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Spatiotemporal Patterns of Road Network and Road Development Priority in Three Parallel Rivers Region in Yunnan, China: An Evaluation Based on Modified Kernel Distance Estimate

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Abstract: Road network is a critical component of public infrastructure, and the supporting system of social and economic development. Based on a modified kernel density estimate (KDE) algorithm, this study evaluated the road service capacity provided by a road network composed of multi-level roads (i.e. national, provincial, county and rural roads), by taking account of the differences of effect extent and intensity for roads of different levels. Summarized at town scale, the population burden and the annual rural economic income of unit road service capacity were used as the surrogates of social and economic demands for road service. This method was applied to the road network of the Three Parallel River Region, the northwestern Yunnan Province, China to evaluate the development of road network in this region. In results, the total road length of this region in 2005 was 3.70×10^4 km, and the length ratio between national, provincial, county and rural roads was 1∶2∶8∶47. From 1989 to 2005, the regional road service capacity increased by 13.1%, of which the contributions from the national, provincial, county and rural roads were 11.1%, 19.4%, 22.6%, and 67.8%, respectively, revealing the effect of 'All Village Accessible' policy of road development in the mountainous regions in the last decade. The spatial patterns of population burden and economic requirement of unit road service suggested that the areas farther away from the national and provincial roads have higher road development priority (RDP). Based on the modified KDE model and the framework of RDP evaluation, this study provided a useful approach for developing an optimal plan of road development at regional scale.
Keywords: road network; kernel density estimate (KDE); road service; road development priority (RDP); Three Parallel Rivers Region; China

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1 Introduction

Based on the high structural and functional connectivity, corridor network plays a critical role in landscape functions (Forman and Gordon, 1986; Kindlman and Burel, 2008), and landscape dynamics, such as habitat fragmentation (Bennett, 1990; Li *et al*., 2004). As a basic linear component in human-dominated landscape, roads appear in the form of the networks with various complexities, and perform as the vessel system of materials, energy, information and mankind itself, driving the evolution of landscape patterns, e.g., urbanization (Forman *et al*., 2003). Being an important part of public infrastructure, the development of road network enhances

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the radiation and attraction of the cities and towns, improves the efficiency of social production and services, and benefits regional economic linkage and coordination (Chen, 2004; Liu *et al.*, 2008; Xu *et al.*, 2011; Yang and Kong, 2012). The total length and spatial structure of road network have a profound effect on the land use and regional socio-economic development (Zhan and Lu, 2003; Pugh and Fairburn, 2008). For example, one of the important experiences for the rapid economic growth in recent 30 years in China was summarized as 'To get rich, build roads first'. On the other hand, as a highly connected and intensively disturbed type of habitat network, roads also have many significant negative effects on ecosystem functions and services at landscape and regional scales (Forman *et al.*, 2003; van der Ree *et al.*, 2011).

The structural and functional properties of road network are represented in two directions, i.e., along and perpendicular to the road itself (Forman *et al.*, 2003). However, among the few methods quantifying road network structure, road density is the most commonly used index, which is based only on the total length of roads in a specific region (Forman and Alexander, 1998), irrespective of the effect of road level and spatial configuration of road network on its function (Demir, 2007; Erath *et al.*, 2009; Wang, 2010). Other methods of landscape pattern analysis, such as buffer analysis, treat the interior structure of corridor as homogeneous, ignoring the environmental gradient within buffer zone (www.esri.com/arcgisde).

KDE was proposed to describe the spatial distribution of density of a particular flux, or impact of a process across the space (Parzen, 1962; Silverman, 1986), and has recently been introduced to study the spatial structure and impacts of road network (Borruso, 2003; Xie and Yan, 2008; Liu *et al.*, 2011; Cai *et al.*, 2013). Applying a two dimensional distance attenuation model for the samples, KDE describes spatial pattern of density change both along and perpendicular to the line (e.g., road, river), and projects the hot-spots of samples distribution with an automatic search method. Ying *et al.* (2012) improved the method by differentiating road levels with regard to the extent and magnitude of road effect, proposed a modified KDE index and applied to quantify the impact of a road network at regional scale. However, the effect of the modification was not tested and the implication unrevealed.

