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Road Lateral Disconnection and Crossing Impacts in River Landscape of Lancang River Valley in Yunnan Province, China

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Abstract: Roads are conspicuous components in a river landscape; however, their impacts on river landscape patterns and ecological processes have not been systematically studied at the watershed scale. In this paper, the Lancang River Valley in Yunnan Province, China was selected as a case to study road lateral disconnection and crossing impacts and identify river-road network interaction. This study was primarily focused on the road impacts on soil erosion intensity and patch density by using GIS analysis at different scales and explored their distribution with terrain factors. The results showed that river density revealed spatial autocorrelation although both of the roads and rivers were distributed unevenly in the valley. The lateral road (road curvature $\geq$ 1.1) proportion correlated with soil erosion intensity ($p \leq 0.01$) at the small sub-basin scale. Soil erosion intensity decreased with increasing lateral road buffer width. Light erosion generally accounted for a large proportion of the erosion in the lateral road buffer zones (1.0–4.0 km), while higher class lateral roads imposed greater impacts on soil erosion than lower class roads, which primarily had a moderate erosion level. In addition, the results of road-river intersection density indicated that road crossing impacts were significantly correlated with patch density at the small sub-basin scale. Topography factor (percent of slope > 25° in each sub-basin had a close relationship with the ratio of total length of road line with curvature value $\geq$ 1.1 to the total number of intersections. The correlation ($p \leq 0.01$) between road impacts and terrain factor revealed that topography affected the road impact distribution in the Lancang River Valley.

Keywords: lateral disconnection; crossing impacts; river landscape; patch density; soil erosion; scale effect

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1 Introduction

Human activities have profoundly transformed river landscapes in many fields, such as watersheds, microclimate, and channels, which in turn modify the hydrologic, biotic, and sediment fluxes through river systems (James and Marcus, 2006). Road construction and utilisation are included in these activities. In fact, a road is a conspicuous landscape component and an anthropogenic disturbance imposing distinct patterns and influencing a wide range of ecological processes (Forman and Alexander, 1998; Forman and Deblinger, 2000; Hawbaker *et al.*, 2005). The ecological impacts of a road may include the following: 1) disruption of hydrological process (Campbell and Doeg, 1989; Jones *et al.*, 2000); 2) alteration of disturbance areas (Bellinger *et al.*, 1989; Kouki *et al.*, 1997), soil movement and erosion (Amaranthus *et al.*, 1985); 3) imposition of edge effects of multiple types (on structure, function and composition) and different depths (Meffe *et al.*, 1997; Voller, 1998); and 4) fragmentation of remaining habitats (Coffin, 2007).

River connectivity varies in three spatial dimensions, i.e., lateral, longitudinal and vertical dimensions

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(Amoros *et al.*, 1987; Ward, 1989). Lateral connectivity includes slope-channel and channel-floodplain relationships that drive the supply of materials to a channel network. Longitudinal connectivity, such as upstream-downstream and tributary-trunk stream relationships, drives the transfer of flow through a system and the channel ability to transfer or accumulate sediments of variable caliber on the valley floor. Vertical connectivity refers to surface-subsurface interactions of water, sediment and nutrients (Brierley *et al.*, 2006). Lateral and longitudinal disconnection, the focus of this study, is recognized as the significant impacts on ecological function in the river landscape (Blanton and Marcus, 2009). The lateral disconnection could cause adverse impacts on the development of floodplain evolution, side-channel habitats, riparian ecosystem processes, and biodiversity in the river landscape (Bravard *et al.*, 1986; Ward and Stanford, 1995). The longitudinal disconnection could negatively affect the transfer of flow and sediments in the river (Ward, 1989). The results of Blanton and Marcus (2009) indicated that consideration at the broader spatial extent suggests that the impacts of a road along a river landscape are primarily divided into two different categories: lateral disconnection impacts such as levees and crossing impacts such as bridges. Roads laid along rivers alter the river system connectivity, such as the exchange of water, sediment, and biota between components of the river landscape (Tockner *et al.*, 2000). Previous studies on road impacts in the river landscape primarily are focused on how roads act as barriers to affect the movement of wildlife populations (Oxley *et al.*, 1974; Wilkins, 1982; Mader, 1984; Mech *et al.*, 1988; Brody and Pelton, 1989; Mader *et al.*, 1990; Develey and Stouffer, 2001; Bhattacharya *et al.*, 2003) and road effects on the fragmentation of the landscape (Heilman *et al.*, 2002). Relatively few studies were concentrated on road impacts on river connectivity at the small sub-basin scale. The study of (dis)connectivity helps to understand road impacts on the river landscape.

During rapid economic development, many high-level roads have been constructed in Yunnan Province under the Western Development Strategy of China, and the road network is one of the largest single disturbance factors in this region (Liu *et al.*, 2008). Researches on the unique ecological characteristics of the natural environment in Yunnan Province, the ecologically important status of the Lancang River Valley, and road impacts have significant practical application in this region (Liu *et al.*, 2005). In this study, the Lancang River Valley was selected as a case to quantify the road lateral disconnection and crossing impacts.

This study examines the following issues: 1) characterisation of the potential road network impacts (lateral disconnection and crossing impacts) in the Lancang River Valley; 2) exploration of the appropriate scale for the analysis of road impacts on the landscape pattern and ecological processes; and 3) the distribution of road impacts with terrain variation in the entire valley.

