Environmental Management (2011) 48:774–780
DOI 10.1007/s00267-011-9719-z

The Influence of Landscape Features on Road Development in a Loess Region, China

Xiaoli Bi · Hui Wang · Rui Zhou

Received: 23 September 2009 / Accepted: 29 June 2011 / Published online: 16 July 2011

Abstract Many ecologists focus on the effects of roads on landscapes, yet few consider how landscapes affect road systems. In this study, therefore, we quantitatively evaluated how land cover, topography, and building density affected the length density, node density, spatial pattern, and location of roads in Dongzhi Yuan, a typical loess region in China. Landscape factors and roads were mapped using images from SPOT satellite (Système Probatoire d'Observation de la Terre), initiated by the French space agency and a digital elevation model (DEM). Detrended canonical correspondence analysis (DCCA), a useful ordination technique to explain species–environment relations in community ecology, was applied to evaluate the ways in which landscapes may influence roads. The results showed that both farmland area and building density were positively correlated with road variables, whereas gully density and the coefficient of variation (CV of DEM) showed negative correlations. The CV of DEM, farmland area, grassland area, and building density explained variation in node density, length density, and the spatial pattern of roads, whereas gully density and building density explained variation in variables representing road location. In addition, node density, rather than length density, was the primary road variable affected by landscape variables. The results showed that the DCCA was effective in explaining road–landscape relations. Understanding these relations can provide information for landscape managers and transportation planners.

Keywords Road · Landscape · Detrended canonical correspondence analysis (DCCA) · Dongzhi Yuan

Introduction

Roads have been recognized as an important landscape component (Forman 1998). Understanding the causes, consequences, and dynamics of road development is critical to assess the ecological effects of roads and to manage road systems (Forman and Alexander 1998; Forman 2000; Forman and Deblinger 2000; McGarigal and others 2001; Hawbaker and Radeloff 2004). Many ecologists have explored the influences of roads on landscape fragmentation (Reed and others 1996; McGarigal and others 2001; Li and others 2010), but few have addressed the reverse influence of landscape factors on road systems. Previous studies have demonstrated that land cover and settlement patterns may play active roles in road development (Saunders and others 2002; Hawbaker and others 2005; Gonzalez-Abraham and others 2007a), whereas soil condition and aquatic ecosystems may inhibit road development (Dale and others 1993; Walsh and others 2003). To understand the complex interactions between landscape factors and the development of road systems, quantitative measurement of the influences of landscape factors on roads is necessary.

It is well known that the ecological effects of roads greatly depend on various road characteristics (Forman and others 2003), such as density, area, spatial pattern, class, location, network system, and road-effect zone (Miller and

X. Bi (✉)
Yantai Institute of Coastal Zone Research, Chinese Academy of Sciences, 17th Chunhui Road, Laishan District, Yantai 264003, People's Republic of China
e-mail: xlbi@yic.ac.cn

H. Wang
National Science Library, Chinese Academy of Sciences, Beijing 100190, People's Republic of China

R. Zhou
Institute of Ecology and Geobotany, Yunnan University, Kunming 650091, People's Republic of China

others 1996; Forman and Deblinger 2000; Jaeger 2000; Hawbaker and Radeloff 2004; Hawbaker and others 2006). Density has been commonly used, but it is too simple to adequately describe the characteristics of entire road systems (Saunders and others 2002; Hawbaker and Radeloff 2004). Compared with density, pattern index is a better indicator for describing the spatial distribution of roads (Jaeger 2000; Bi and others 2010). Consideration of road location is also important for evaluating the ecological functions of roads. For instance, the proximity of roads to regions of riparian and aquatic habitat was important for successful nature reserve management (Forman and others 2003). In addition, network indices, such as connectivity, circuitry, and corridor density, are effective in evaluating the ecological consequences of roads, and these measures have been widely used in geography and transportation studies (Kansky 1963; Haggett and Gauthier 1969; Taaffe and Gauthier 1973). It remains unknown whether or not various landscape factors show quantitative differences in how they influence these road characteristics.