Based on the modified KDE algorithm (Ying *et al.*, 2012), we designed a framework in this study to estimating the spatiotemporal patterns of road service capabilities in the Three Parallel Rivers Region of the northwestern Yunnan Province, China, and proposed a quantitative approach to evaluate the spatial pattern of priority for road development in the future, based on the estimate of social and economic requirements for road services, a positive road impacts. As a world natural and cultural heritage, the Three Parallel Rivers Region possesses unique and abundant geological relics and high biodiversity. Primarily stimulated by the rapid development of tourism in this region, the road building has been accelerated in last two decades, and has raised the concern of balance between the economic development and environmental conservation. Therefore, it is of great significance to estimate the change of service capabilities of the road network and its social and economic effects in this region. By applying the method to the road data of the Three Parallel River Region in 1989 and 2005, we tried to answer the following questions: 1) What changes occurred to the road service in the studied region from 1989 to 2005? 2) How do effective extent and intensity of road impact differ for roads of different levels? 3) According to the social and economic requirement for road service, how to determine the area of priority for regional road development?

2 Materials and Methods

2.1 Study area

The Three Parallel Rivers Region (25°25′–29°15′N, 98°7′–101°16′E) is famous for its location, where the Jinsha River, the Lancang River and the Nujiang River flow parallel approximately to north-south direction (Fig. 1). It is composed of a total of 161 administrative towns that belong to three counties (i.e., Dêqên, Weixi and Xamgyi'nyilha) of the Tibetan Autonomous Prefecture of Dêqên, four counties (i.e., Gongshan, Fugong, Lushui, and Lanping) of the Lisu Autonomous Prefecture of Nujiang, two counties (Yulong and Ninglang) of Lijiang City, and six counties (Yunlong, Dali, Jianchuan, Eryuan, Binchuan and Heqing) of the Bai Autonomous Prefecture of Dali, with the area of about 64 000 km^2 (Chen *et al.*, 2004).

2.2 Data sources and processing

The vector data of road network of two periods, 1989 and 2005, in the Three Parallel River Region are used in this study, with the road data of 1989 and the administrative boundary data extracted from the topographic map of the region at the scale of 1∶100 000. The road data of 2005 were obtained from the National Geometrics Center of China (NGCC) (http://ngcc.sbsm.gov.cn/). With the 1989 data used as a standard for calibration, the data of two years were projected to the same scale under the projection system of Beijing 1954_GK_Zone_17N. According to the standard of the National Ministry of Traffic and Transportation, the road system is divided into four levels, i.e., national, provincial, county and rural road. Social and economic statistical data of 2005 at the administrative level of town were downloaded from the Yunnan Digital Villages Web (http://www.ynszxc.gov.cn), which included the population and the annual rural income by town (Fig. 2).