2 Materials and Methods

2.1 Study area

The Lancang River Valley is located in the western part of Yunnan Province, China (21°08′–29°15′N, 98°36′–102°19′E) (Fig. 1). The 1247 km river course includes an area of approximately 88 655 km^2 across 39 counties, comprising 37.2% of the area of Yunnan Province. Strong runoff seasonality existed in the Lancang River with 70% of the overall annual water flow and water flow peak usually in August and September (Jacobs, 2002). The average rainfall is approximately 250 mm in the northwest and 500 mm in the southeast parts of the river (Liu *et al.*, 2008). From the river source to the river mouth, the Lancang River passes through a variety of climatic zones, from the frigid zone to the torrid zone, including a dry-cold zone, a dry-hot zone, and a wet-hot zone. The river gorge is steep in Yunnan, with slopes ranging from 1.5‰ in the upper part to 0.8‰–1.0‰ in the middle and lower parts, and the average elevation is approximately 2000 m. The climate types, complicated topography, rich biological diversity and complex ecosystems make the Lancang River Valley a key region in Yunnan Province (Liu *et al.*, 2008). Together with the complex climate and topography and various forms of human activities, road construction has resulted in many isolated ecosystems and a diverse landscape mosaic. Recently, the demand for larger and better road networks has remarkably increased with rapid local economic development, and two international passages and several expressways that cross the valley are now under construction. The ecological impacts of road network on the valley's river landscape have become an important topic to scientists.

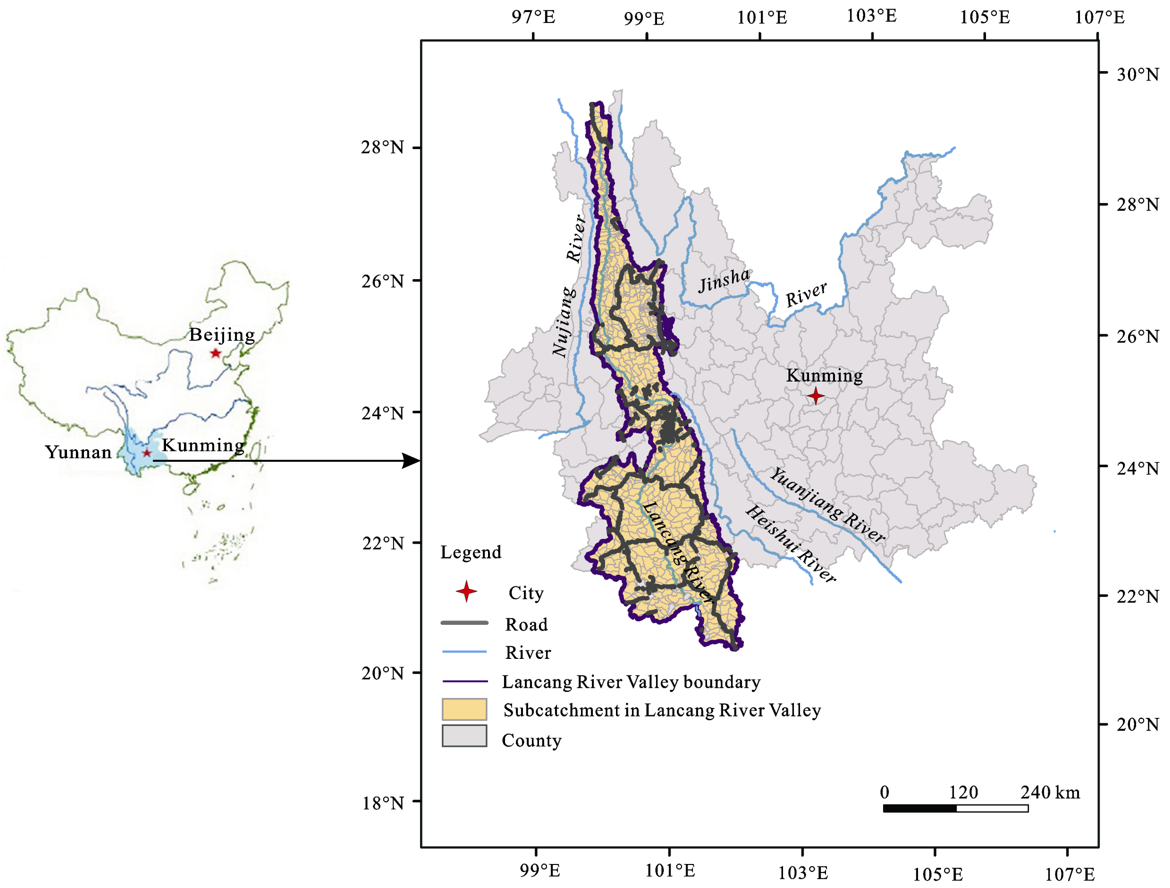

Fig. 1 Location of Lancang River Valley in Yunnan Province

2.2 Methodology

2.2.1 Data sources

The Lancang River Valley was subdivided into 956 small sub-basins to compare the regional-extent indicative metrics of the potential road impacts on the riverscape with GIS software. The road data in vector format in this study were digitised by using the transportation map of Yunnan Province and confirmed with the 1∶250 000 scale road database produced by National Fundamental Geographical Information Centre in 2008. According to Shi (2008), the roads were classified into 4 classes: trunk roads, town roads, village roads and unpaved roads. Landsat TM images in 2007 were classified into forest, grassland, farmland, saline land and marshland, urban land, rural residential land, and construction land for land cover mapping. Then, the map was validated by using ground truth data, which indicated an overall accuracy of at least 90% and a Kappa coefficient of 0.88. The soil erosion map at a scale of 1∶100 000 of the Lancang River Valley were used to analyze road ecological impacts. The soil erosion intensity detected by the spectral features in remote images was primarily identified in three classes, namely, light erosion, moderate erosion, and severe erosion (Liu *et al.*, 2005).

2.2.2 Methods

According to the framework suggested by Forman *et al.* (2003), the following approaches were primarily applied to analyze the interaction between road and river networks: 1) the general interaction pattern of the road-river network; and 2) the analysis of the road impacts with the soil erosion intensity and patch density.