Dongzhi Yuan, the largest tableland in the Loess Plateau of China, is a typical loess region that has been densely settled for >2000 years (Zhu 1954). It has historically been the main region for grain and flax production in the Loess Plateau and even for northeastern China (Li and others 2000). With the development of agriculture, large numbers of roads have been constructed in the tableland. In particular, road expansion at the verge areas of gullies has accelerated soil erosion in fragile areas in the region (Wang 2007). The unique natural environment and the pattern of agricultural development make this region an appropriate place to explore the influence of landscape factors on road systems.

The main objective of this study was to quantify how landscape factors have influenced road characteristics in Dongzhi Yuan. Land cover, topography, and rural building density were selected as the main landscape factors in our study, whereas length density, node density, spatial pattern, and location of roads in the area were used to describe the characteristics of existing road systems. We expected that farmland, the main land cover in the tableland, and building density would be positively related to road development, whereas topographical features would be negatively related to it. In addition, we developed several integrated road characteristics to investigate what set of road variables were best explained by those landscape factors.

Materials and Methods

Study Area

Dongzhi Yuan is located in Qingyang County in Gansu Province, China (35°40′N, 107°51′E, elevation = 1298 m a.s.l.) (Fig. 1). In this article, a rectangular region (20 × 24 km), including two towns (Dongzhi and Xiaojin) with populations of 53,000 and 45,000 people, respectively, was selected to examine how a typical loess landscape may influence the development of road system. The study area was divided into 120 samples, each 2 × 2 km, for further spatial analysis. In recent decades, the number of roads in the study area has increased rapidly (Fig. 2).

Data—Landscape Variables

In this study, three types of landscape variables were selected for use in exploring road–landscape relations. These variables included land cover, topography, and rural building density. Land cover has been widely recognized as a dominant component defining landscape patterns (Forman and others 2003). Land-cover data were obtained from multiband SPOT images in 2005 (with 10-m resolution) by unsupervised classification in ERDAS Images 8.6 (Leica Geosystems). Before the classification, the images were georeferenced and mosaiced using aerial photographs taken in 1979 (Bi and others 2010).

Topography is also an important landscape component in the Loess Plateau owing to its great variability in this region (Wang and others 2008b). Digital elevation model (DEM) data were digitalized from a topographical map (1:10,000-scale) (Bi and others 2010). The coefficient of variation of elevation (CV of DEM) in each sample was calculated as the ratio of SD to elevation mean (Gustafson and others 2005; Wang and others 2008a) for use as an indicator of topographical heterogeneity. In addition, gullies, a common topographical feature in Dongzhi Yuan, were digitized based on single-band SPOT images taken in 2005 (with 5-m resolution), and gully density (km/km^2) was defined as the ratio of linear gully length to sample area.

Buildings have been shown to be a critical landscape factor accompanying road development, and the presence of buildings was shown to correlate positively with road occurrence (Hawbaker and others 2005, 2006). The number of rural building in Dongzhi Yuan has increased greatly since the 1970s. Therefore, how rural buildings influenced road development was also considered in this study. Rural buildings were digitalized as a polygon layer, using the same single band SPOT images as described previously, where buildings were characterized by black and white squares. Building density (km^2/km^2) was calculated for each sample.