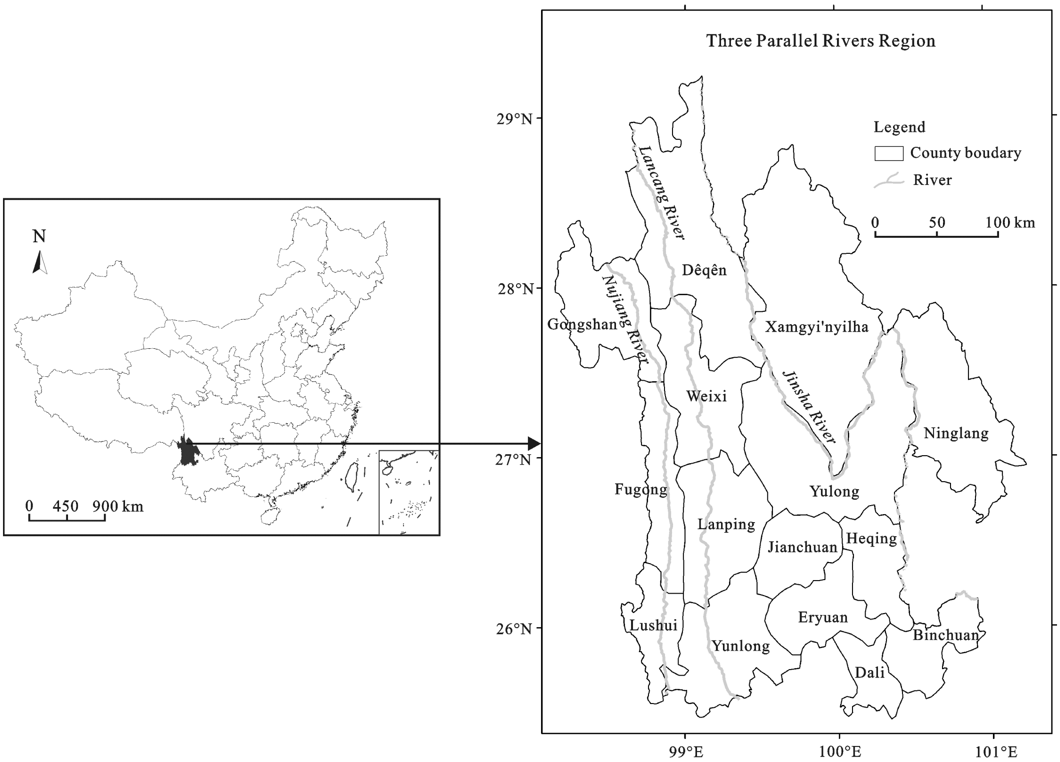

Fig. 1 Location of study area in Yunnan Province of China

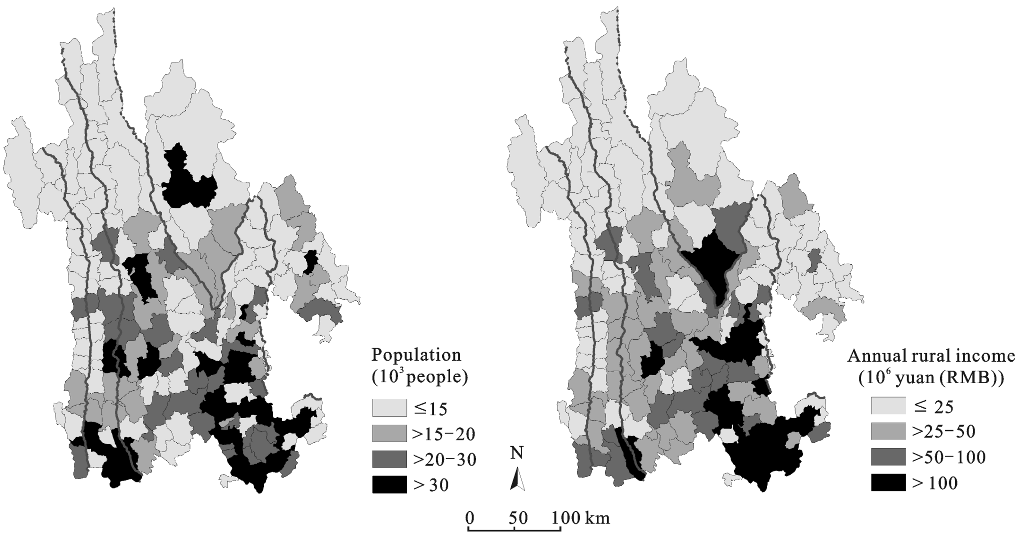

Fig. 2 Spatial patterns of social and economic conditions in Three Parallel River Region in 2005

2.3 Methods

2.3.1 Road density

The road density in a region (D) is calculated as:

$$D = L/A \quad (1)$$

where L is the total length of the roads in the region, with the unit km; A represents the area of the region, with the unit km^2.