The following approaches were used to obtain the general interaction pattern of the road-river network: 1) road and river network density, 2) road network curvature, 3) road-river intersection density, 4) topography metrics and 5) buffer analysis. The measurement of road and river network density was firstly performed in this study for two reasons; density is the simplest spatial measure of ecological impacts, and many ecological patterns are strongly linked to density patterns (Forman *et al.*, 2003). Spatial distribution of road and river network density was examined by spatial autocorrelation analysis by using the Moran I index in the GIS software. Based on the isomorphism (similarity in pattern) between transportation networks and river networks (Haggett, 1967), the road curvature index (RCI) proposed by Blanton and Marcus (2009) was applied to differentiate the straight road lines from the curvy lines as follows:

$$RCI = L_s / L_{sf} \quad (1)$$

where L_s is the curvilinear length of a section of road line, and L_{sf} is the linear distance between the start and finish points for each line segment. Blanton and Marcus (2009) suggested that curvature values ≥ 1.1 represented the locations where road lines followed the pattern of river valleys, while the values lower than 1.1 were associated with radial patterns in low relief areas, and road lines with curvature values ≥ 1.1 as portions of the road network indicate a high potential for lateral disconnection along their lengths. We calculated the percent of the total road length with curvature values ≥ 1.1 in each region and identified the roads with curvature values ≥ 1.1. The road-river crossings were obtained through the intersection of road layer and river layer in the GIS software and the road-river crossing density was obtained by dividing the crossings by the sub-basin area. We selected the average slope of each sub-basin to characterise the potential contribution of topography to the distribution of the road impacts type. The slope degree was derived from DEM (short for digital elevation model, derived from National Geomatics Center of China with the resolution of 25 m) and reclassified into five ranks: 0°–2°, 2°–6°, 6°–15°, 15°–25° and above 25°. We calculated the percentage of the total area of each region which was classified into the last rank (> 25°) to obtain an indicator of the topography. The quartile map of the proportion of areas with a slope degree above 25° is shown in Fig. 2.

Patch density and soil erosion intensity were selected to indicate the landscape pattern and ecological process. Patch density, the indicator of landscape fragmentation and spatial heterogeneity, was widely applied to indicate the landscape pattern change. The patch density (at landscape level) in each sub-basin was calculated by using GIS software. Soil erosion, which significantly affects the floodplain of the river system, is an important ecological process observed in the Lancang River Valley. The soil erosion intensity was obtained as soil erosion area divided by the total area. Based on the previous research on this topic and the correlative studies in this region (Liu *et al.*, 2008; Shi *et al.*, 2008), we set four different buffers (1 km, 2 km, 3 km and 4 km, respectively) for all road classes. This two-sided buffer distance does not account for road width. To study the correlation between road networks and soil erosion, we calculated the soil erosion proportion in each buffer and determined the variation as the buffer width increased.

3 Results

3.1 General interaction pattern of road and river network

3.1.1 Road and river network density

The sub-basins located in the southwest part of the valley have the highest road densities and the least difference between road and river network densities (Fig. 3). In contrast, the sub-basins in the south and central of the valley have lower road densities and the largest difference between river and road densities. The distribution of the difference of road and river network densities revealed the general pattern of an east-west, high-to-low gradient. The sub-basins located in the central part of the valley have relatively higher road and river network densities as many sub-basins with the third highest road/river densities and above located there.

The correlogram for spatial autocorrelation of the road and river network density was obtained through the Global Moran′s Index calculation, and the values were 0.10 and 0.47, respectively. The values indicated that the distribution of the river network was not completely random and had a certain degree of spatial concentration, while the road network revealed almost no spatial concentration. The spatial link characteristics suggested that the sub-basins near those with high river network density values also have high density values of river network, while the subcatchments near those with low river network density values often have low river network density values. The positive spatial correlation property certified the spatial difference in river network in the Lancang River Valley.

3.1.2 Intersection and network curvature

Figure 4 shows the distribution of road-river intersection density. The subcatchments in the north and parts of the central region of the valley have more intersections per 1000 km^2, while the south regions have relatively fewer intersections. The correlation between the intersections in each sub-basin and road network density was analyzed, and the results showed significant correlation (r = 0.387).

