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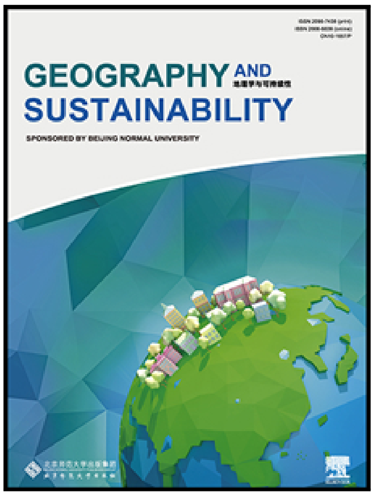

Landscape fragmentation associated with the Qinghai-Tibet Highway and its influencing factors—A comparison study on road sections and buffers

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Highlights:

- A multi-buffer and multi-section study was performed to explore landscape change.
- Disparities between road sections were larger than those between buffers.
- Geodetector was applied to detect the factors that influence landscape fragmentation.
- Road impacts may be over- or underestimated by setting fixed-width buffers.

Landscape fragmentation associated with the Qinghai-Tibet Highway and its influencing factors—A comparison study on road sections and buffers

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Abstract: Many studies have examined the effect of roads on landscape fragmentation. Yet they rarely considered local characteristics of the road and road buffer widths. Therefore, this study that took place in the Qingzang Highway (QH) examined the variations in road buffers and road sections of landscape fragmentation. The QH was divided into 32 sections with 23 buffer areas. Based on the indicators of landscape fragmentation from 1980 to 2018, we found significant spatial heterogeneity between sections and buffers. Generally, landscape fragmentation decreased with increasing buffer distance to the QH. For different sections, the coefficients of variation between buffers were rather high and significantly different. Therefore, fixed-width buffers may overestimate or underestimate the spatial scope and influence intensity of a road. The impacts of road sections around provincial capitals, prefecture-level cities and main counties on landscape fragmentation were relatively extensive and formed clusters of highly fragmented areas. Geodetector results indicated that natural and anthropogenic factors, such as altitude, climate, distance to major settlements and socioeconomic conditions, could well explain the spatiotemporal characteristics of landscape fragmentation. Altitude, precipitation and the distance to major settlements had higher explanatory power for landscape fragmentation in permafrost regions, whereas slope and socioeconomic condition had higher explanatory power for non-permafrost regions in Xizang Autonomous Region.

Keywords: Qingzang Highway; Landscape fragmentation; Road section; Buffer; Geodetector

1. Introduction

Landscape fragmentation refers to the conversion of formerly continuous landscape elements into many discontinuous patches. Although it can happen naturally, more recently humans, by developing transport infrastructure, have generated significant landscape fragmentations. The field of road ecology emerged due to unprecedented destructions of natural ecosystems caused by road networks and traffic corridors (Andrews, 1990; May et al., 1996). Early case studies found that regions with high road densities experience significant declines in areas that are unfragmented, including the average patch area (Saunders et al., 2002; Anděl et al., 2010). Increasing use of motor vehicles also results in increasing landscape fragmentation (Jaeger et al., 2006), indicating that impacts can continue long after the construction of highways.

Previous studies have found that landscape separated by roads may lose their potential to fulfil their original functions (Forman et al., 1998; Chen et al., 2003; Ascensão et al., 2019). Road networks interrupt horizontal ecological flow, alter the spatial pattern of landscape and animal behaviour. They also cause species mortality because of collisions and alterations to the physical and chemical environment (Miller et al., 1996; Reed et al., 1996; Forman et al., 1998; Trombulak et al., 2000; Chen et al., 2003; Ascensão et al., 2019), reducing ecosystem functions and biodiversity (Fu and Chen, 1996; Serrano et al., 2002). Vegetation types often differ in the degree to which they are affected by roads, resulting in differences in landscape fragmentation (Karlson et al., 2015).

Early studies on landscape fragmentation primarily focused on European and American countries (Oxley et al., 1974; Free et al., 1975). But with the rapid construction of transport infrastructure in China and other Asian countries, the focus has shifted to impacts in these countries. In China, the degree of fragmentation in North China and East China is much higher than that in the Qingzang Plateau and Northwest China (Li et al., 2005; Li et al., 2010). In addition to spatial differences, the road centrality density, road grade, urban development, slope and altitude all contribute to the effect of roads on landscape patterns (Cai et al., 2014; Liang et al., 2014; Liu et al., 2014; Liu et al., 2015).

Although ecosystem vulnerability and other environmental conditions limit the development of transport infrastructure in the Qingzang Plateau (Gao et al., 2019; Miao et al., 2020), research found that the construction and operation of transport infrastructure in the region directly alter the land-use structure, disturb the ecosystems, intensify landscape fragmentation and ecological vulnerability, and affect the function and stability of regional ecosystems (Zhang et al., 2002; Kang, 2008; Zhang et al., 2012). Wang (2015) pointed out that the Qingzang Railway construction decreased vegetation richness by 2.9% during its construction period (2001–2007), compared to only 0.4% during the subsequent period (2007–2010). Chen (2003) examined the spatial extent of road construction effects around the Qingzang Highway (QH) and found that losses in primary productivity and biomass in a 1-km buffer on both sides of the QH and railway are much higher than those in a 10-km buffer.

