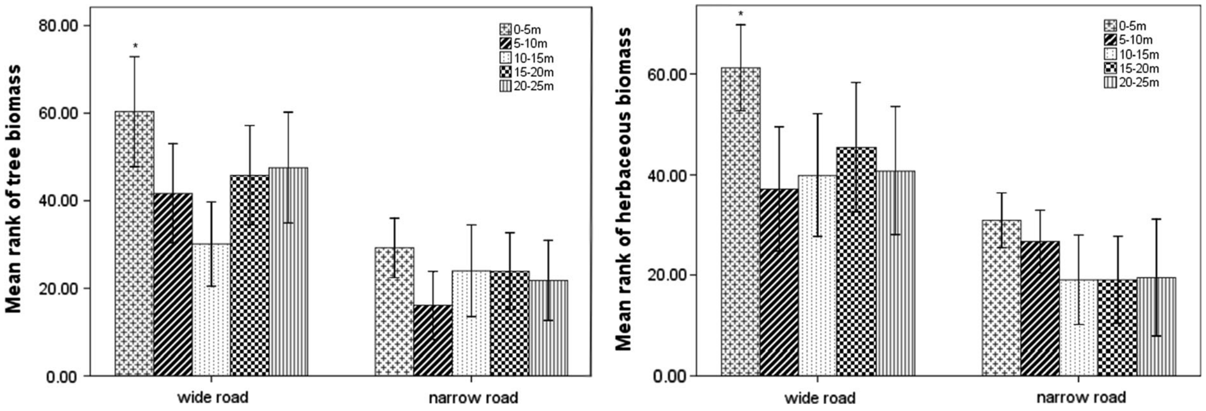

Fig. 4 Differences in plant (tree and herbaceous) biomass in transects along roads. The width of wide roads is 6–8 m, and the width of narrow roads is 2 m. The asterisks indicate significant differences at the 0.05 level among transects. Vertical bars represent standard errors

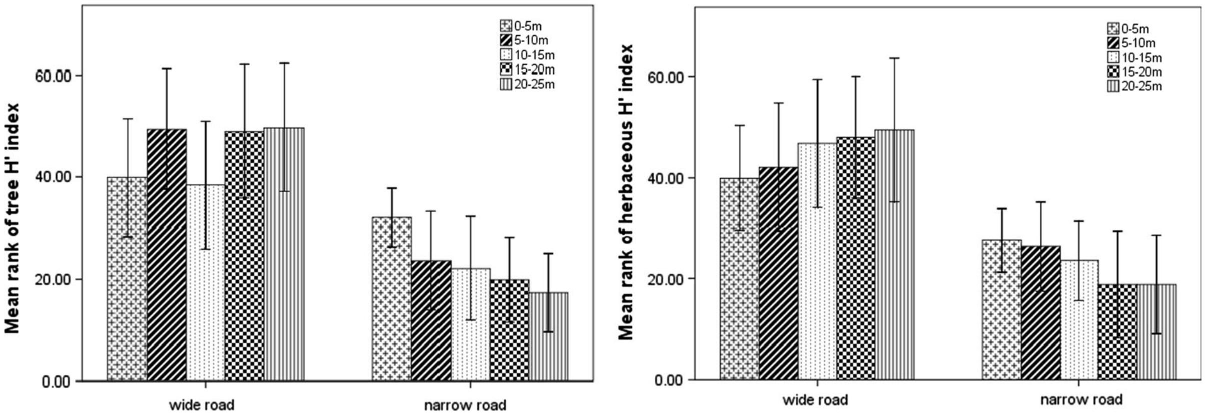

Fig. 5 Differences in plant (tree and herbaceous) diversity (Shannon–Wiener diversity index) in transects along roads. Vertical bars represent standard errors