The geographic distribution pattern of the percentage

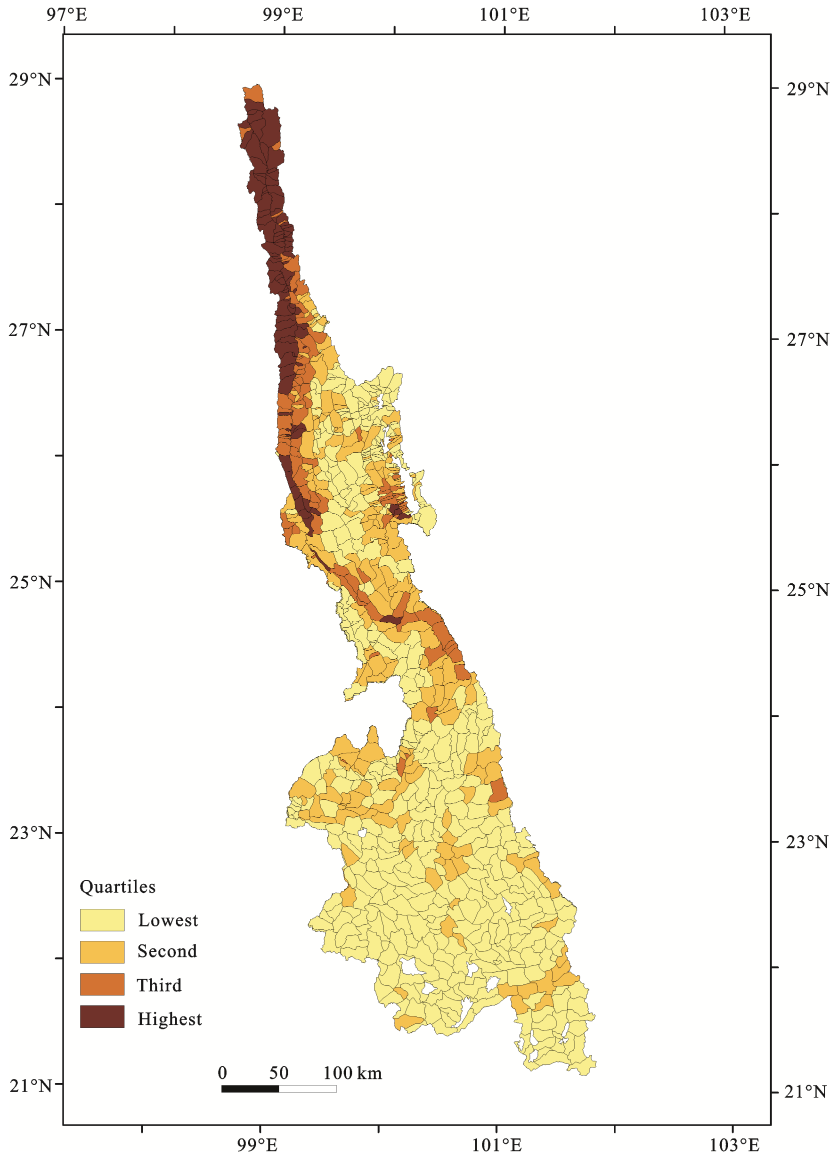

Fig. 2 Quartile map of proportion of areas with slope degree above 25° in each region. The 'highest' quartile ranking indicates the highest proportion of areas in subcatchments with slope above 25°

of roads with curvature value ≥ 1.1 revealed a similarity to the intersection distribution (Fig. 5). More roads with curvature value ≥ 1.1 are located in the north and central regions of the valley, while relatively fewer lateral roads are located in the south regions, and the differences still existed.

3.2 Relationship between road impact and soil intensity and patch density

The correlations between soil erosion and road impacts, including lateral disconnection and crossing impacts, were calculated, and the results indicated that the road-river intersection density did not significantly correlate with the soil erosion intensity in each sub-basin. The road network curvature index revealed the significant correlation with the soil erosion intensity in each sub-basin (Table 1). The degree of correlation here indicated that the road network curvature index revealed no correlation with the patch density in each sub-basin, while the road-river intersection density revealed significant correlation with the patch density in each sub-basin (Table 1).

3.3 Erosion distribution in buffer zones alongside lateral roads

The results of Fig. 6 showed that light erosion was a major erosion type in the buffer zones on both sides of the road. Except in the town road buffer, the erosion proportion of the three erosion types generally followed the pattern below: light erosion > moderate erosion >

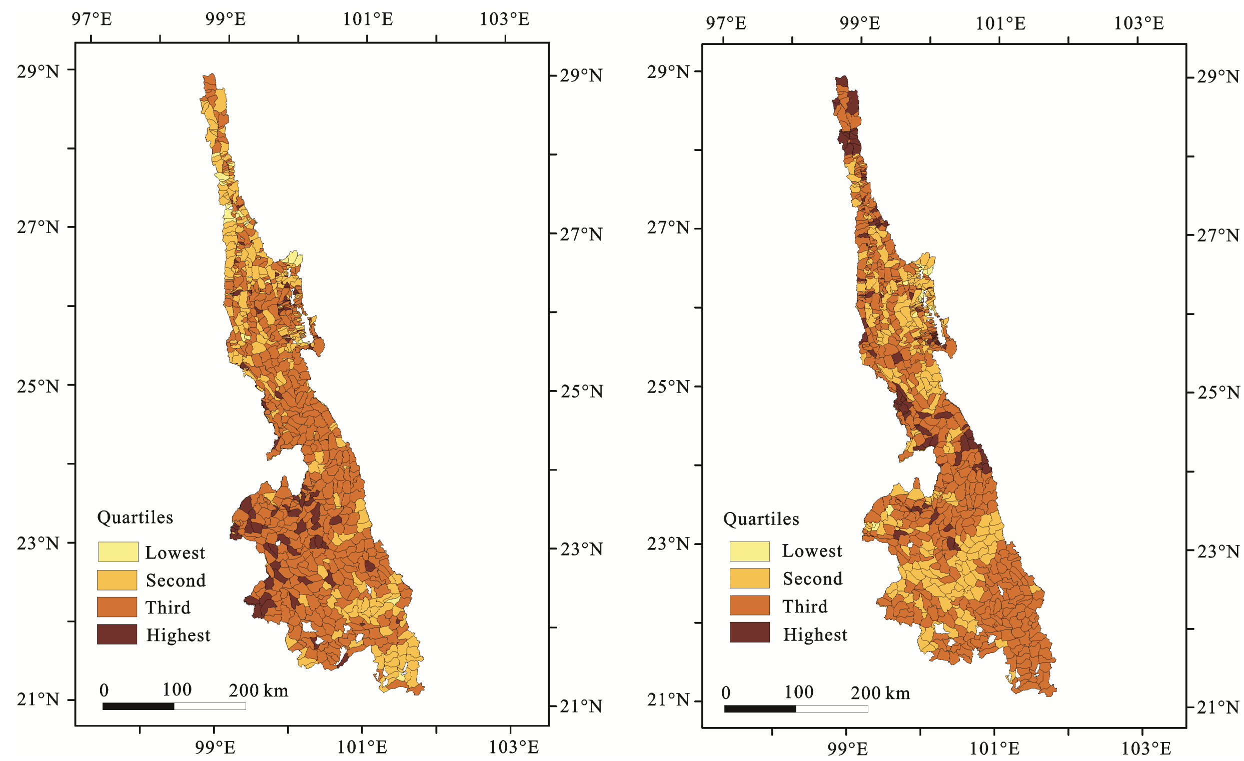

Fig. 3 Quartile maps of road and river network density. Left, road network density; right, river network density. The 'highest' quartile ranking indicates the highest river/road network density in subcatchments

severe erosion. The erosion proportion in the buffer zones reduced with increasing distance to roads; the minimum erosion proportion was found in the 3.0–4.0 km buffer, and the maximum erosion proportion was found in the 0–1.0 km buffer. Severe erosion covered a relatively limited area, and this trend had a relatively slow change compared to light and moderate erosion. Light soil erosion was less related to the distance to trunk and town roads and more related to village and unpaved roads, but moderate soil erosion showed an opposing relationship with the distance to the roads. The distance to village and unpaved roads had a greater effect on light erosion, and the distance to the trunk and town roads had a greater effect on moderate erosion. Therefore, more attention should be paid to soil conservation during the construction of higher class roads which have greater impacts on soil erosion.