In studies that evaluate landscape fragmentation, multiple data sources and landscape indices have been widely employed (Zhang et al., 2002; Xie et al., 2016; Mehdipour et al., 2019). However, these studies used fixed-width buffers to delimit their study areas before analyzing landscape fragmentation. Although the approach may be suitable for landscape that have homogenous conditions, the same approach may not be appropriate for roads that vary in terms of environmental characteristics and human influences. To bridge the knowledge gap, this study focused on examining the impacts of different road buffer widths and sections. We focused on evaluating the impacts of QH on landscape fragmentation in the Qingzang Plateau because this region has international and even global ecological significance. Known as 'The Roof of the World' and 'The Third Pole of the Earth', the Qingzang Plateau contains the headwaters of most streams in Asia.

The main purpose of this research is to analyze the impacts of main roads on landscape fragmentation based on buffers and road sections. Because there have been few studies that used quantitative methods, such as logistic regression, to analyze the effect of natural or human influences (e.g., Liang et al., 2014), this work used Geodetector to provide more detailed insights into the relationship between transportation infrastructure and ecological problems. By determining the influencing factors and considering the spatial heterogeneity of different factors, we can link natural and social elements that are central to research on sustainable development (Fu, 2020).

2. Materials and methods

2.1 Study area

This study examined the QH, one of the most important regional large-scale transport lines in Qingzang Plateau region and was the first major roadway to enter the Qingzang Plateau's interior. The Qingzang Plateau stretches between 25°59′37″N and 39°49′33″N and 73°29′56″E and 104°40′20″ E and has an area of approximately 2,542,400 km^2 (Fig. 1). The start and endpoints of the QH are Xining and Lhasa, and it passes through prefecture-level cities, including Haibei, Haixi, Hainan and Nagqu. The total length of the highway is 1,937 km and the average altitude is 4,141.8 m. Construction of the QH began in 1950 and it was fully operated in 1954. In 1974, the QH was upgraded to a secondary highway by laying asphalt pavement. The upgrade was completed in two stages, in 1978 (from Xining to Golmud) and in 1985 (from Golmud to Lhasa).

Fig. 1. Location of Qingzang Plateau and the QH.

In this study, according to Zhang et al. (2002), we set 23 buffer widths, those with one km increments within 15 km from the QH, those with five km increments for buffer distance ranging from 20 km to 50 km, and one 60-km buffer with a total area of 213,549 km^2. To explore variations along the road, the QH was equally divided into 32 sections from Lhasa to Xining. The length of each section was 60.5 km. In addition, the 32 road sections were also divided into 3 groups by natural and administrative regions. Section 9–18 are located in the permafrost regions and the other sections are in the non-permafrost regions: Xizang Autonomous Region (section 1–8) and Qinghai Province (section 19–32).

2.2 Data

Road vector data and land-use data were employed in a landscape pattern analysis to explore the impacts of the QH on landscape fragmentation. Vector data of the QH were obtained by combining data from the China Traffic Atlas and OpenStreetMap. We combined the land-use classification data in 1980, 1990, 2000, 2010 and 2018 to discuss the effect of the QH on landscape fragmentation. These data, which were 1 km in resolution and were divided into six categories (cultivated land, grassland, forestland, waterbody, construction land and bare land), were obtained from the Resource and Environment Data Cloud Platform of the Chinese Academy of Sciences (www.resdc.cn/).

The Digital Elevation Model (DEM), which was 0.1 km in resolution, and annual temperature and precipitation datasets, which were 1 km in resolution, were obtained from the Resource and Environment Data Cloud Platform of the Chinese Academy of Sciences and the National Qingzang Plateau/Third Pole Environment Data Centre (Li et al., 2008; Ran et al., 2012; Ding, 2019). The slope was calculated based on the DEM. The distance to the Qingzang Railway, provincial capitals, prefecture-level cities and counties were based on spatial Euclidean distances. Socioeconomic spatial characteristics were depicted by night-time light data (Liang et al., 2020), including annual stable DMSP/OLS (1992, 2000, 2010) and NPP/VIRS (2017) data which were processed to 1 km in resolution, all of them are available in NOAA website (http://ngdc.noaa.gov/eog/download.html).

2.3 Analysis framework

The goals of this paper were to characterize the spatiotemporal evolution of landscape fragmentation along the QH and to analyze the effect of different factors on changes in landscape fragmentation (Fig. 2).

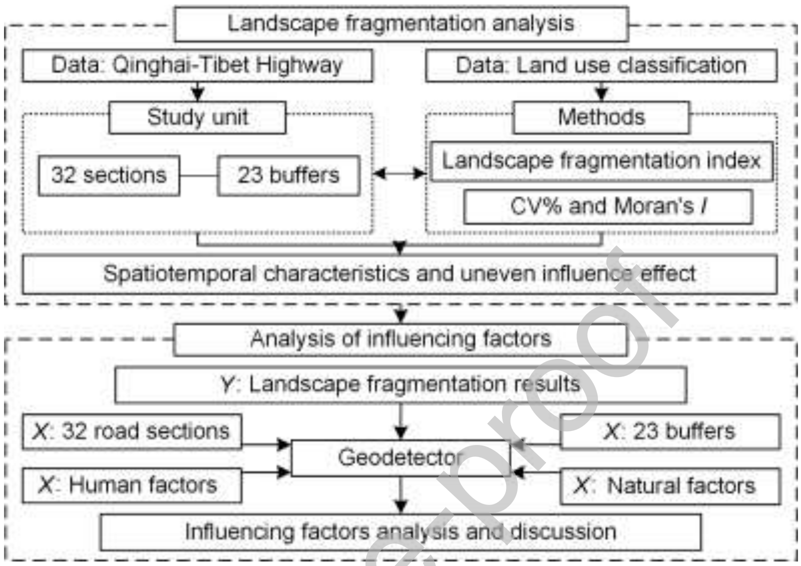

Fig. 2. Analytical framework.