2.3.2 Modified kernel density estimate algorithm

Modified KDE algorithm is a spatial interpolation algorithm provided in the Spatial Analyst module of GIS software ArcGIS 9.0. According to this method, the density of pints or lines within each cell is calculated through a shifting window. The algorithm is defined as: z_1, ..., z_n are the independent and identically distributed samples drawn from the population with a probability density function f. Then the value of f at z, i.e., $f_n(z)$, is calculated as Rosenblatt-Parzen′s KDE:

$$f_n(z) = \frac{1}{nh}\sum_{i=1}^{n} k\left(\frac{|z - z_i|}{h}\right) \quad (2)$$

where z is the central location of the current cell; z_i is the central location of the ith point of the road network in the studied area; and $|z–z_i|$ represents the Euclidian distance between z and z_i; n is the total number of the samples; h is the radius of the shifting window, or ′bandwidth′. $k(x)$ is the kernel function, taking the following form in ArcGIS (Silverman, 1986):

$$k(x) = \begin{cases} \frac{1}{3\pi}\left(1 - x^2\right)^2 & \text{if} \quad x^2 < 1 \\ 0 & \text{otherwise} \end{cases} \quad (3)$$

The algorithm runs with following steps: 1) set a radius to define a shifting window (circle) to search the sample of points or lines inside it; 2) determines the size of the output cell based on the required density precision; 3) with the kernel function, calculate the contribution of each sample inside the window to the predicted density of the current cell; and 4) assign the density value to each cell, as the sum of the contribution from all samples within the window.

By taking account of the difference of effect range and intensity between the roads of different levels, we modified the KDE algorithm to extract a more reasonable estimate of the road effect, as a surrogate of the transportation service capabilities of a road network composed of multi-level roads. According to the KDE algorithm, the variation of the sliding average density decreases when the search radius h increases, or vice versa (Shi, 2010). However, the empirical values of affecting range for roads of different levels are lack in the literature. Based on the fact that the typical mountains and valleys landform of the studied area has significant constraint on the affecting range of road, we assigned 6 km, 4 km, 2 km and 0.5 km as tentative values to h for the national, provincial, county, and rural roads, when calculating the modified KDE for the roads of corresponding levels.

According to Equation (2), the kernel density at z, i.e., $f_n(z)$ depends on both h and the distance between z and z_i, given a kernel function $k(x)$. Therefore, $f_n(z)$ is negatively correlated with h, resulting in the highest density at the center of the rural road (Fig. 3a). This is obviously conflict with the empirical facts. To overcome the bias, the density $f_n(z)$ was multiplied by the corresponding bandwidth h of each level of road. We assume

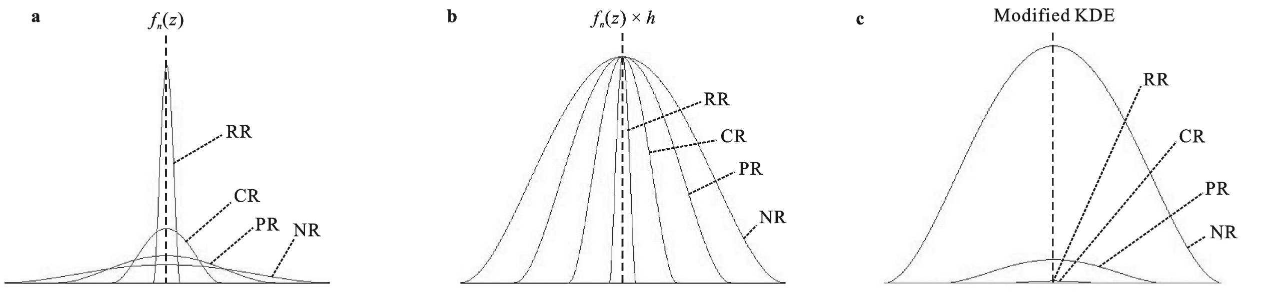

Fig. 3 Curves of kernel density estimate (KDE) algorithm for roads of different levels, modified by considering the difference of effect range and intensity between road of different levels. a. Assign the effect ranges of 6.0 km, 4.0 km, 2.0 km, 0.5 km to the road of national, provincial, county and rural level; b. set identical value to the central value of density for road of different levels; c. assign the effect intensity of 400, 100, 10, 1 to the roads from high to low levels. NR: national road; PR: provincial road; CR: county road; RR: rural road

that the value at the center of the road are equal for roads of different levels, so, $|z - z_i|$ for the road of different levels have an order of values as follows: national road > provincial road > county road > rural road (Fig. 3b).