Data—Road Variables

Roads were digitalized from the same single-band SPOT images, where they were represented by white lines. In this study, the length and location of a given road, and the

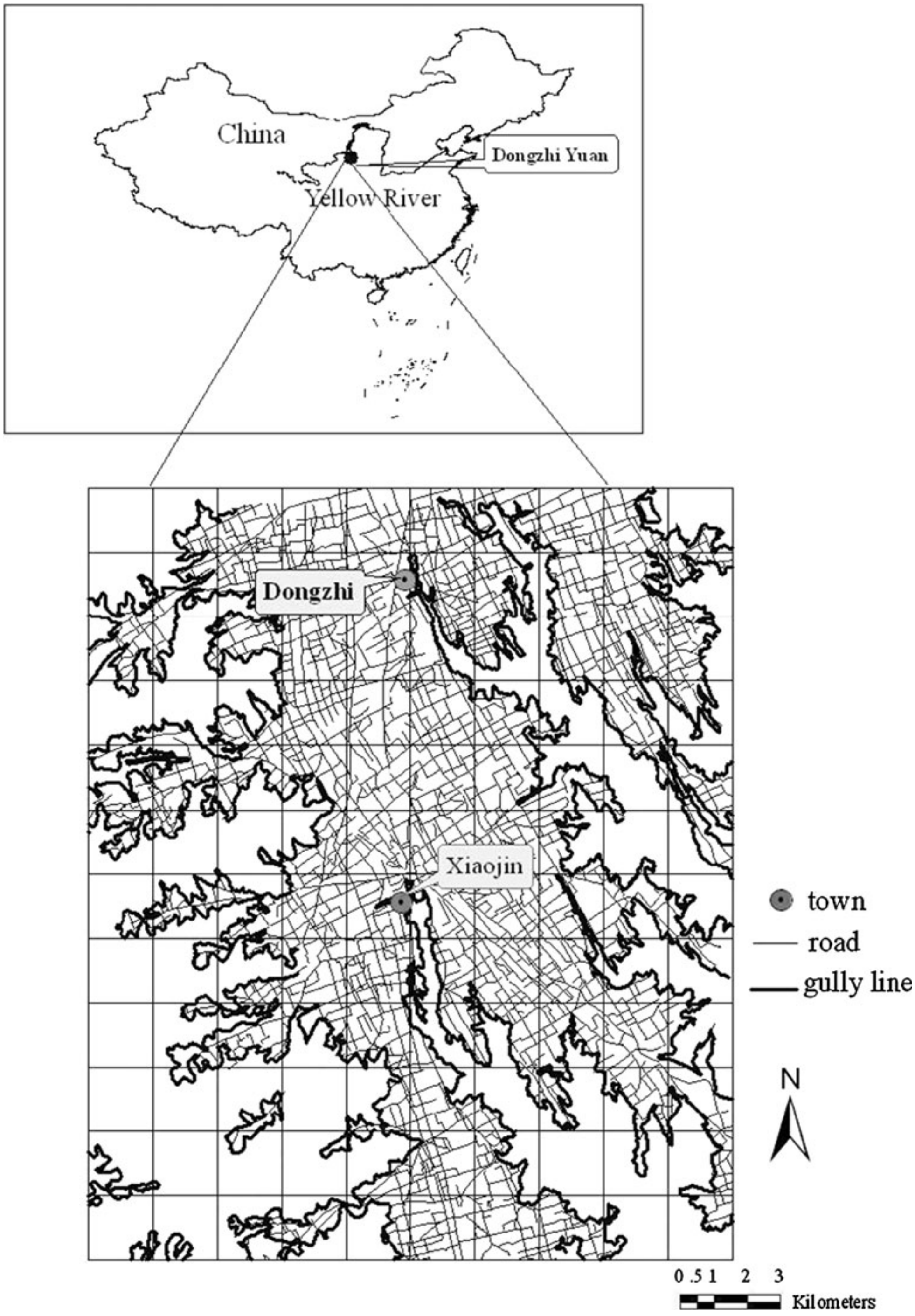

Fig. 1 Study area in Dongzhi Yuan, China. Sample units are 2.0 × 2.0 km

spatial pattern and intersections of roads in a given area, were used as descriptors of road characteristics, whereas area, class, and road-effect zone were not considered due to the absence of relevant data.