First, a landscape fragmentation analysis was conducted based on 736 research units (23 buffers multiplied by 32 road sections) using vector data of the QH and land-use classification. Landscape fragmentation index was calculated based on land-use classification to obtain the average of the 23 buffers and the 736 research units. Then, using the coefficient of variation (CV) and global Moran's *I*, the spatiotemporal characteristics of these data were analyzed to characterize the differences observed within a buffer. These analyses were performed to identify specific impacts of the QH on landscape fragmentation and to determine whether the impacts of this road on landscape fragmentation varied among its sections.

Second, Geodetector was used to analyze the factors contributing to landscape fragmentation along the QH. Landscape fragmentation indices were used as the dependent variable, while the 32 road sections, 23 buffers and related natural and anthropogenic factors were used as the independent variables. On this basis, an analysis of the influencing factors and a comparison between our results and previous studies were performed (e.g., Zhang et al., 2002).

2.4. Methods

The following indices or models were used in this paper to identify the characteristics of landscape fragmentation. First, the landscape fragmentation index (LF) was adopted following Fu et al. (1996) and Zhang et al. (2002). LF is the ratio of the number of patches n_i to patch area A, which indicates the segmentation degree of patches in a landscape system. Larger values correspond to more patches per unit area and thus a greater degree of fragmentation. The formula is as follows:

$$LF = \sum_{i=1}^{m} n_i / A \quad (1)$$

The coefficient of variation (CV) was used to measure the differences between the results of different sections in the same buffer. CV is a common method for measuring the degree of dispersion in data in a dimensionless way. Its formula is the ratio of the standard deviation σ to the mean.

For different buffers of different road sections, Global Moran's *I* was used to detect the spatial patterns of fragmentation. Global Moran's *I* can be used to measure the autocorrelation of regions based on locations and attribute values (Liu et al., 2018). The formula is as follows:

$$I = n \cdot \sum_{i}^{n} \sum_{j \neq i}^{n} w_{ij} (x_i - \overline{x})(x_j - \overline{x}) / \sum_{i}^{n} \sum_{j \neq i}^{n} w_{ij} \sum_{i}^{n} (x_i - \overline{x})^2 \quad (2)$$

where x is the mean value, w_{ij} is the spatial weights matrix, x_i represents the observed value of the i-th region, and $i \neq j$. The I score ranges from [–1, 1], where zero indicates no correlation, positive values and negative values indicate positive and negative correlations, respectively. The significance of spatial autocorrelation can be verified by the normalized statistic Z value using the following formula:

$$Z = [I - E(I)] / \sqrt{VAR(I)} \quad (3)$$

Geodetector is used to detect the stratified heterogeneity of the process of landscape fragmentation, and it is a tool that aims to measure and find the stratified heterogeneity of a variable *Y* and to test the coupling between two variables *Y* and *X* according to their spatial distributions without making assumptions of the linearity of the association (Wang et al., 2010). Four subdetector tools are provided by Geodetector. In this paper, we used two sub-tools, factor detector and interaction detector, to explore the impacts of natural and anthropogenic factors on landscape fragmentation. Different detectors were calculated using the *q*-statistic:

$$q = 1 - \sum_{h=1}^{L} N_h \sigma_h^2 / N \sigma^2 \quad (4)$$

Based on the basic units of different buffers of road sections, the explained variable *Y* was the change in the degree of landscape fragmentation. Explanatory variables were selected based on previous related studies (Cai et al., 2014; Liang et al., 2014; Liu et al., 2014; Liu et al., 2015), including natural and anthropogenic factors, such as X_1 (Altitude), X_2 (Slope), X_3 (Precipitation), X_4 (Air temperature), X_5 (Distance to Qingzang Railway), X_6 (Distance to nearest provincial capital), X_7 (Distance to nearest prefecture-level region), X_8 (Distance to county-level region), X_9 (Socioeconomic condition), X_{10} (Road section), X_{11} (Buffer) and X_{12} (1 for in the permafrost regions and 0 for other regions). The socioeconomic condition was represented by the DN (digital number) value of night-time light data.

3. Results

3.1. Temporal-spatial features of the landscape fragmentation process of 23 buffers

We found an inverse correlation between the degree of landscape fragmentation and the width of the buffers, forming a power-law distribution (Fig. 3). Buffers with widths larger than 10 km tended to be stable, implying that this highway might not have significant impacts on the landscape, similar to the findings by Zhang et al. (2002). These results were consistent from 1980 to 2010, with several slight decreases, although relatively higher values were observed in 2018. The ratio of landscape fragmentation in buffers to the background value of the Qingzang Plateau was consistent with the distribution of LF. Specifically, it decreased as the distance from the QH increased but was still more than 1.5 times the average value of landscape fragmentation on the Qingzang Plateau.