4 Discussion

4.1 Comprehensive effects of roads and terrain conditions on soil erosion

Blanton and Marcus (2009) proposed an index for the proportion of potential lateral disconnection to crossing impact, which was the ratio of total length of road line with curvature value ≥ 1.1 to the total number of intersections. The index revealed significant correlation (r = 0.111) with the percent of region with the slope degree above 25° in each subcatchment; the results verified that the terrain in the valley determined the configuration of the road network, and the configuration determined the categories of the road impacts along the valley. However, the results indicated that more lateral roads were located in the steep regions in the Lancang River Valley, which might partially explain why the regions with a high curvature value had a larger area of soil erosion. Slope was an additional primary factor affecting soil erosion intensities, indicating that the soil erosion in the Lancang River Valley was caused by multiple factors rather than the lateral road factor. Landscape, including land use, parent material, landform, alongside the roads of various classes, affected soil erosion (Pan *et al.*, 2005). The construction of lateral roads (especially the trunk and town roads) destroyed the forests nearby because the zones close to roads were relatively easy to destroy. Therefore, it is concluded that the road impacts on soil erosion were strengthened by steep landforms and anthropogenic activities.

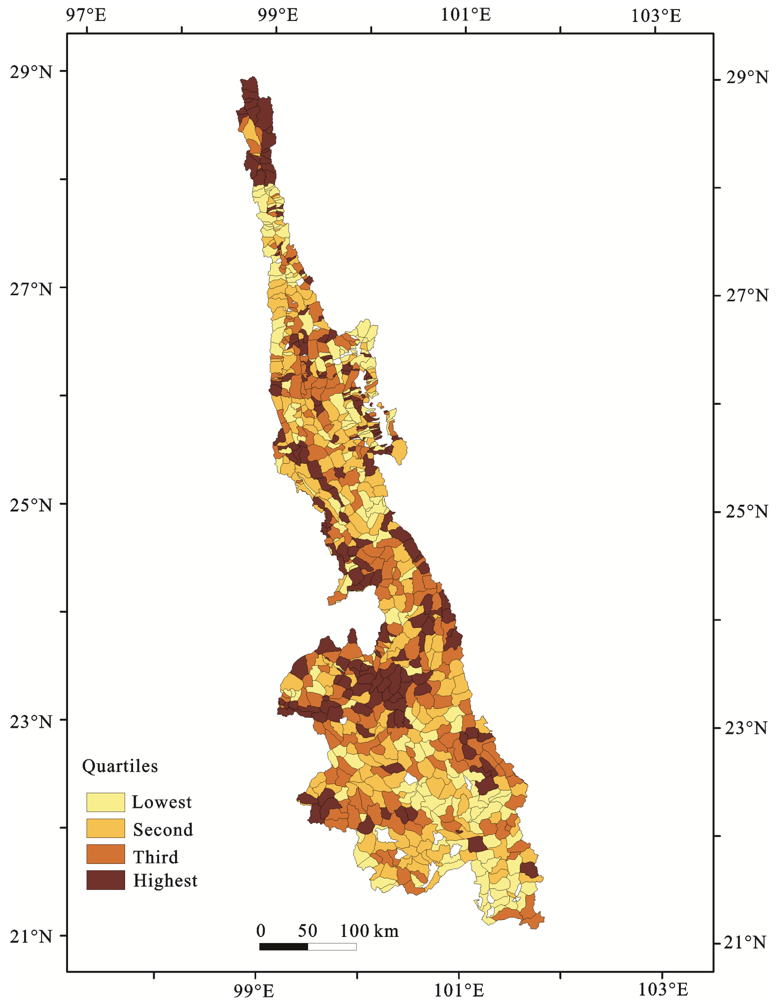

Fig. 4 Quartile map of road-river intersections. The 'highest' quartile ranking indicates the highest road-river intersection density in subcatchments

4.2 Scale effects on road impacts in river landscape

Spatial patterns are widely recognised as changing with the scale of observation or analysis, which could be viewed as a scale-dependent effect (Gardner, 1998; Wu *et al.*, 2000). We explored the scale effects on road impacts in the river landscape by maintaining the grain size constant as the extent varied. We divided the entire Lancang River Valley into three patterns according to the area of the sub-basin to represent small, medium and large scales. The results in Table 2 show that significant correlation was only found between road lateral impact and patch density at the medium scale, and no significant correlations were found among these factors at the large scale. The relationships at the medium and large scales were clearly quite different from those at the small scale, indicating that road impacts were not identified at the relatively large scale and that changes in scale affected the spatial analysis results.

The road crossing impacts were significantly correlated with patch density at the small scale (Table 1), and road lateral disconnection impacts were correlated significantly with patch density at the large scale, indicating that changing the scale altered the main type of road impacts on the river landscape, which might be partly attributed to the variation of the patch density pattern with the extent altering (Wiens, 1989; Wu, 1999). Notably, the results of soil erosion intensity and patch density revealed significant correlation with road lateral disconnection and crossing impacts only at the small scale (Table 1), which indicated that the small scale was appropriate for analysis of the road impacts on the river landscape.