Roads of different levels have different transportation capacity, but the direct or indirect measure of capacity for different road levels is not available. For an experimental estimate, we assigned tentative values of 400, 100, 10 and 1 as the relative transportation capacity of national, provincial, county and rural roads according to empirical experience. In the Map Algebra module of ArcGIS, these values were multiplied by the corresponding values of $f_n(z) \times h$ to result in the summarized road effect of currently computed cell, provided by the multi-level roads within the searching range (Fig. 3c). By taking the length, effect range and intensity of multi-level roads into account, we defined the comprehensive estimate of the road effect in each cell as a non-dimensional index of road service capacity (RSC), and compared the regional pattern of RSC estimated with both the original and the modified KDE algorithms (Fig. 4). Although experimental parameter is not available, we assume, according to empirical experiences, that the effect range and intensity of higher level road are larger than lower level road by order of magnitude. So we think the modified KDE algorithm is more reasonable than the original algorithm, and the following estimate of road service capacity was all based on the modified algorithm.

2.3.3 Road development priority based on social-economic requirement

The population divided by RSC was used as an indicator of social requirement for road development, while the annual income of rural economy divided by RSC was used as an indicator of economic efficiency (or economic requirement) of the road development. Therefore, a measure of RDP based on social and economic requirement was proposed by integrating the two items:

$$RDP = a \times R_s + (1 - a) \times R_e \quad (4)$$

where R_s is social requirement for road service, measured as population burden per unit of RSC; R_e is economic requirement of road service, measured as annual income of rural economy per unit of RSC. In Equation (4), the two indexes are normalized to transfer the values into values within [0, 1] before calculation. Coefficient a reflects the importance of social requirement of the road service, and in this study, we make it as important as the economic efficiency of the road, that is, a = 0.5. Thus, the ultimate index, RDP, is also in the 0 to 1 inclusive, which is used to evaluate the relative priority of the road development in the study area.

We estimate RDP at the cell size of 30 m × 30 m, and took the median value of all cells within a specific administrative town as the RDP value for the town. Overall, there are 161 towns in the Three Parallel Rivers Region. The data processing and spatial analysis were im-

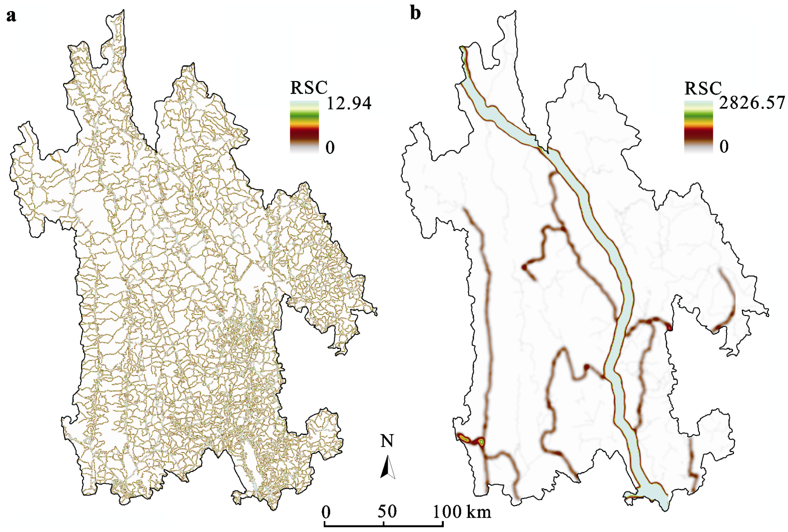

Fig. 4 Road service capacity (RSC) in Three Parallel Rivers Region in 2005, estimated with original KDE algorithm (a) and modified KDE algorithm (b)

plemented in ArcGIS 9.3 (www.esri.com/software/arcgis/) and other statistical analysis was implemented in R software (www.r-project.org/).

3 Results

3.1 Road density and changes

In 2005, the total length of roads in the Three Parallel Rivers Region was about 3.70×10^4 km, with an regional average road density of 0.619 km/km^2. The length ratio between road of the four levels was about 1 (national) ∶ 2 (provincial) ∶ 8 (county) ∶ 47 (rural) (Table 1). Taken together, the regional road length increased by 63.7% from 1989 to 2005, and the mean densities of national, provincial, county and village road increased 1, 8, 14, and 162 m/km^2, respectively (Table 1).