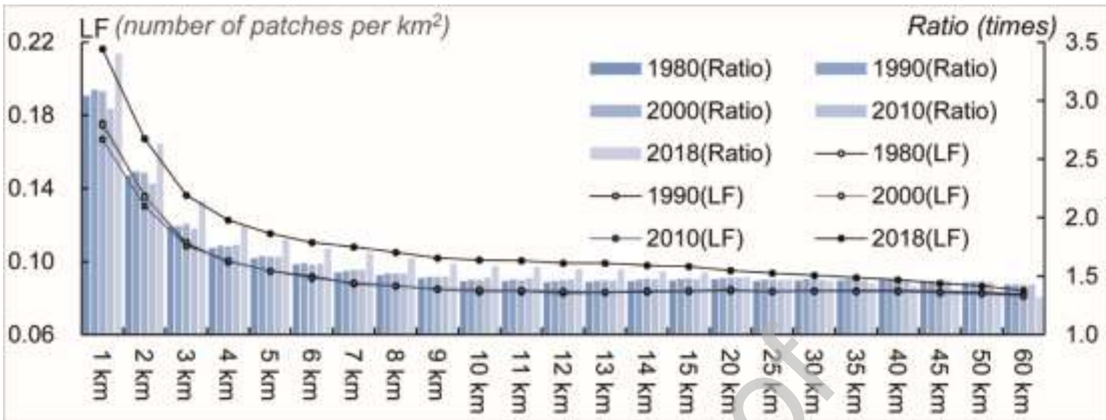

Fig. 3. Landscape fragmentation around the QH.

Except for construction land, other land-use types had similar pattern to the overall trend: landscape fragmentation was lower as buffer size increased (Fig. 4). Changes in the degree of fragmentation of forestland, grassland and bare land showed stronger correlations. This finding implies that changes in non-human land use, such as grassland or forest, were the main cause of landscape fragmentation. As these land-use types are important factors in the provision of regional ecological services, this outcome indicated that roads had negative effects on the environment.

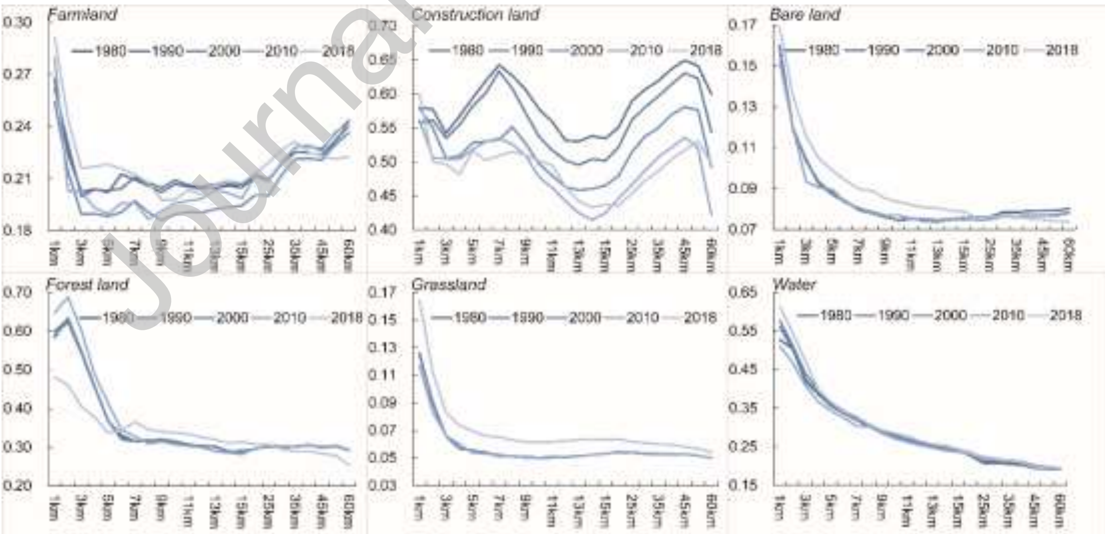

Fig. 4. Changes in landscape fragmentation of different land-use types.

We also found that changes in landscape fragmentation were concentrated in buffers closer to the highway (Fig. 5). Although an overall decrease in landscape fragmentation was observed between 1980 and 2010 when the buffers were enlarged, several buffers far located from the highway showed a slightly higher landscape fragmentation than those located closer to the highways. However, the results of landscape fragmentation in 2018 showed a distinct pattern of regional differentiation. The observed changes suggested that the gradient differentiation features of landscape fragmentation tended to be enhanced for buffers along the QH.

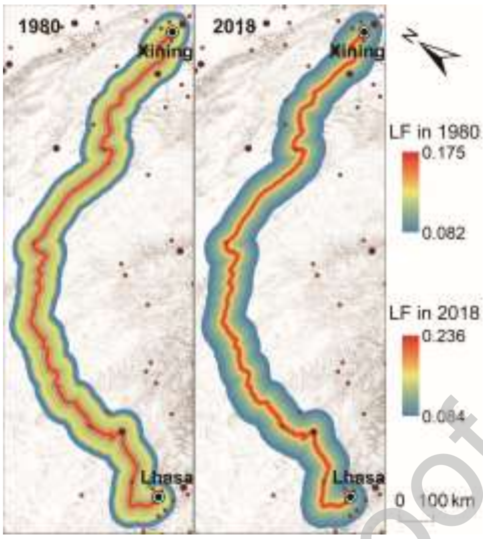

Fig. 5. Changes in landscape fragmentation among different buffers of the QH.