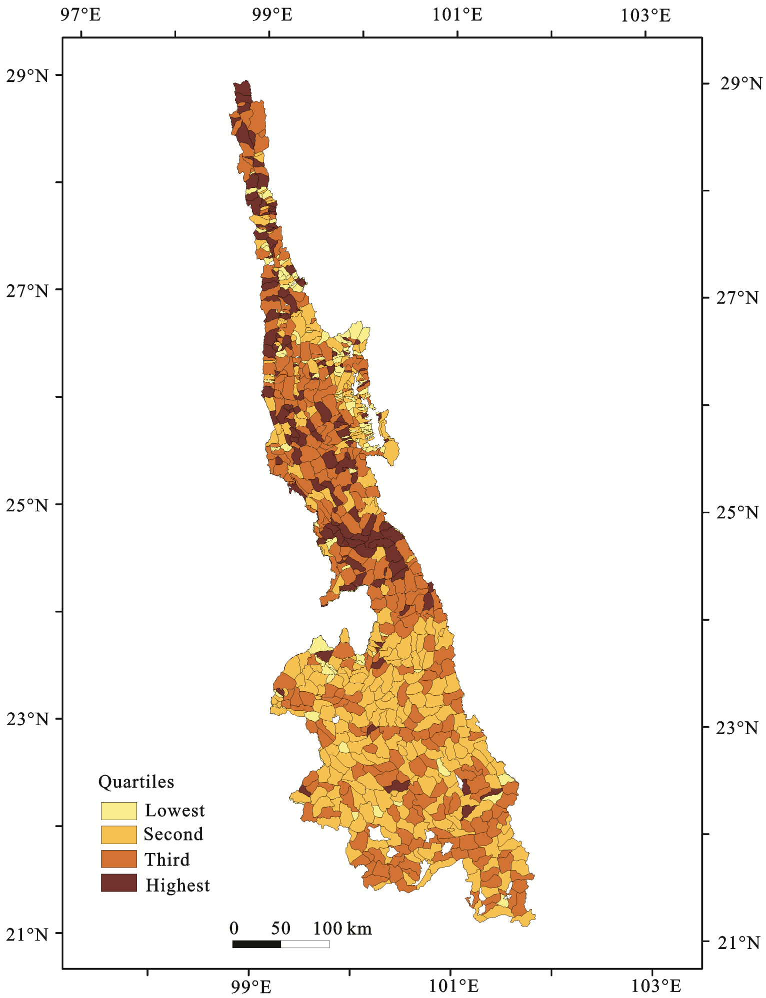

Fig. 5 Quartile map of proportions of roads with curvature ≥ 1.1. The 'highest' quartile ranking indicates the highest proportion of road with curvature ≥ 1.1 in subcatchments

Table 1 Spearman rank correlation of road impact and metrics in small sub-basins

Metrics	Road-river intersection density	Road network curvature value index
Patch density	0.085*	–0.014
Erosion intensity	0.067	0.156**
Terrain factor	–0.063	0.294**

Notes: Values given are Spearman's Rho (rs). *, significance at 0.05 level; **, significance at 0.01 level

4.3 Implications of this study and future research

According to the results of Liu *et al*. (2008), we used road data to assess the potential road impacts on the river landscape and applied a network that contained all road types. Our results showed that lateral road disconnection caused soil erosion. This finding was consistent with the result from Blanton and Marcus (2009), suggesting that disconnection led to floodplain habitat richness and degraded riparian ecosystems. Lateral roads in the Lancang River Valley, especially high-class roads, were identified as impacting the soil erosion intensity. The above results revealed that the disconnection caused by the roads in the valley required more investigation. Identification of the lateral roads in the region could show sites with higher erosion risk, and this information would be helpful for road planning in the valley region. Our results certified the impact of the longitudinal disconnection caused by the road-river intersection on the landscape fragmentation in the valley, while future research should be conducted on the effects of the fragmentation on the river systems. We assessed how roads as a whole impact the valley, which serves as an important preliminary study to understand the magnitude and distribution of the impact caused by roads across the Lancang River Valley and provides a basis for integrated measures in the further research.