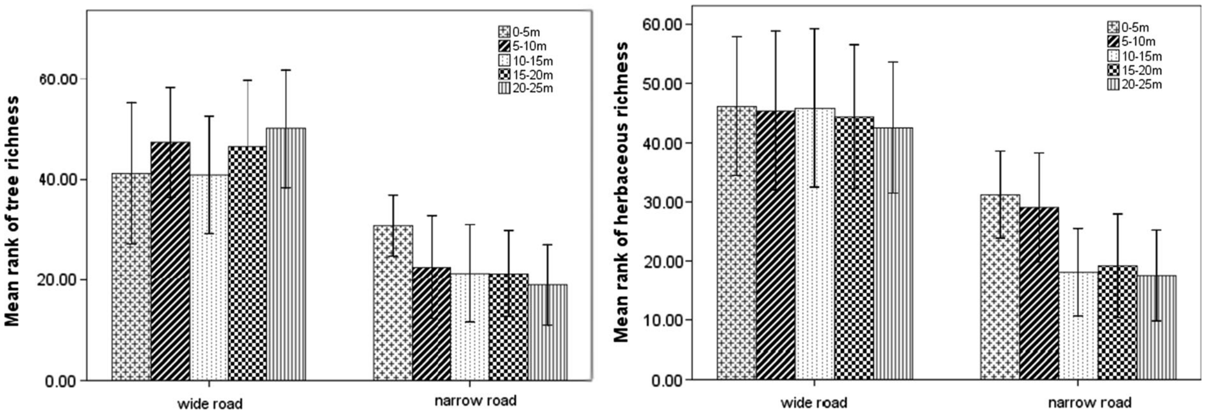

Fig. 6 Differences in species richness in transects along roads. Vertical bars represent standard errors

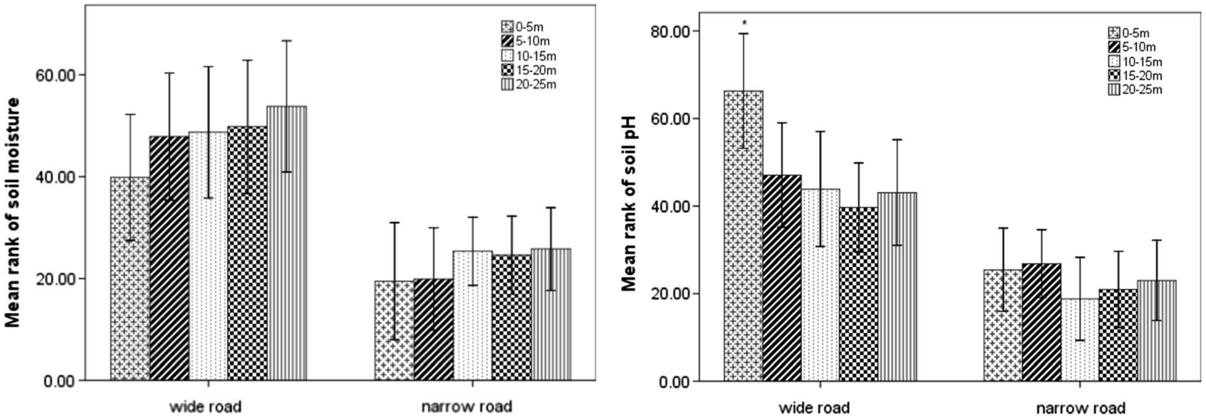

Fig. 7 Differences in soil moisture and pH in transects along roads. The asterisks indicate significant differences at the 0.05 level among transects. Vertical bars represent standard errors