3.2. Differences in the degree of landscape fragmentation between different road sections

Although the above results were similar to that of previous studies (Zhang et al., 2002; Wang, 2015), the results changed when different sections of the QH were considered. The CV of each buffer (all include 32 road sections) ranged from 20% to 60%. The CV was greater than 50% when the buffer was less than 12 km and decreased gradually as buffer width increased (Fig. 6). These patterns were consistent from 1980 to 2010. In 2018, however, the CV was greater than 30% for 1–20 km buffer width and was lower than 30% for buffers over 20 km. Overall, these findings strongly suggested that there were significant differences in the degree of landscape fragmentation among 32 road sections, even within the same buffer. In other words, the effects of road on landscape fragmentation was uneven. This uneven effect of the QH on landscape fragmentation was also detected from the results of Moran's *I* (Table 1), which revealed positive spatial agglomeration. The CV also decreased as the buffer size increased, suggesting that greater differences in landscape fragmentation occurred in buffers adjacent to the QH, but less so in buffers far away from the highway.

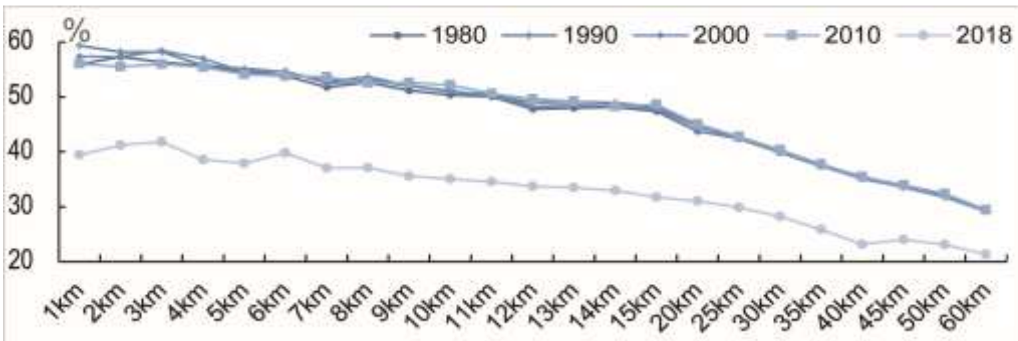

Fig. 6. Coefficient of variation (%) of landscape fragmentation based on different buffers.

Table 1. Results of the Moran's *I* analysis.

	1980	1990	2000	2010	2018	1980–1990	1990–2000	2000–2010	2010–2018
I	0.12	0.12	0.11	0. 13	0. 03	0.00	0.01	0.00	0.20
Z	76.31	77.38	74.33	83.74	21.14	2.67	9.02	2.95	129.56

Based on the specific description of the average landscape fragmentation of different road sections (Fig. 7) and the spatial distribution of the landscape fragmentation at each time period (Fig. 8), we found that some road sections had more impacts on landscape fragmentation than others. In general, landscape fragmentation in Xizang (sections 1–8) increased more prominently. Road sections around main settlements such as in two provincial capitals, Xining (section 32) and Lhasa (section 1), and main counties, Dulan (section 25) and Golmud (section 20), also had a more extensive influence of landscape fragmentation. Spatially, the type of agglomeration showed a block-clustering pattern based more on road sections rather than buffers.