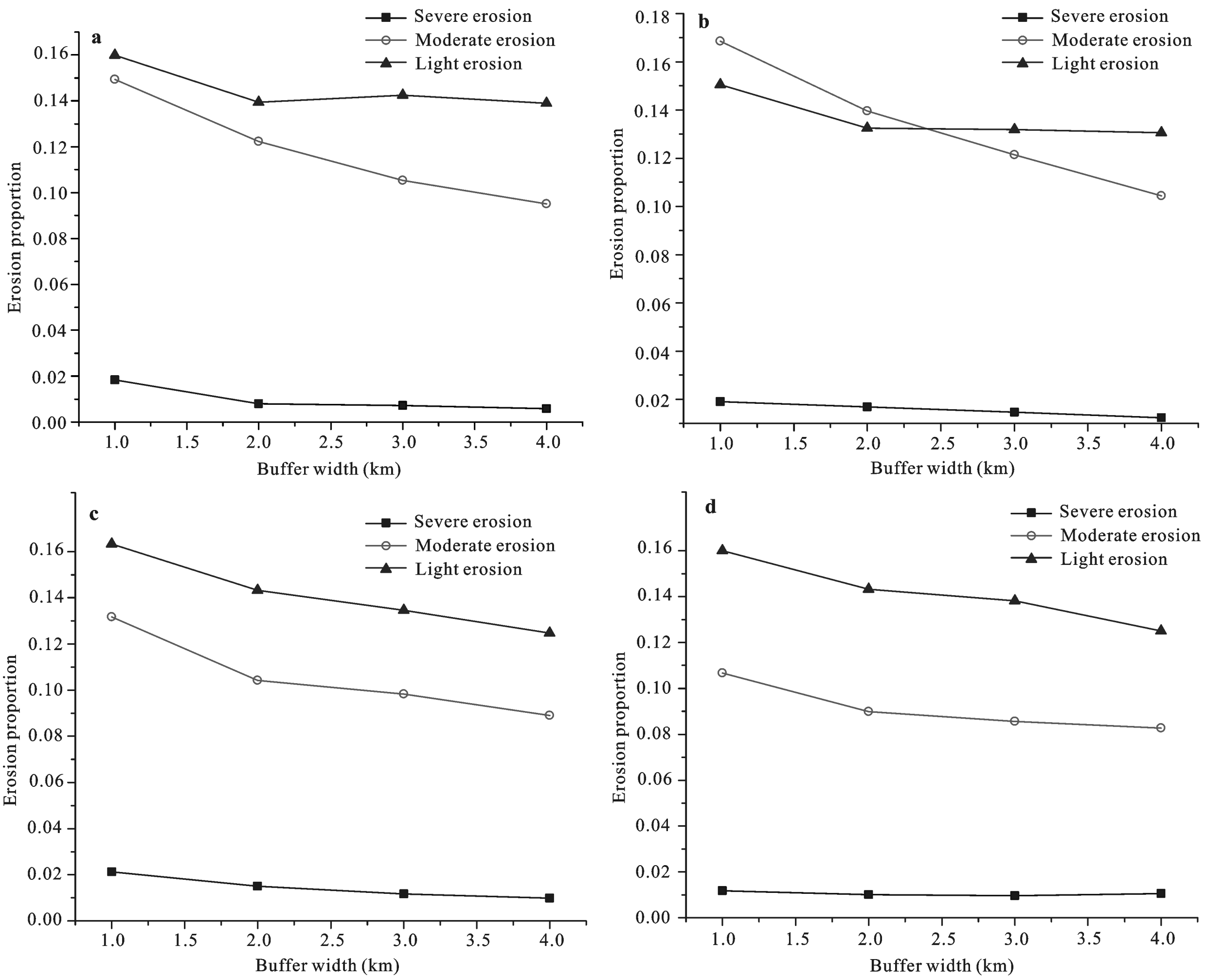

Fig. 6 Erosion proportion variation in buffer zones of different classes of lateral roads. a, trunk road; b, town road; c, village road; d, unpaved road

Table 2 Correlation of road impacts and metrics at medium and large scales

Metrics	Large Scale		Medium Scale	
	Road-river intersection density	Road network curvature value index	Road-river intersection density	Road network curvature value index
Patch density	–0.156	–0.365	–0.016	0.235*
Erosion intensity	–0.164	0.032	–0.145	0.046

Notes: Values given are Pearson's R. *, significance at 0.05 level; **, significance at 0.01 level. Large scale: 25 sub-basins with average basin area of 2889.89 km^2; medium scale: 93 sub-basins with average basin area of 776.85 km^2

5 Conclusions

This study characterised the potential road network impacts on the patch density and soil erosion in the Lancang River Valley, explored the scale effects of road impacts and discussed the variation of road impacts distribution along with the terrain variation. In the Lancang River Valley, we found that the road network in different configurations impacted the landscape pattern and soil erosion, and scale effects existed on road impacts in the river landscape. The results of buffer analysis showed that high-class lateral roads had greater impacts on soil erosion, to which more attention was needed to pay. In addition, the results indicated that the valley terrain determined the road network configuration and the road impact type along the Lancang River Valley.

This study provided useful information for understanding the road lateral disconnection and crossing impacts. However, further research is needed to 1) understand the mechanism on how the road network in different configurations affects the landscape pattern and the ecological processes, and 2) analyze the effects of fragmentation on the river systems.

References

Amaranthus M P, Rice R M, Barr N R *et al*., 1985. Logging and forest roads related to increased debris slides in southwestern Oregon. *Journal of Forestry*, 83(4): 229–233.

Amoros C, Roux A, Reygrobellet J *et al*., 1987. A method for applied ecological studies of fluvial hydrosystems. *Regulated Rivers*: *Research & Management*, 1(1): 17–36. doi: 10.1002/rrr.3450010104

Bellinger R G, Ravlin F W, McManus M L, 1989. Forest edge effects and their influence on gypsy moth (Lepidoptera: Lymantriidae) egg mass distribution. *Environmental Entomology*, 18(5): 840–843.

Bhattacharya M, Primack R B, Gerwein J, 2003. Are roads and railroads barriers to bumblebee movement in a temperate suburban conservation area? *Biological Conservation*, 109(1): 37–45. doi: 10.1016/S0006-3207(02)00130-1

Blanton P, Marcus W A, 2009. Railroads, roads and lateral disconnection in the river landscapes of the continental United States. *Geomorphology*, 112(3–4): 212–227. doi: 10.1016/j.geomorph.2009.06.008

Bravard J P, Amoros C, Pautou G, 1986. Impact of civil engineering works on the successions of communities in a fluvial system: A methodological and predictive approach applied to a section of the Upper Rhône River, France. *Oikos*, 47(1): 92–111. doi: 10.2307/3565924

Brierley G, Fryirs K, Jain V, 2006. Landscape connectivity: The geographic basis of geomorphic applications. *Area*, 38(2): 165–174. doi: 10.1111/j.1475-4762.2006.00671.x

Brody A J, Pelton M R, 1989. Effects of roads on black bear movements in western North Carolina. *Wildlife Society Bulletin*, 17(1): 5–10.

Campbell I C, Doeg T J, 1989. Impact of timber harvesting and production on streams: A review. *Marine and Freshwater Research*, 40(5): 519–539. doi: 10.1071/MF9890519

Coffin A W, 2007. From roadkill to road ecology: A review of the ecological effects of roads. *Journal of Transport Geography*, 15(5): 396–406. doi: 10.1016/j.jtrangeo.2006.11.006

Develey P F, Stouffer P C, 2001. Effects of roads on movements by understory birds in mixed-species flocks in central Amazonian Brazil. *Conservation Biology*, 15(5): 1416–1422. doi: 10.1046/j.1523-1739.2001.00170.x

Forman R T T, Alexander L E, 1998. Roads and their major ecological effects. *Annual Review of Ecology and Systematics*, 29(1): 207. doi: 10.1146/annurev.ecolsys.29.1.207

Forman R T T, Deblinger R D, 2000. The ecological road effect zone of a Massachusetts (USA) suburban highway. *Conservation Biology*, 14(1): 36–46. doi: 10.1046/j.1523-1739.2000.99088.x

Forman R T T, Sperling D, Bissonette J A *et al*., 2003. *Road Ecology*: *Science and Solutions*.Washington, D.C.: Island Press, 418.