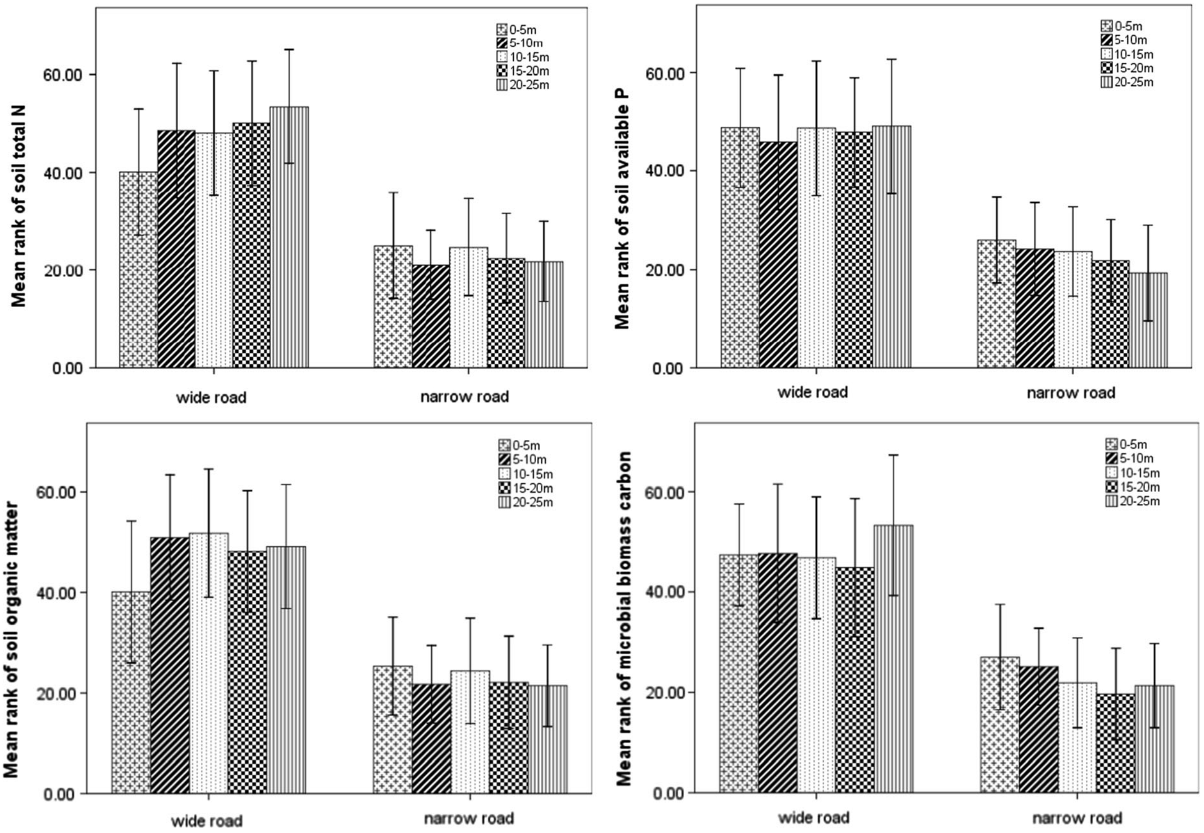

Fig. 8 Differences in soil total N, soil available P, soil organic matter and soil microbial biomass carbon in transects along roads. Vertical bars represent standard errors

(Fig. 9). These results indicate that patches in forests with different shapes will produce different effects on forests.

Discussion

Road width as the main factor behind various road effects on forests

Although our study sites cover different climatic zones, forest ages and road ages, the results indicated that three variables measured here changed significantly with increasing distance from the road to the forest interior along wide roads, including biomass (tree and herbaceous plant) and soil pH. The increase of biomass may be due to the fact that the roads have created open spaces that provide more sunlight and space for the growth of plants. For the narrow roads, none of the measured variables showed statistically significant differences between the edge and the interior. Narrow roads had no measurable effects on the biological-environmental conditions of the forest, and the differences between wide roads and narrow roads are caused by road width. Previous studies reported that the highest species richness and diversity were found in the plots closest to the trail (Queiroz et al. 2014), while other road segments (5–6 m wide) had no significant effects on plant species diversity (Tehrani et al. 2015). Even for non-native species spread, verges hosted but did not facilitate the spread of alien species, and it is necessary to highlight the importance of considering regional climatic gradients, landscape context and road-verge properties themselves (Kalwij et al. 2008). Especially for a well-preserved region, where road dependency is strong, and the proportion of uncommon non-native species is small (Liao et al. 2019). Therefore, these effects were mainly caused by road width, which is a comprehensive factor that integrates multiple factors (usage