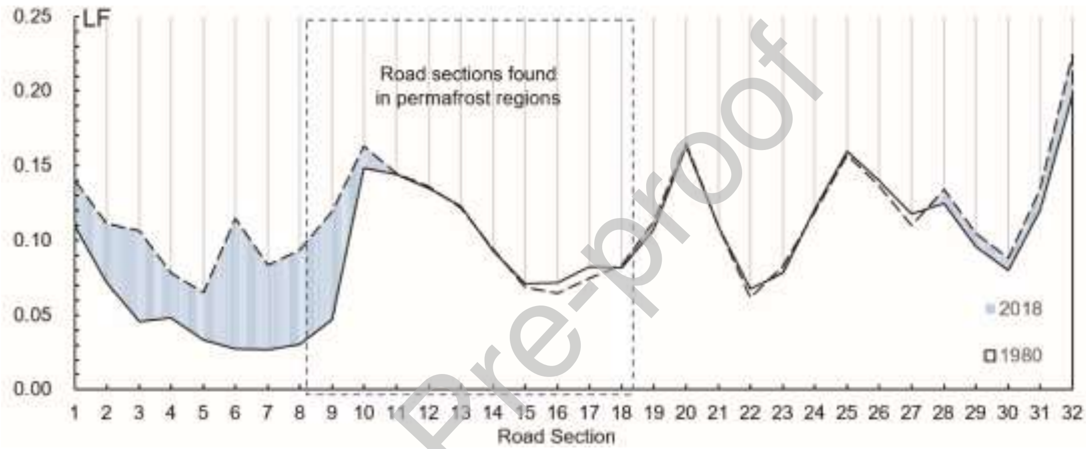

Fig. 7. Average landscape fragmentation of 32 road sections

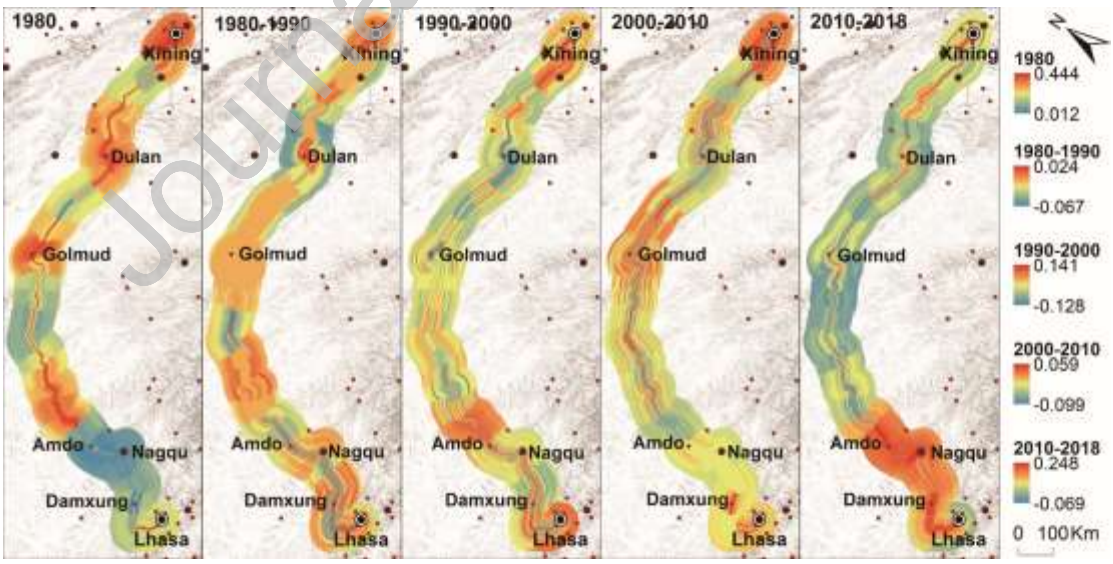

Fig. 8. Landscape fragmentation index based on different buffers in different road sections.

Fig. 9 shows some trends that highlight the importance of sections. Section 32 (Xining) and section 20 (Golmud) both showed a continuous spatial decreasing feature with increasing buffer width (Fig. 9a; Fig. 9b). Landscape fragmentation around Nagqu (section 6) was exacerbated during the recent years (2010–2018), mainly when the buffers were less than 8 km (Fig. 9c). In contrast, Section 15 (between Lhasa and Nagqu) experienced changes within 5 km buffer width, with almost no change if the buffers were over 6 km (Fig. 9d). These results indicated that landscape fragmentation along a road may be overestimated or underestimated if the road is not divided into different sections.

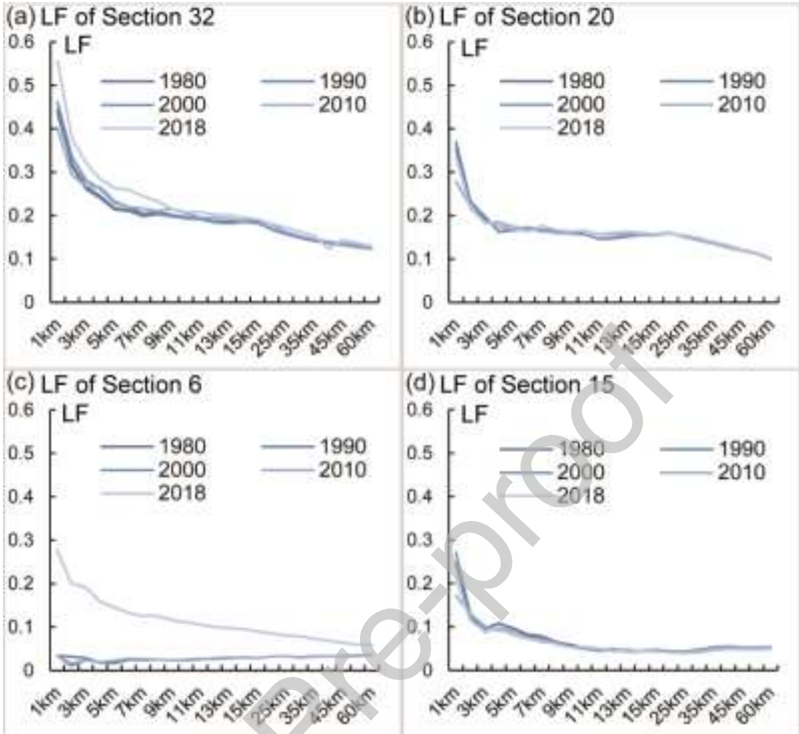

Fig. 9. Landscape fragmentation of 4 typical road sections. (a) Section 32 is located in Xining; (b) Section 20 is around Golmud, a county-level city; (c) Section 6 is in a permafrost region, which is also in the middle of the study area and far away from main settlements; and (d) Section 15 is around Nagqu, a prefecture-level city in Xizang.

3.3. Analysis of influencing factors

The factor detector and interaction detector in Geodetector were used to identify the explanatory power of related natural and anthropogenic factors as well as the buffers and road section (Table 2; Table 3). The results of the factor detector of each period (Table 2.) showed that the explanatory power of natural factors, especially X_1 (altitude), X_3 (precipitation), X_4 (temperature), and the distance to major settlements were relatively higher. From a temporal perspective, most factors tend to decrease. However, there were two noteworthy factors from the 2018 results. First, the explanatory power of X_9 (socioeconomic condition) increased prominently and became significant. Second, the explanatory power of buffer classification increased and slightly exceeded that of road sections. These results implied that the overall landscape integrity may be deteriorated with regional development and construction, although some road sections currently have insignificant landscape fragmentation. Permafrost region and non-permafrost region had weak explanatory power for landscape fragmentation in the whole QH.