Road length density (km/km^2) was calculated for each sample. Data on road network "nodes," i.e., points of intersection of at least two roads, were used to assess degree of spatial connectivity in the road network (Liu and others 2007). Road-node density (node number/km^2) in each sample was calculated using ArcInfo 9.0 (ESRI).

The spatial pattern of roads was characterized using a simple pattern index as the proportion of "occupied" grid-cell (50 × 50 m each) in each sample. A grid-cell was considered occupied if it contained at least one road; hence, this measure reflects the minimum influence of roads in this region. A proportion of occupied grid-cell close to 1

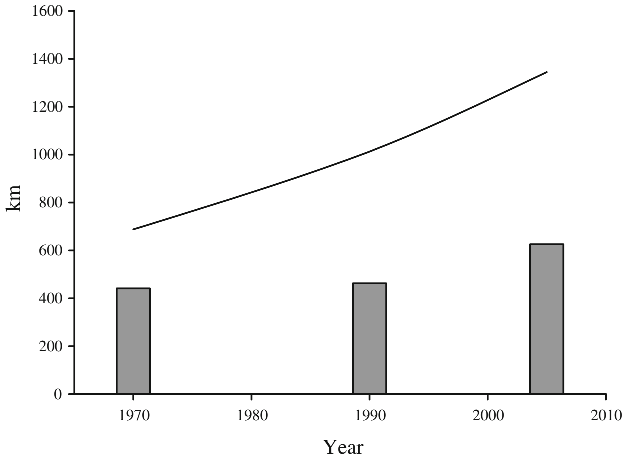

Fig. 2 Total road length (*line*) and gully length (*bar*) have increased in Dongzhi Yuan since the 1970s

indicates a high dispersion pattern (Gonzalez-Abraham and others 2007a; Bi and others 2010).

Road location is typically described as the distance from a road to an area of interest, such as riparian habitat (Forman 1998). In this study, two distance grid layers, to towns and to gullies, were obtained using the Distance function in ArcInfo 9.0. Then we calculated the mean values of those distance grids crossed by roads in each samples.

Detrended Canonical Correspondence Analysis

We used detrended canonical correspondence analysis (DCCA) to explore the relations between landscape and road variables. DCCA, a multivariate direct-gradient analysis method, is used to infer species–environment relations in community ecology. Based on two sets of data collected at the same sites, both occurrence or abundance data for individual species and environmental variables to which all of the species respond, this ordination technique produces an ordination diagram in which points represent species, vectors represent environmental variables, and the DCCA axes integrate both species and environmental variables. The diagram efficiently summarizes variation in species composition as explained by the environmental variables and indicates how species' distributions correspond to each environmental variable (Ter Braak 1986). DCCA remains a popular tool for community ecologists to analyze the influence of complex environmental variables on the biotic community (Dzwonko 1993; Cingolani and others 2003).

In this study, species variables were replaced with road variables and environmental variables with landscape variables. DCCA was performed using CANOCO 4.5 (Ter Braak 1988). The significance of the overall and first DCCA axes were tested using Monte Carlo permutation tests (Ter Braak 1988). All variables were normalized before analysis.

Results

General Description of Landscape and Road Data

The accuracy of unsupervised classification, verified by actual field data, was >80%. Land cover was classified as farmland, grassland, shrub, forest, and river; these classes had areas of 380.16, 55.68, 38.40, 4.81 and 1.00 km^2, respectively. Farmland was the dominant class, accounting for approximately 80% of the entire area. Gully density ranged from 0 to 2.43 km/km^2 (mean 0.01), indicating a highly heterogeneous distribution, whereas building density ranged from 0 to 0.22 km/km^2 (mean 0.16), indicating a relatively homogeneous distribution in this area. The total road length was 1055.95 km, and there were 2029 nodes (points of road intersection). Eight landscape and five road variables were selected to perform DCCA (Table 1), and *P*-values of the first canonical axis and of all canonical axes from the DCCA ordination were both 0.002. The sum of all of the eigenvalues was 0.21, meaning that the DCCA axes explained 21% of the variance in the weighted averages of the road variables (with respect to landscape variables).