There were significant differences of frequency distribution of road density among different levels in the Three Parallel Rivers Region, and evident changes from the year 1989 to 2005 (Fig. 5). The frequency distributions of national and provincial road densities were significantly left-skewed, implying its limited distribution in a small number of towns, while the distribution tend to be uniform for low level roads. From 1989 to 2005, the frequency distribution of road density at national and provincial levels changed little, while the number of towns with low road density of rural and county levels reduced markedly, indicating a significant spatial expansion of low-level roads across the region (Fig. 5d).

3.2 Spatio-temporal pattern of road service capacity

According to the modified KDE algorithm, the spatial pattern of RSC in the studied region was dominated by the distribution of high level (national and provincial) roads (Figs. 6a and 6b). The area with RSC value larger than 10.0 was composed of only 19.3% in 1989 and 21.9% in 2005 in the region, all along the national and provincial level roads, and the area with RSC larger than 200 was only along the national road. The overall RSC of the studied region increased 13.1% in the 1989–2005, and the contributions from the national, provincial, county and rural roads was 11.1%, 19.4%, 22.6%, and 67.8%, respectively.

Summarizing the increment of RSC within 1989–2005 by towns (Fig. 6c), it was found that most towns with increment of RSC > 50% were located relatively remote from the national and provincial roads, and the RSC

Table 1 Mean and coefficient of variance (CV) for road density of different levels in Three Parallel Rivers Region in 1989 and 2005

Year	National road		Provincial road		County road		Rural road	
	Mean (km/km^2)	CV	Mean (km/km^2)	CV	Mean (km/km^2)	CV	Mean (km/km^2)	CV
1989	0.010	2.52	0.026	1.38	0.067	0.90	0.331	0.78
2005	0.011	2.52	0.034	1.33	0.081	0.85	0.493	0.44

Note: CV is based on the mean and standard deviation values of road density of 161 towns in this region

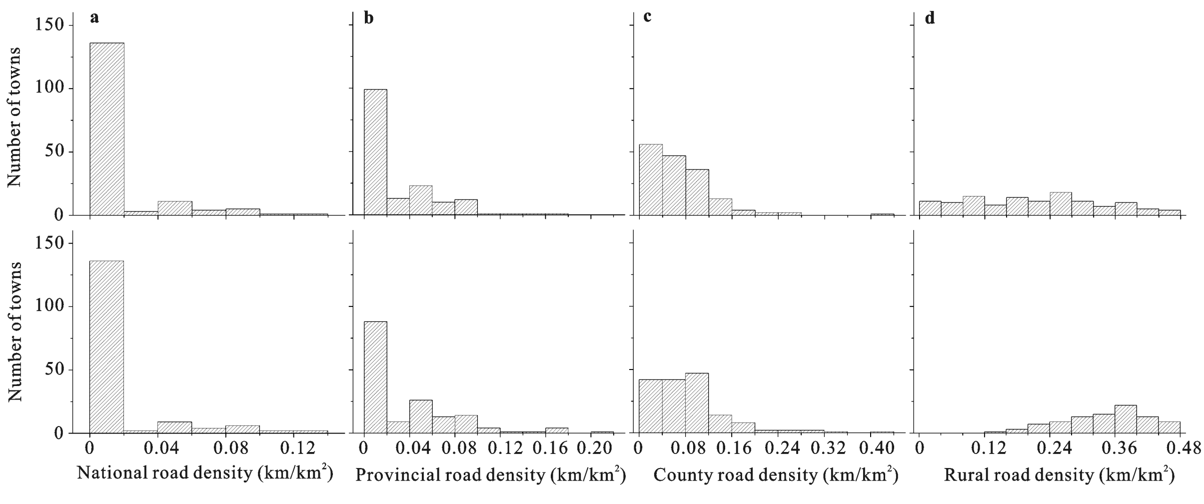

Fig. 5 Frequency distribution of road densities of different levels in Three Parallel Rivers Region in 1989 (the upper row) and 2005 (the lower row). a. national road; b. provincial road; c. county road; d. rural road

increment has a significantly negative correlation (r = –0.476, p = 1.67E–10) with the RSC value in 1989 estimated at town level.