Table 2. Results of the indicator detector

	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}	X_{12}

1980	0.29*	0.08*	0.41*	0.31*	0.49*	0.48*	0.43*	0.21*	0.11	0.57*	0.25*	0.00
1990	0.29*	0.08*	0.43*	0.36*	0.49*	0.48*	0.44*	0.21*	0.11	0.58*	0.24*	0.00
2000	0.29*	0.08*	0.43*	0.34*	0.49*	0.48*	0.42*	0.20*	0.10	0.57*	0.25*	0.00
2010	0.32*	0.09*	0.35*	0.31*	0.22*	0.54*	0.48*	0.22*	0.14	0.64*	0.20*	0.00
2018	0.29*	0.07*	0.31*	0.25*	0.11*	0.35*	0.29*	0.21*	0.26*	0.41*	0.43*	0.00

Note: * indicates that the result can pass the 0.01 prominent test.

From 1980 to 2018, we found that the influence of most factors was prominent except for local socioeconomic conditions (Table 3). Similar to previous findings, road sections had greater explanatory power than road buffers. The interaction detector results indicated that the explanation of most factors showed nonlinear enhancement and explained much of the observed variation in landscape fragmentation (Table 3). The interaction between the road sections and the socioeconomic conditions better explained the dependent variable. The superposition of terrain and climate factors also significantly improved the explanatory power of the dependent variables. Permafrost or non-permafrost region (X_{12}) also had significant explanatory power when interacting with altitude and precipitation. In terms of human influence, the combination of socioeconomic conditions and the distance to provincial capitals and prefecture-level regions also had good explanatory power. The superposition of natural and anthropogenic factors, especially X_1 (altitude) and X_6 (the distance to provincial capitals), also favored landscape fragmentation.

Table 3. Results from 1980–2018 based on the indicator detector and interaction detector.

	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}	X_{12}
q statistic	0.23	0.06	0.50	0.22	0.21	0.49	0.53	0.28	0.09	0.61	0.06	0.04
p value	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00
X_1	0.23											
X_2	0.44*	0.06										
X_3	0.77*	0.76*	0.50									
X_4	0.83*	0.64*	0.73*	0.22								
X_5	0.53*	0.44*	0.56	0.64*	0.21							
X_6	0.82*	0.76*	0.73	0.69	0.60	0.49						
X_7	0.79*	0.76*	0.73	0.77*	0.60	0.61	0.53					
X_8	0.77*	0.57*	0.73	0.71*	0.53*	0.61	0.61	0.28				
X_9	0.43*	0.29*	0.75*	0.56*	0.36*	0.73*	0.80*	0.49*	0.09			
X_{10}	0.82	0.867*	0.73	0.80	0.61	0.61	0.61	0.61*	0.91*	0.61		
X_{11}	0.46*	0.34*	0.83*	0.66*	0.37*	0.80*	0.85*	0.49*	0.18*	1.00*	0.06	
X_{12}	0.61*	0.16*	0.54*	0.24	0.48*	0.49	0.54	0.35*	0.14*	0.61	0.11*	0.04

Note: * indicates a nonlinear increase in *q* after the factor's interaction compared with the results of the indicator detector.

Based on the presence or absence of permafrost, we found that landscape fragmentation in permafrost regions (sections 9–18) was primarily explained by the distance to Qingzang Railway or settlements, altitude and precipitation, but not so much by socioeconomic conditions (Table 4). The road differentiation of landscape fragmentation was significantly higher than that of buffer differentiation. For non-permafrost regions in Xizang (section 1–8), we found that natural factors, such as terrain and socioeconomic conditions, had large explanatory power for landscape fragmentation. However, it is worth noting that the spatial pattern of landscape fragmentation was more obvious as buffer differentiation occurs in this region. For other non-permafrost sections in Qinghai (section 19–32), altitude and precipitation were the most significant natural factors, in addition to distance to provincial capitals and prefecture-level regions. In Qinghai, differences due to road sections were more obvious than those due to buffers, although the differences were much lower than those in permafrost regions.

Table 4. Results from 1980–2018 for 3 regions

Region		X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}	X_{12}
Road sections found in permafrost regions	*q* statistic	0.49	0.10	0.49	0.15	0.52	0.56	0.56	0.55	0.04	0.56	0.05	-
	p value	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.87	0.00	0.00	-
Other road sections in Xizang	*q* statistic	0.33	0.47	0.21	0.26	0.08	0.28	0.23	0.10	0.38	0.30	0.38	-
	p value	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	-
Other road sections in Qinghai	*q* statistic	0.33	0.04	0.42	0.12	0.15	0.29	0.24	0.10	0.04	0.29	0.06	-
	p value	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.82	0.00	0.71	-

4. Discussion

The purpose of this study was to explore landscape fragmentation process and the temporal and spatial characteristics along the QH. The results showed that fragmentation decreased with wider buffer, consistent with previous studies (Zhang et al., 2002; Wang, 2015). However, landscape fragmentation varied across road sections, which indicated that using fixed buffers without distinguishing road sections might exaggerate the spatial scope and the intensity of landscape fragmentation. This finding also implied that the environmental impact of roads must be considered in different sections, especially for traffic trunk lines with long lengths passing through areas that are ecologically fragile or have different characteristics.