Table 1 General description of landscape variables and road variables for DCCA ($n = 120$)

Landscape variable	Maximum	Minimum	Mean	Road variable	Maximum	Minimum	Mean
CV of DEM	0.06	0.00	0.03	Node density (number/km^2)	45	0.00	4.23
Gully density (km/km^2)	2.43	0.00	0.01	Length density (km/km^2)	4.89	0.00	2.19
Farmland (km^2)	3.76	0.00	3.16	Pattern index	1.00	0.00	0.48
Grassland (km^2)	2.24	0.00	0.46	Distance to gully (km)	3.25	1.96	2.51
Shrub (km^2)	1.14	0.00	0.32	Distance to town (km)	4.04	0.81	3.49
Forest (km^2)	0.04	0.00	0.04				
River (km^2)	0.02	0.00	0.00				
Building density (km^2/km^2)	0.22	0.00	0.16				

Landscape Variables Related to Ordination Axes

Correspondence between the landscape variables and the ordination axes was examined using correlation coefficients. As listed in Table 2, the CV of DEM (elevation) was significantly correlated to the first DCCA axis (DCCA1) as were the farmland, grassland, building density, and shrub variables (in decreasing order of the strength of the relation). Gully density was the variable most strongly correlated with the second DCCA axis (DCCA2), followed by building density and CV of DEM. Greater values of DCCA1 indicated lower elevations and greater farmland cover, whereas the number of buildings increased and gullies decreased with increasing values of DCCA2 (Fig. 3). In addition, both farmland area and building density were positively correlated to both DCCA axes, whereas CV of DEM, grassland area, shrub cover, and gully density showed a negative relation (Table 2).

Road Variables Related to Ordination Axes

All canonical axes combined (summed eigenvalues = 0.21) accounted for as much as 77.80% of the variation in road variables (Table 2), with most of this variation accounted for by DCCA1 (65.10%, eigenvalue = 0.17) and only a minor fraction accounted for by DCCA2 (6.30%, eigenvalue = 0.02).

Table 2 Results of DCCA ordination

Results of DCCA ordination	DCCA1	DCCA2
Correlations of landscape variables with the first two axes of DCCA		
CV of DEM	−0.87**	−0.50*
Farmland	0.84**	0.40
Grassland	−0.78**	−0.32
Building	0.71**	0.64*
Shrub	−0.50*	−0.23
River	−0.38	0.04
Gully	−0.24	−0.82**
Forest	−0.14	−0.12
Road-landscape correlation coefficients	0.92	0.86
Cumulative percentage variance		
Of road data	65.10	71.40
Sum	77.80	
Of road–landscape relation	80.80	98.50
Sum	99.90	
Eigenvalues	0.17	0.02
Sum of all eigenvalues	0.21	
Test of significance of first canonical axis	$P = 0.002$	
Test of significance of all canonical axes	$P = 0.002$	

* $P < 0.05$, ** $P < 0.01$

The five road variables were divided into three groups by the DCCA ordination. Node density, length density, and road spatial pattern formed one group at the upper range of DCCA1, whereas distance to gully and distance to town each formed a separate group at the upper and lower extremes of DCCA2, respectively (Fig. 3). Node density mapped closest to the DCCA1 axis, indicating the closest relation among the variables with DCCA1.

Relations Between Road and Landscape Variables

DCCA1 explained 80.80% of the variation in the relation between road and landscape variables, whereas DCCA2 explained 17.70%; all canonical axes together accounted for 99.9% of the variance. The road–landscape correlations were 0.92 (DCCA1) and 0.86 (DCCA2) (Table 2), indicating that the measured landscape variables were able to explain the majority of the variation among road variables.