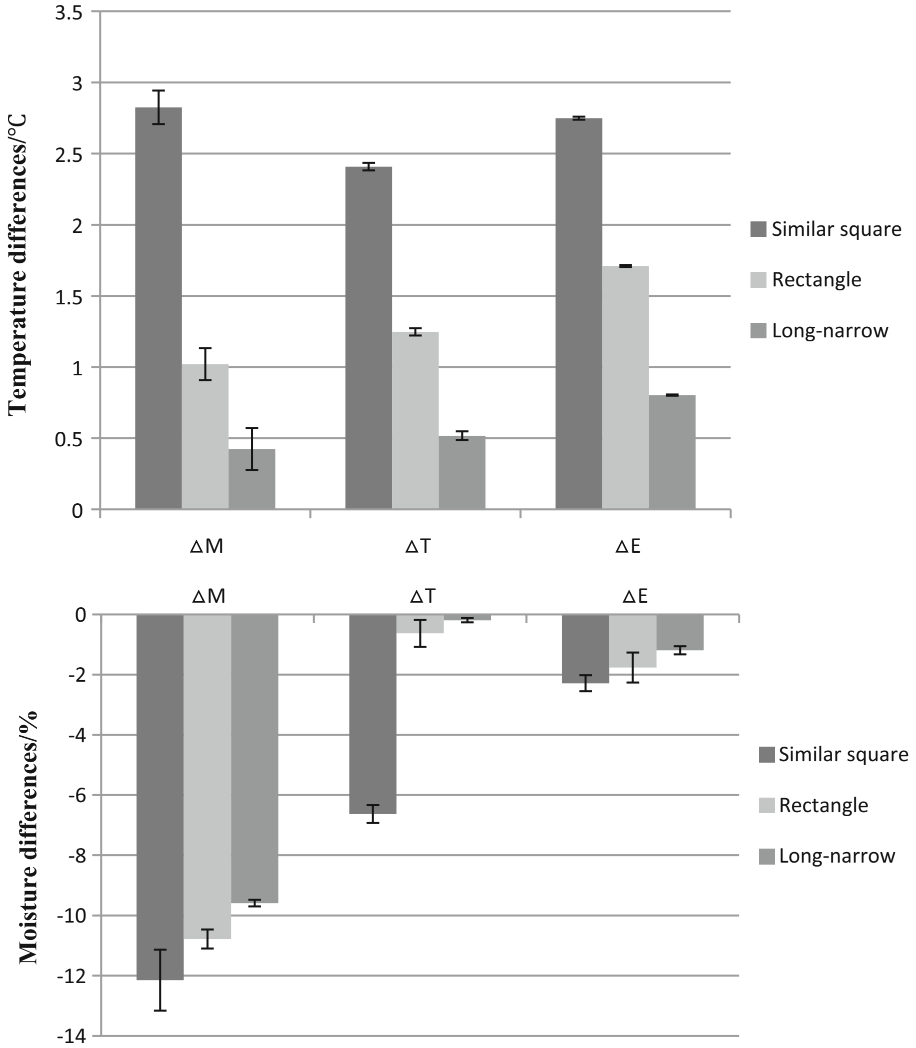

Fig. 9 ANOVA test for temperature and moisture differences of various glade and forest interior shapes. Three glade shapes were selected, including long-narrow (2 m/width * 150 m/length), rectangle (6 m/Width m/Width*150 m/Length)50 m/Length) and Similar square (30 m/Width *10 m/Length). ΔM indicates the difference between glade or road middle (M) and forest interior, ΔT indicates the difference between glade or road transition (T) area and forest interior, ΔE indicates the difference between glade or road edge (E) and forest interior

frequency, disturbance intensity, traffic volume, surfacing material, animal behavior and so on).

We propose a shape-dependent model to explain the road width effects. Two patches with the same area will produce completely different effects due to different shapes (Fig. 10). In all locations (middle, transition area or edge) in a glade, the differences in temperature and moisture were associated with glade shape (similar square, rectangle, or long-narrow). There were similar trends in the middle of the glade, in the transition zone between the glade and forest, and at the edge of forest. The temperature and moisture differences between the middle of the glade and the forest interior were largest in the similar square glade, followed by the rectangle and then the long-narrow glade. This result indicates that different shapes of forest patches will have different effects on forests. Previous research suggests that road permeability can be improved by maintaining canopy cover along short sections of roads (Chen and Koprowski 2016). That is,

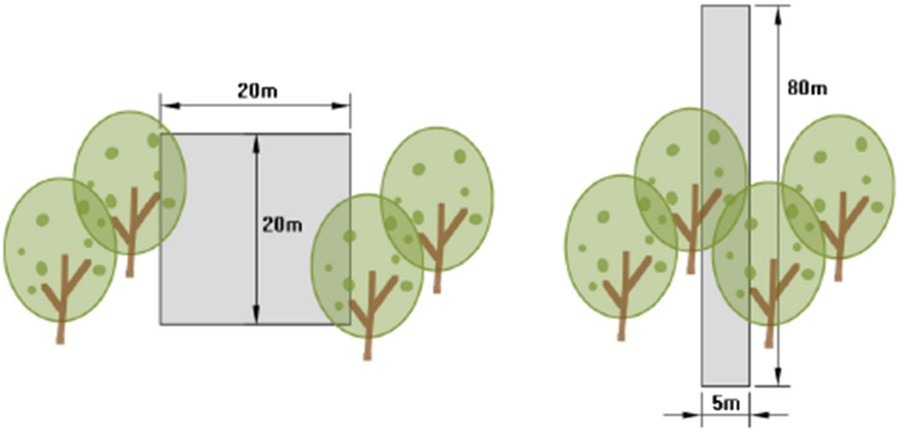

Fig. 10 The shape-dependent model of road effects on forests. Two road segments with the same area may produce quite different ecological effects due to their different shapes, with the wider road having a greater influence

canopy shelter causes the path to not have a significant impact. Our model indicated that road effects are induced by large forest gaps. Because a road has a large open area and a substantial influence on the entire forest path, there is no interference from the canopy, so the impact is relatively small.