3.3 Assessment of road development priority

Although road density calculated by towns showed a strong decreasing trend from southeast to northwest of the region (Fig. 7a), the road service capacity was dominated by the spatial pattern of national and provincial roads (Fig. 6). As the population decreases roughly from southeast to northwest in the study area (Fig. 2a), the population load of unit RSC (R_s) was generally lar-

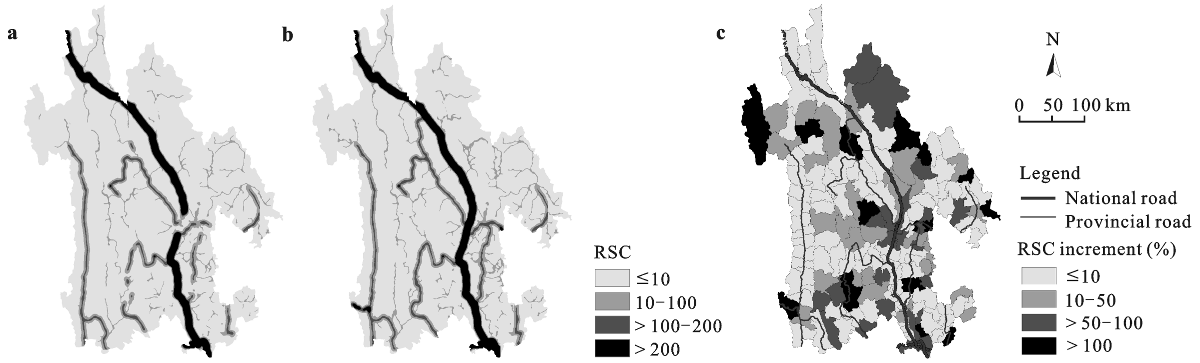

Fig. 6 Pattern of road service capacity (RSC) and its increment in Three Parallel Rivers Region. a. RSC in 1989; b. RSC in 2005; c. RSC increment in 2005