From the DCCA ordination diagram, node density, length density, and road spatial pattern were positively correlated with farmland area and building density and negatively related to CV of DEM, whereas mean distances to gully and town were negatively related to gully density and building density, respectively (Fig. 3).

Discussion

Because DCCA is not affected by multicollinearity in the "species" data set, in contrast to other types of correlation analysis (Ter Braak 1986), multicollinearity of the road variables could be ignored in our study. Our two-dimensional ordination diagram was quite informative, even although it explained a low percentage of the total variance (sum of all eigenvalues = 0.21). Hence, the use of DCCA represents a feasible mean of explaining road–landscape relations.

Land cover and human activities related to each cover class both have been shown to affect the development of road systems (Forman and others 2003). Ever since the Tang Dynasty (approximately 1400 BP), agricultural industries have been common in Dongzhi Yuan (Zhu 1954). Distribution of farmland in the area has played an important role in determining both density and spatial pattern of roads because roads were designed to connect local agricultural resources and people with markets. In addition, the relation between farmland and road network development has changed with time due to new travel demands and transportation needs (Bi and others 2010; Hess and others 2001). Therefore, it is important to properly understand the dynamic aspects of interactions between farmland and road development in Dongzhi Yuan to fully characterize this system.

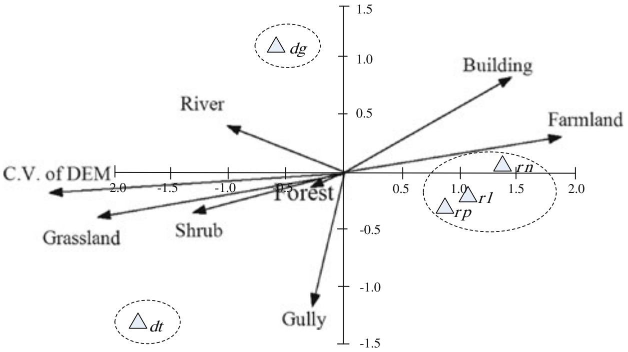

Fig. 3 DCCA ordination diagram with road variables (*triangles*) and landscape variables (*arrows*). The horizontal axis is the first DCCA axis, and the vertical axis is the second DCCA axis. Road variables are as follows: rl = road length density, rn = road node density, rp = road pattern, dt = distance to town, and dg = distance to gully. Landscape variables are as follows: gully = gully density, building = building density, and CV of DEM = coefficient of variation of elevation. Farmland, Shrub, Grassland, Forest, and River represent the areas (km^2) of these land-cover classes

It is relatively dificult to change the local topography during road development (Forman and others 2003), therefore, topographical features should be carefully considered when planning and managing road network. High variability in elevation and gully density has constrained road development in Dongzhi Yuan due to the high cost of building near unstable geological areas. However, the number of roads in gully buffer areas has increased gradually in this region to satisfy transportation demands for local development (Fig. 2). This expansion has indirectly accelerated gully erosion (Wang 2007; Bi and others 2010); hence, such further road expansion should be strictly controlled.

The spatial pattern of existing buildings was significantly correlated with five road variables (Fig. 3). In Dongzhi Yuan, >2000 years of settlement history have greatly influenced the density and spatial pattern of buildings, consequently influencing road development. Recently, many researchers have focused on the close relation between road and building placement because of their similar development processes (Hammer and others 2004; Hawbaker and others 2005, 2006; Gonzalez-Abraham and others 2007b). Compared with land cover and topography, existing buildings can be easily removed in a short amount of time; hence, this may be considered during road development. The spatial layout of structures in an area could also indirectly influence road layout by affecting the spatial pattern of land cover classes (Gonzalez-Abraham and others 2007b), but the spatial pattern of local buildings (as a variable) was not included in the DCCA as it was closely correlated with building density ($R^2 = 0.97$).