In fact, road width is the main factor of various road effects on forests. For example, compared with informal trails (4 m), formal trails (2 m) had a protective effect on vegetation cover (Huang et al. 2015). Various effects of roads on forests are essentially caused by the road width. Narrow and gated roads, unlike wider and ungated roads, did not appear to contribute to edge effects on terrestrial salamanders (Marsh 2007). Road width and traffic density are major determinants of the barrier effect, whereas road surface (asphalt or concrete versus gravel or soil) is generally a minor factor (Forman and Alexander 1998). Road width was a good predictor of the magnitude of the effects (Marsh 2007). Additionally, road width explained the magnitude of edge effects much better than the total break in the forest canopy (Marsh 2007). Forman (2005) proposed simple spatial models, which indicated that road effects are relatively minor around narrow corridors, and roads have the least impact on small patches (Haskell 2000). The most severe effect is where a highway crosses a small natural patch, and the smallest effect occurs where a small road passes alongside a large patch (Forman 2006). When the road is small, the road effect is practically nonexistent, even when the road has a high overall length and coverage over a large area. Long-narrow roads contribute to the exchange of adjacent habitats, and wider roads could hamper energy interactions. For example, wider roads tended to produce steeper declines in abundance and richness of macroinvertebrate fauna and leaf litter (Haskell 2000) when the road was 24 m wide and surrounded by uninterrupted tropical forest; these roads created a strong contrast in the microclimate (Kunert et al. 2015). In addition, the effects have proportionally more impacts on forest areas in small fragments or fragments with convoluted shapes, both of which have higher perimeter-to-area ratios (Ewers and Didham 2007), increasing the edge-to-area ratio, which corresponded to a decrease in diversity within glades (Smith et al. 2007). Wide roads have greater effects on square patches than patches of other shapes. The same effects can be found for animal behavior; for example, this phenomenon has been observed with ladybird beetles, who emigrate from rectangular patches faster than square patches. Much of the observed variation in emigration rates from a series of published studies could be explained by the scaled effect of patch size (Nams 2011).

Implications for forest road management

An important question for the management and mitigation of road effects on forests is how wide the road should be. If narrow roads cause fewer edge effects than wider roads, newly built roads should not be wider than necessary (Marsh 2007). The necessary width discussed in this study can also be seen as a threshold. Roads have inseparable positive and negative effects on plant communities, but the negative effects are of greater concern (Berges et al. 2013). However, there are no negative effects if the road width is under a threshold value. In addition, the ability of the ecosystem to repair itself can mitigate the negative effects of roads (Tehrani et al. 2015). Specifically, the perception of forest road management should change in the following three ways.

First, paths have no impact on forests, which means that if roads are needed (for research, management, or recreation purposes), they should be established at their minimum required size to minimize the impacts. "Minimum required size" here is a threshold; that is, the construction of roads at certain thresholds does not affect forests. Road construction is forbidden in many areas; however, this view may not be correct. Since a path appears to create a very small level of interference, such interference does not lead to the destruction of the forest canopy and does not affect forests. Then, we can infer that paths can be a part of the management of nature reserves, as long as they are kept below the threshold of minimum impact. Therefore, the appropriate construction of roads can be permitted, rather than completely banned.

Second, roads have negative impact on forests, and it can be inferred that wider roads would have greater impacts on forests. If a road exceeds the threshold of maximum effects, it may cause a collapse of the forest ecosystems, which would cause disastrous effects. For example, some models show that the viability of a population is determined not only by road density but also by the sizes and shapes of patches (Borda-de-Agua et al. 2011). Rainforest fragments in central Amazonia were found to experience a dramatic loss of aboveground tree biomass. These losses were largest within 100 m of fragment edges, where tree mortality sharply increased. Permanent study plots within 100 m of edges lost up to 36% of their biomass in the first 10 to 17 years after fragmentation (Laurance et al. 1997). Importantly, if the reality is that wider roads likely impact forest ecosystems, then the management of road thresholds in nature reserves may be a vital way to ensure future viability. This should be taken into account when considering the environmental impacts of new roads (Angold 1997).