While landscape fragmentation slightly decreased in several sections prior to 2010, the overall variation in landscape fragmentation increased from 1980 to 2018. Our findings were thus different from Shen (2004) and Wang (2015) who presented optimistic expectations based on the observed reduction in ecological impacts by the construction of the Qingzang railway. Such differences may occur because the impacts of railway passengers are limited to stations while those of road traffic is dispersed along the road (Jaeger et al., 2006; Yin et al., 2007). This finding underscores that different transportation modes generate different impacts on the landscape and that the impacts of highway transportation is continuous.

We also found that the impacts of roads on landscape fragmentation were higher in areas with higher regional development levels and housing densities, consistent to other studies (Hawbaker et al., 2005; Li et al., 2010; Liu et al., 2014). Although terrain and climate factors also showed significant impacts on landscape fragmentation on the Qingzang Plateau, different factors generated different explanatory effects in different regions. In permafrost regions, road section differentiation was a major factor, possibly because local ecosystems are very sensitive to global climate change, in addition to significant land-use cover changes (Wang et al., 2008; Wang et al., 2011; Luo et al. 2012; Cheng et al., 2019). For non-permafrost region in Xizang, socioeconomic condition was a major factor influencing landscape fragmentation. The high values of landscape fragmentation were observed in Lhasa, the administrative capital of the Xizang Autonomous Region, in Nagqu and other smaller counties, which implied that human activities had significant impacts on landscape fragmentation.

In summary, the above findings can help policy makers to better understand the relationship between ecosystem and transport infrastructure, for example, the environmental impacts of road sections close to cities and the interaction between human and nature in ecologically fragile areas. Although previous studies may have exaggerated landscape pattern influence of roads to some extent, relevant policies should carefully consider complex relations at different spatial scales with a longer-term perspective. Such considerations are important given the unique location and ecological functions of the Qingzang Plateau as well as the serious landscape fragmentation along the QH in recent years (Serrano et al., 2002; Liu et al., 2020; Miao et al., 2020).

5. Conclusions

Based on data from 1980 to 2018, we found that landscape fragmentation along the QH decreased as buffer width increased. Changes in fragmentation were most pronounced during the last eight years (2010–2018). However, the CV of all buffers was relatively high (> 40%), especially the CV of buffers with less than 20 km wide, indicating that different road sections along this highway might differ in their impacts on landscape fragmentation.

From a spatial perspective, the increase in landscape fragmentation along the QH was much higher in Xizang. Road sections with obvious landscape fragmentation impacts first occurred around road sections close to main cities and some counties, such as Golmud and Dulan, and then occurred close to Nagqu and some other counties. Highly fragmented areas formed block clustering agglomerations, making road section differentiation more obvious than buffer differentiation. Thus, we argue that understanding the effect of roads on landscape fragmentation requires the consideration of different road sections, especially for traffic trunk lines with long lengths passing through ecologically fragile areas.

Based on Geodetector, the process of landscape fragmentation along the QH was also uneven and caused by a complex mixture of natural and anthropogenic factors, such as terrain, climate, socioeconomic conditions and distance to major settlements. In addition, their superimposition can well explain the spatiotemporal characteristics of landscape fragmentation. Climate change also exerted significant impacts on landscape fragmentation process. Altitude, precipitation and the distance to major settlements had higher explanatory power for landscape fragmentation in ecologically-fragile permafrost regions while slope and socioeconomic condition had higher power for non-permafrost regions in Xizang Autonomous Region.

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.

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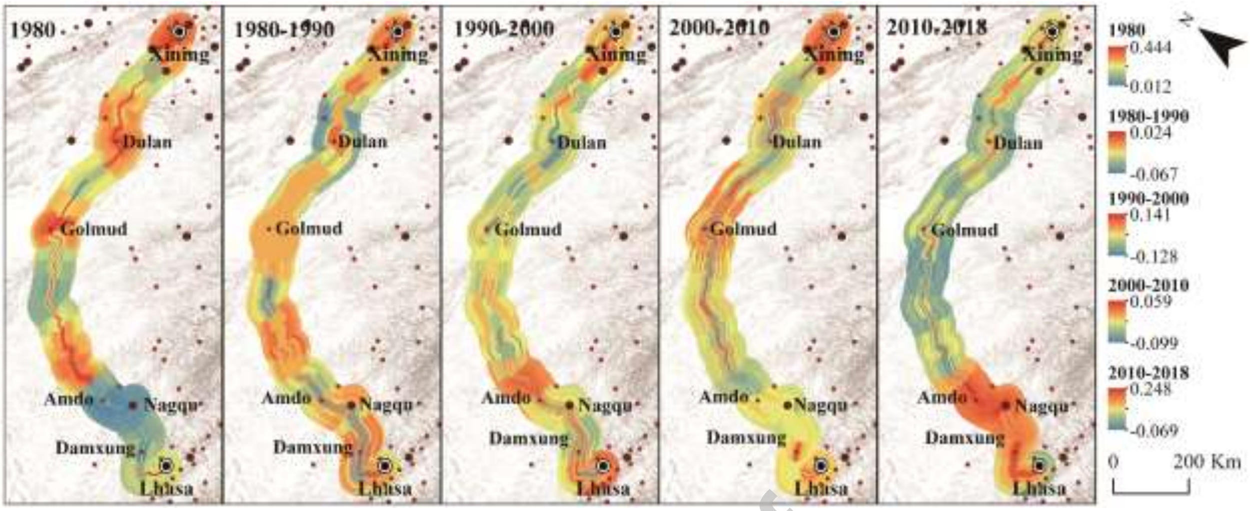
Graphical Abstract:



Landscape fragmentation index (change) results based on different buffers of different road sections.