The five road variables describing road network attributes in our study show different responses to landscape features. DCCA1 explained more of the variance in node density than in the length density and spatial pattern of roads (Fig. 3), suggesting that landscape variables have influenced road network more strongly than individual road segments. Road location showed a different relation with landscape variables and was influenced largely by densities of gullies and buildings. In Dongzhi Yuan, new road networks have been constructed to supplement the original unpaved road system and improve the connectivity between farmland and built-up areas, exacerbating the ecological effects of roads in the area. Therefore, to assess the impacts of such a complex road network, an integrated framework, such as DCCA, is needed for practical application.

Conclusion

DCCA was applied to evaluate how various landscape factors have altered road system development in Dongzhi Yuan. The ordination diagram suggests that landscape variables may explain variation in road variables to different degrees. CV of DEM (elevation), farmland area, and building density were all strongly correlated with DCCA1, the axis associated with node density, road-length density, and spatial pattern; gully density and building density were correlated with DCCA2, the axis associated with the mean distances from gully and town to road. In addition, node density, rather than length density and spatial pattern, was the road variable affected the most strongly by landscape factors. In conclusion, this study has shown that the use of DCCA would be an effective tool for assessing landscape influences on road systems.

Acknowledgments The authors thank all reviewers of this manuscript for their time, effort, and thoughtful comments, which greatly improved our final product. We thank Bin Wang for constructive comments. We also thank Emily Drummond at the University of British Columbia for assistance with English language and grammatical editing of the manuscript. This research was supported by the Chinese National Key Project for Basic Scientific Research (Grant No. 2002BC11507) and the Knowledge Innovation Program of Chinese Academy of Sciences (Grant No. kzcx2-yw-224).

References

Bi XL, Wang H, Ge JP (2010) The changes of densities and patterns of roads and rural buildings: a case study on Dongzhi Yuan of the Loess Plateau, China. Environmental Monitoring and Assessment 164:549–560

Cingolani AM, Cabido MR, Renison D, Solis VN (2003) Combined effects of environment and grazing on vegetation structure in Argentine granite grasslands. Journal of Vegetation Science 14:223–232

Dale VH, Oneill RV, Pedlowski M, Southworth F (1993) Causes and effects of land-use change in central Rondonia, Brazil. Photogrammetric Engineering and Remote Sensing 59:997–1005

Dzwonko Z (1993) Relations between the floristic composition of isolated young woods and their proximity to ancient woodland. Journal of Vegetation Science 4:693–698

Forman RTT (1998) Road ecology: a solution for the giant embracing us. Landscape Ecology 13:III–V

Forman RTT (2000) Estimate of the area affected ecologically by the road system in the United States. Conservation Biology 14: 31–35

Forman RTT, Alexander LE (1998) Roads and their major ecological effects. Annual Review of Ecology, Evolution, and Systematics 29:207–231

Forman RTT, Deblinger RD (2000) The ecological road-effect zone of a Massachusetts (USA) suburban highway. Conservation Biology 14:36–46

Forman RTT, Sperling D, Bissonette JA, Clevenger AP, Cutshall CD, Dale VH et al (2003) Road ecology: science and solutions. Island Press, Washington, DC

Gonzalez-Abraham CE, Radeloff VC, Hammer RB, Hawbaker TJ, Stewart SI, Clayton MK (2007a) Building patterns and landscape fragmentation in northern Wisconsin, USA. Landscape Ecology 22:217–230

Gonzalez-Abraham CE, Radeloff VC, Hawbaker TJ, Hammer RB, Stewart SI, Clayton MK (2007b) Patterns of houses and habitat loss from 1937 to 1999 in northern Wisconsin, USA. Ecological Applications 17:2011–2023

Gustafson EJ, Hammer RB, Radeloff VC, Potts RS (2005) The relationship between environmental amenities and changing human settlement patterns between 1980 and 2000 in the midwestern USA. Landscape Ecology 20:773–789