Furthermore, road networks can impact biodiversity partly independently and hence add to any effects of habitat loss (Ahmed et al. 2014), and it may be driving the global loss of biodiversity (Cuaron 2000). Especially for animals, road networks have negative effects on four of the five bird categories tested (Mammides et al. 2015). For example, the movement of small animals is known to be inhibited by roads, this is likely to increase population isolation among vegetation remnants (Ascensão et al. 2017), which should result in lower rates of immigration into and recolonization of habitats in landscapes with high road density (Rytwinski and Fahrig 2007). In particularly, new road construction could have detrimental effects on animal populations (Prokopenko et al. 2017). Like snakes, anurans, lizards and so on, most susceptible to negative road impacts (Brehme et al. 2018). Based on the independent roadkill data, more than 70% of roadkill events occurred within the top 30% priority segments (Lin et al. 2019). Furthermore, significant positive correlation can be found between the fractal dimension of forest stands and road density across all scales (Miller et al. 1996). As a result, road networks and road density are important factors when studying the effects of roads on forests.

Third, there is a shift in the perspective on forest road management if thresholds are included. There should be a threshold of the road width that affects forests, as an abrupt impact may occur with increasing road width. Since our study indicated that the effects of wide and narrow roads differed, we can infer that the impacts of roads on forests are dependent on the threshold of road width: an abrupt effect may appear when the road width is larger than the threshold. In other words, if there is a change in the size of the road, which can indicate the effects of the roads on forest ecosystems, ranging from no effect to a sustainable effect and from a sustainable effect to a destructive effect, this change can be depicted through ecological thresholds. In fact, an application of the threshold concept should consider where extrinsic factors constrain the structure and function of ecosystems. When the level or intensity of an extrinsic factor reaches a threshold, the structure of the ecosystem, the rate of an ecological process, or the level of ecosystem function/service that can be attained is altered (Groffman et al. 2006). In fact, all kinds of thresholds should be studied to conserve ecosystems. How much of something do we need to keep people safe and well (Oliver 2016)? In this case, a road is one kind of extrinsic factor, and this factor is associated with size. Previous research has indicated that roads should be a minimum of 15 m in width and glades should be a minimum of 625–900 m^2 in area for open spaces to significantly contribute to the biodiversity of plantation forests (Smith et al. 2007). A template is needed for proactively zoning and prioritizing roads during the most explosive era of road expansion in human history (Laurance et al. 2014). Different forest roads have different threshold values of tolerance or habituation to human disturbance. However, so far, no study has quantified the threshold value for the width of a road. Road effect thresholds should be studied more in the future.

Acknowledgements This research was financially supported by the National Natural Science Foundation of China (31300401), Pearl River S&T Nova Program of Guangzhou (201806010150), Special funds of Guangdong Province for Promoting Economic Development (For the Development of Marine Economy) GDOE[2019]A50, Science and Technology Planning Project of Guangdong Province, China (2018A030321013). We thank the colleagues of Kunyushan Nature Reserve, Hengshan Nature Reserve, Danxiashan Nature Reserve, Dinghushan Nature Reserve, Heishiding Nature Reserve, and Baiyunshan Mountain Forest Park for providing valuable help during this study, and we are also grateful to Dr. Yi Yu, Dr. Jingang Liu, Dr. Gang Liu, and Dr. Keke Wu for their assistance in the investigation and experiment. We are grateful to Dr. Huixuan Liao and Ms Bei Huang for their help in manuscript revision.

References

Ahmed SE, Lees AC, Moura NG, Gardner TA, Barlow J, Ferreira J, Ewers RM (2014) Road networks predict human influence on Amazonian bird communities. Proc R Soc B. https://doi.org/10.1098/rspb.2014.1742

Angold PG (1997) The impact of a road upon adjacent heathland vegetation: effects on plant species composition. J Appl Ecol 34(2):409–417

Arevalo JR, Delgado JD, Fernandez-Palacios JM (2008) Changes in plant species composition and litter production in response to roads and trails in the laurel forest of Tenerife (Canary Islands). Plant Biosyst 142:614–622

Ascensão F, Lucas PS, Costa A, Bager A (2017) The effect of roads on edge permeability and movement patterns for small mammals: a case study with Montane Akodont. Landsc Ecol 32(4):781–790