Gardner R H, 1998. *Pattern*, *Process*, *and the Analysis of Spatial Scales*. New York: Ecological Scale Colombia University Press, 17–34.

Haggett P, 1967. Network models in geography. In: Chorely R J (ed.). *Models in Geography*. London: Methuen & Co., 609–688.

Hawbaker T J, Radeloff V C, Hammer R B *et al*., 2005. Road density and landscape pattern in relation to housing density, and ownership, land cover, and soils. *Landscape Ecology*, 20(5): 609–625. doi: 10.1007/s10980-004-5647-0

Heilman G E, Strittholt J R, Slosser N C *et al*., 2002. Forest fragmentation of the conterminous United States: Assessing forest intactness through road density and spatial characteristics. *BioScience*, 52(5): 411–422. doi: 10.1641/0006-3568(2002)052[0411:FFOTCU]2.0.CO;2

Jacobs J W, 2002. The Mekong River Commission: Transboundary water resources planning and regional security. *Geographical Journal*, 168(4): 354–364. doi: 10.1111/j.0016-7398.2002.00061.x

James L A, Marcus W A, 2006. The human role in changing fluvial systems: Retrospect, inventory and prospect. *Geomorphology*, 79(3–4): 152–171. doi: 10.1016/j.geomorph.2006.06.017

Jones J A, Swanson F J, Wemple B C *et al*., 2000. Effects of roads on hydrology, geomorphology, and disturbance patches in stream networks. *Conservation Biology*, 14(1): 76–85. doi: 10.1046/j.1523-1739.2000.99083.x

Kouki J, McCullough D G, Marshall L D, 1997. Effect of forest stand and edge characteristics on the vulnerability of jack pine stands to jack pine budworm (Choristoneura pinus pinus) damage. *Canadian Journal of Forest Research*, 27(11): 1765–1772. doi: 10.1139/cjfr-27-11-1765

Liu S L, Cui B S, Dong S K *et al*., 2008. Evaluating the influence of road networks on landscape and regional ecological risk: A case study in Lancang River Valley of Southwest China. *Ecological Engineering*, 34(2): 91–99. doi: 10.1016/j.ecoleng.2008.07.006

Liu Shiliang, Yang Zhifeng, Cui Baoshan, 2005. Effects of road on landscape and its ecological risk assessment: Case study of Lancang River Valley. *Chinese Journal of Ecology*, 24(8): 897–901. (in Chinese).

Mader H J, 1984. Animal habitat isolation by roads and agricultural fields. *Biological Conservation*, 29(1): 81–96. doi: 10.1016/0006-3207(84)90015-6

Mader H J, Schell C, Kornacker P, 1990. Linear barriers to arthropod movements in the landscape. *Biological Conservation*, 54(3): 209–222. doi: 10.1016/0006-3207(90)90052-Q

Mech L D, Fritts S H, Radde G L *et al*., 1988. Wolf distribution and road density in Minnesota. *Wildlife Society Bulletin*, 16(1): 85–87.

Meffe G K, Carroll C R, Contributors M J, 1997. *Principles of Conservation Biology* (*2nd edition*). Sunderland, Massachusetts: Sinauer Associates Inc., 729.

Oxley D J, Fenton M B, Carmody G R, 1974. The effects of roads on populations of small mammals. *Journal of Applied Ecology*, 11(1): 51–59. doi: 10.2307/2402004

Pan J, Zhang T, Zhao Q, 2005. Dynamics of soil erosion in Xingguo County, China, determined using remote sensing and GIS. *Pedosphere*, 15(3): 356–362.

Shi X, Wang K, Warner E D *et al.*, 2008. Relationship between soil erosion and distance to roadways in undeveloped areas of China. *Catena*, 72(2): 305–313. doi: 10.1016/j.catena.2007.06.004

Tockner K, Malard F,Ward J V, 2000. An extension of the flood pulse concept. *Hydrological processes*, 14(16–17): 2861–2883. doi: 10.1002/1099-1085(200011/12)14:16/17<2861::AID-HYP124>3.0.CO;2-F

Voller J, 1998. Managing for edge effects. In: Voller J *et al*. (eds.). *Conservation Biology Principles for Forested Landscapes*. Vancouver, Canada: University of British Columbia Press, 215–233.

Ward J V, 1989. The four-dimensional nature of lotic ecosystems. *Journal of the North American Benthological Society*, 8(1): 2–8. doi: 10.2307/1467397

Ward J V, Stanford J A, 1995. Ecological connectivity in alluvial river ecosystems and its disruption by flow regulation. *Regulated Rivers*: *Research & Management*, 11(1): 105–119. doi: 10.1002/rrr.3450110109

Wiens J A, 1989. Spatial scaling in ecology. *Functional Ecology*, 3(4): 385–397. doi: 10.2307/2389612

Wilkins K T, 1982. Highways as barriers to rodent dispersal. *Southwestern Naturalist*, 27(4): 459–460. doi: 10.2307/3670722

Wu J, 1999. Hierarchy and scaling: Extrapolating information along a scaling ladder. *Canadian Journal of Remote Sensing*, 25(4): 367–380.

Wu J, Jelinski D E, Luck M *et al*., 2000. Multiscale analysis of landscape heterogeneity: Scale variance and pattern metrics. *Geographic Information Sciences*, 6(1): 6–19. doi: 10.1080/10824000009480529