Haggett P, Gauthier HL (1969) Network analysis in geography. St. Martin's Press, New York

Hammer RB, Stewart SI, Winkler RL, Radeloff VC, Voss PR (2004) Characterizing dynamic spatial and temporal residential density patterns from 1940–1990 across the North Central United States. Landscape and Urban Planning 69:183–199

Hawbaker TJ, Radeloff VC (2004) Roads and landscape pattern in northern Wisconsin based on a comparison of four road data sources. Conservation Biology 18:1233–1244

Hawbaker TJ, Radeloff VC, Hammer RB, Clayton MK (2005) Road density and landscape pattern in relation to housing density, and ownership, land cover, and soils. Landscape Ecology 20:609–625

Hawbaker TJ, Radeloff VC, Clayton MK, Hammer RB, Gonzalez-Abraham CE (2006) Road development, housing growth, and landscape fragmentation in northern Wisconsin: 1937–1999. Ecological Applications 16:1222–1237

Hess PM, Moudon AV, Logsdon MG (2001) Measuring land use patterns for transportation research. Land Development and Public Involvement in Transportation 1780:17–24

Jaeger JAG (2000) Landscape division, splitting index, and effective mesh size: New measures of landscape fragmentation. Landscape Ecology 15(2):115–130

Kansky KJ (1963) Structure of transportation networks: relationships between network geometry and regional characteristics. Department of Geography, University of Chicago, Chicago

Li FR, Zhao SL, Geballe GT (2000) Water use patterns and agronomic performance for some cropping systems with and without fallow crops in a semi-arid environment of northwest China. Agriculture, Ecosystems & Environment 79:129–142

Li TA, Shilling F, Thorne J, Li FM, Schott H, Boynton R et al (2010) Fragmentation of China's landscape by roads and urban areas. Landscape Ecology 25:839–853

Liu SL, Cui BS, Wen MX, Wang J, Dong SK (2007) Statistical regularity of road network features and ecosystem change in the Longitudinal Range-Gorge Region (LRGR). Chinese Science Bulletin 52:82–89

McGarigal K, Romme WH, Crist M, Roworth E (2001) Cumulative effects of roads and logging on landscape structure in the San Juan Mountains, Colorado (USA). Landscape Ecology 16: 327–349

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

Reed RA, Johnson Barnard J, Baker WL (1996) Contribution of roads to forest fragmentation in the Rocky Mountains. Conservation Biology 10:1098–1106

Saunders SC, Mislivets MR, Chen JQ, Cleland DT (2002) Effects of roads on landscape structure within nested ecological units of the Northern Great Lakes Region, USA. Biological Conservation 103:209–225

Taaffe EJ, Gauthier HL (1973) Geography of transportation. Prentice-Hall, Englewood Cliffs

Ter Braak CJF (1986) Canonical correspondence analysis: a new eigenvector technique for multivariate direct gradient analysis. Ecology 67:1167–1179

Ter Braak CJF (1988) CANOCO—an extension of DECORANA to analysis species–environment relationships. Vegetation 75: 159–160

Walsh SE, Soranno PA, Rutledge DT (2003) Lakes, wetlands, and streams as predictors of land use/cover distribution. Environmental Management 31:198–214

Wang H (2007) Ecological analysis of the gully erosion in the Jinghe River basin. Doctoral dissertation, Beijing Normal University, Beijing, China (in Chinese)

Wang D, Fu BJ, Zhao WW, Hu HF, Wang YF (2008a) Multifractal characteristics of soil particle size distribution under different land-use types on the Loess Plateau, China. Catena 72:29–36

Wang H, Wang TM, Yang MB, Xiong YC (2008b) Quantitative monitoring of gully erosion in hilly gully area of Loess Plateau based on aerial images. Chinese Journal of Applied Ecology 19:127–132

Zhu XM (1954) Soil erosion in Jinghe river basin. Acta Pedologica Sinica 2:209–222