Avon C, Berges L, Dumas Y, Dupouey JL (2010) Does the effect of forest roads extend a few meters or more into the adjacent forest? A study on understory plant diversity in managed oak stands. For Ecol Manag 259(8):1546–1555

Bartels SF, Chen HYH (2010) Is understory plant species diversity driven by resource quantity or resource heterogeneity? Ecology 91(7):1931–1938

Berges L, Chevalier R, Avon C (2013) Influence of forest road, road-surfacing material and stand age on floristic diversity and composition in a nutrient-poor environment. Appl Veg Sci 16(3):470–479

Borda-de-Agua L, Navarro L, Gavinhos C, Pereira HM (2011) Spatio-temporal impacts of roads on the persistence of populations: analytic and numerical approaches. Landsc Ecol 26(2):253–265

Brehme CS, Hathaway SA, Fisher RN (2018) An objective road risk assessment method for multiple species: ranking 166 reptiles and amphibians in California. Landsc Ecol 33(6):911–935

Chen HL, Koprowski JL (2016) Barrier effects of roads on an endangered forest obligate: influences of traffic, road edges, and gaps. Biol Conserv 199:33–40

Cuaron AD (2000) A global perspective on habitat disturbance and tropical rainforest mammals. Conserv Biol 14(6):1574–1579

Delgado JD, Arroyo NL, Arevalo JR, Fernandez-Palacios JM (2007) Edge effects of roads on temperature, light, canopy cover, and canopy height in laurel and pine forests (Tenerife, Canary Islands). Landsc Urban Plan 81(4):328–340

Ewers RM, Banks-Leite C (2013) Fragmentation impairs the microclimate buffering effect of tropical forests. PLoS ONE 8:e58093

Ewers RM, Didham RK (2007) The effect of fragment shape and species' sensitivity to habitat edges on animal population size. Conserv Biol 21(4):926–936

Forman RTT (2005) Good and bad places for roads: effects of varying road and natural pattern on habitat loss, degradation, and fragmentation. In: Irwin CL, Garrett P, McDermott KP (eds) Proceedings of the 2005 international conference on ecology and transportation. Center for Transportation and the Environment, North Carolina State University, Raleigh, pp 164–174

Forman RTT (2006) Good and bad places for roads: effects of varying road and natural pattern on habitat loss, degradation, and fragmentation. In: Irwin CL, Garrett P, McDermott KP (eds) Proceedings of the 2005 international conference on ecology and transportation. Center for Transportation and the Environment, North Carolina State University, Raleigh, pp 164–174

Forman RTT, Alexander LE (1998) Roads and their major ecological effects. Annu Rev Ecol Syst 8:629–644

Garcia JDD, Arevalo JR, Fernandez-Palacios JM (2007) Road edge effect on the abundance of the lizard *Gallotia galloti* (Sauria : Lacertidae) in two Canary Islands forests. Biodivers Conserv 16(10):2949–2963

Godefroid S, Koedam N (2004) The impact of forest paths upon adjacent vegetation: effects of the path surfacing material on the species composition and soil compaction. Biol Conserv 119(3):405–419

Gravel D, Canham CD, Beaudet M, Messier C (2010) Shade tolerance, canopy gaps and mechanisims of coexistence of forest trees. Oikos 119(3):475–484

Groffman P et al (2006) Ecological thresholds: the key to successful environmental management or an important concept with no practical application? Ecosystems 9(1):1–13

Haskell DG (2000) Effects of forest roads on macroinvertebrate soil fauna of the Southern Appalachian mountains. Conserv Biol 14(1):57–63

Huang X, Sheng Z, Zhang Y, Ding J, He K (2015) Impacts of trails on plants, soil and their interactions in the subalpine meadows of Mount Jade Dragon, Northwestern Yunnan of China. Grassl Sci 61(4):204–216

Kalwij JM, Milton SJ, McGeoch MA (2008) Road verges as invasion corridors? A spatial hierarchical test in an arid ecosystem. Landsc Ecol 23(4):439–451

Kunert N, Aparecido LMT, Higuchi N, Santos Jd, Trumbore S (2015) Higher tree transpiration due to road-associated edge effects in a tropical moist lowland forest. Agric For Meteorol 213:183–192

Laurance WF, Laurance SG, Ferreira LV, Rankin-de Merona JM, Gascon C, Lovejoy TE (1997) Biomass collapse in Amazonian forest fragments. Science 278(5340):1117

Laurance WF et al (2014) A global strategy for road building. Nature 513:229

Liao H, Wang H, Dong Q, Cheng F, Zhou T, Peng S (2019) Estimating non-native plant richness with a species-accumulation model along roads. Conserv Biol. https://doi.org/10.1111/cobi.13402

Lin Y-P, Anthony J, Lin W-C, Lien W-Y, Petway JR, Lin T-E (2019) Spatiotemporal identification of roadkill probability and systematic conservation planning. Landsc Ecol 34(4):717–735

Mammides C, Kadis C, Coulson T (2015) The effects of road networks and habitat heterogeneity on the species richness of birds in Natura 2000 sites in Cyprus. Landsc Ecol 30(1):67–75

Marcantonio M, Rocchini D, Geri F, Bacaro G, Amici V (2013) Biodiversity, roads, & landscape fragmentation: two Mediterranean cases. Appl Geogr 42:63–72

Marsh DM (2007) Edge effects of gated and ungated roads on terrestrial salamanders. J Wildl Manag 71(2):389–394

McDonald RI, Urban DL (2006) Edge effects on species composition and exotic species abundance in the North Carolina Piedmont. Biol Invasions 8(5):1049–1060

Miller JR, Joyce LA, Knight RL, King RM (1996) Forest roads and landscape structure in the southern Rocky Mountains. Landsc Ecol 11(2):115–127

Nabe-Nielsen J, Severiche W, Fredericksen T, Nabe-Nielsen LI (2007) Timber tree regeneration along abandoned logging roads in a tropical Bolivian forest. New For 34(1):31–40

Nams VO (2011) Emergent properties of patch shapes affect edge permeability to animals. PLoS ONE 6(7):e21886

Oliver TH (2016) How much biodiversity loss is too much? Science 353(6296):220–221

Prokopenko CM, Boyce MS, Avgar T (2017) Extent-dependent habitat selection in a migratory large herbivore: road avoidance across scales. Landsc Ecol 32(2):313–325

Queiroz RE, Ventura MA, Silva L (2014) Plant diversity in hiking trails crossing Natura 2000 areas in the Azores: implications for tourism and nature conservation. Biodivers Conserv 23(6):1347–1365

Reed RA, JohnsonBarnard J, Baker WL (1996) Contribution of roads to forest fragmentation in the Rocky Mountains. Conserv Biol 10(4):1098–1106

Rytwinski T, Fahrig L (2007) Effect of road density on abundance of white-footed mice. Landsc Ecol 22(10):1501–1512

Selva N et al (2011) Roadless and low-traffic areas as conservation targets in Europe. Environ Manag 48(5):865–877

Smith GF, Iremonger S, Kelly DL, O'Donoghue S, Mitchell FJG (2007) Enhancing vegetation diversity in glades, rides and roads in plantation forests. Biol Conserv 136(2):283–294

Tehrani FB, Majnounian B, Abdi E, Amiri GZ (2015) Impacts of forest road on plant species diversity in a Hyrcanian forest, Iran. Croat J Eng 36(1):63–71

Thornton DH, Branch LC, Sunquist ME (2011) The influence of landscape, patch, and within-patch factors on species presence and abundance: a review of focal patch studies. Landsc Ecol 26(1):7–18

Trombulak SC, Frissell CA (2000) Review of ecological effects of roads on terrestrial and aquatic communities. Conserv Biol 14:18–30

Turner JM (2006) Conservation science and forest service policy for roadless areas. Conserv Biol 20(3):713–722

Watts RD, Compton RW, McCammon JH, Rich CL, Wright SM, Owens T, Ouren DS (2007) Roadless space of the conterminous United States. Science 316(5825):736–738

Wolf ID, Croft DB (2014) Impacts of tourism hotspots on vegetation communities show a higher potential for self-propagation along roads than hiking trails. J Environ Manag 143:173–185

Zeng S-L, Zhang T-T, Gao Y, Ouyang Z-T, Chen J-K, Li B, Zhao B (2011) Effects of road age and distance on plant biodiversity: a case study in the Yellow River Delta of China. Plant Ecol 212(7):1213–1229

Zhou YB, Buesching CD, Newman C, Kaneko Y, Xie ZQ, Macdonald DW (2013) Balancing the benefits of ecotourism and development: the effects of visitor trail-use on mammals in a Protected Area in rapidly developing China. Biol Conserv 165:18–24

Zhou T, Peng S, Lin Z (2009) Edge effect of road in Dinghushan forests. Chin J Ecol 28(3):433–437