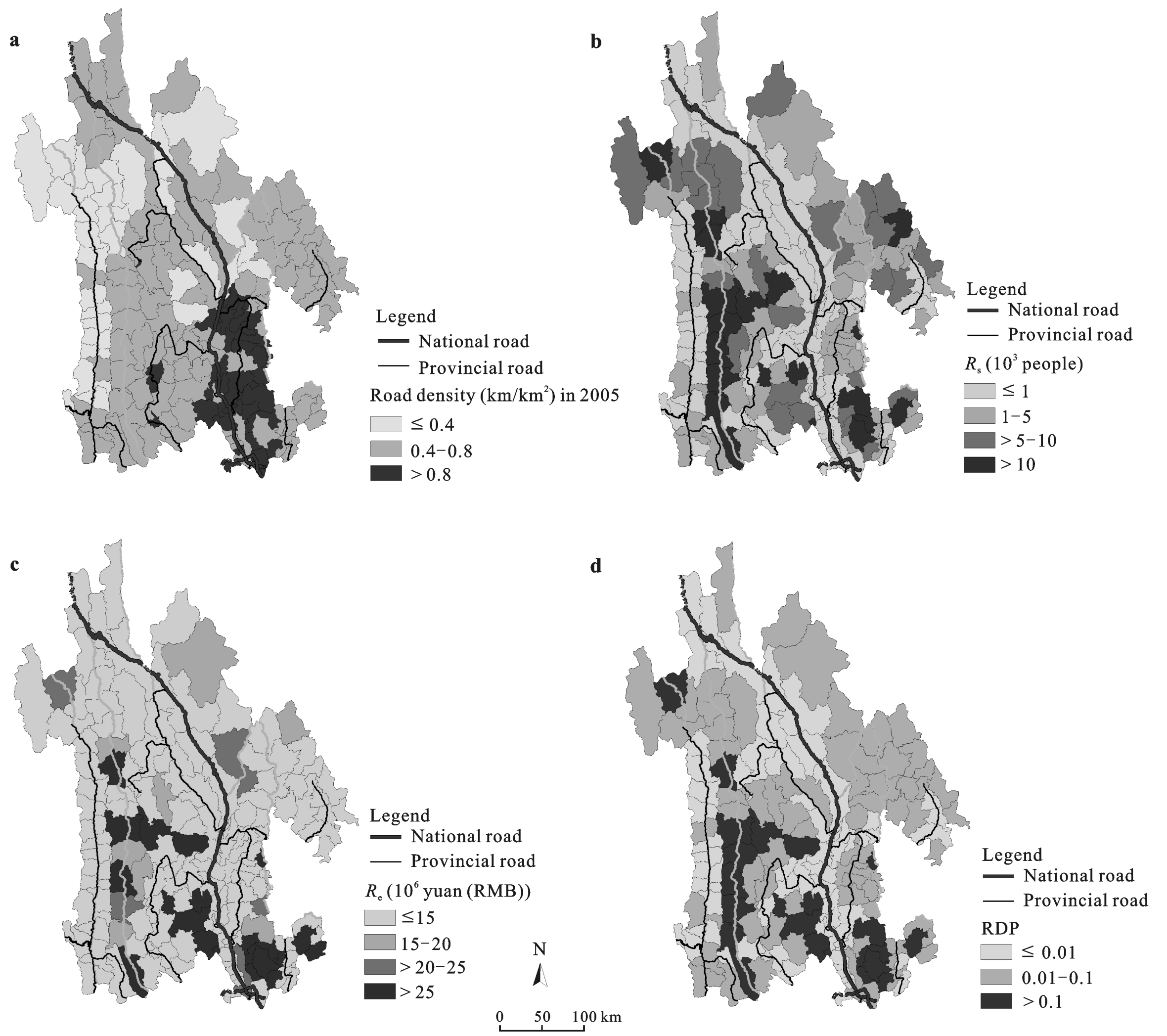

Fig. 7 Spatial patterns of present road distribution and future road development priority (RDP) in Three Parallel Rivers Region

ger in the towns away from the national and provincial roads. The areas with high social requirement of road service included the majority of Gongshan County lying in the northwestern corner, most towns along the Lancang River in Weixi, Lanping and Yunlong counties, as well as some towns of Dali, Binchuan and Ninglang counties, in the southeastern part of the region (Fig. 7b).

The annual income of rural economy of unit RSC (R_e) relate the economic products and road service capabilities, and reflect the economic efficiency of (or potential economic feedback to) road development. Overall, annual incomes of rural economy (at town level) along the national and provincial roads were relatively low in 2005. In contrast, the high economic efficiency of road service occurred in the areas far away from high level roads, such as the towns along the Lancang River in Weixi County and Yunlong County, the towns along Yangbi River, a tributary of Lancang River in Eryuan County, and some towns in Dali and Binchuan County (Fig. 7c).

By combining the information of both population burden and economic efficiency, the spatial pattern of RDP highlighted the regional heterogeneity of social and economic demands for road development in 2005. The towns along Lancang River and Yangbi River, some of the towns along the northern section of Nujiang River in Gongshan County and some towns in Dali and Binchuan County were evaluated as the area of priority for road development in the future. In contrast, the requirement for road development in the near future is relatively low (Fig. 7d).

4 Discussion

Road system is the most important human-made corridor network in landscape. The studies of the social, economic, and environmental effects of materials, energy and information flows transmitted through road network is a frontier of landscape ecology and related disciplines (Spellerberg, 1998; Forman *et al.*, 2003; Coffin, 2007). In the Three Parallel Rivers Region, the total density (0.126 km/km^2) of national, provincial and county roads was much lower than the average of Yunnan Province (0.437 km/km^2, the No.1 province of highway density in China) and the average of China (0.201 km/km^2) in 2005 (National Bureau of Statistics of China, 2006). Although the total length of roads increased by 63.7% in this region during 1989–2005, the national and provincial roads together contributed only 5% length, indicating the backward condition of the road system, consistent with the regional features characterized by the remote location, rugged landform, frequent geological hazards, as well as under-developed economy (Ma *et al.*, 2000; Tang and Zhu, 2001; Moseley, 2006). On the other hand, the increment of road length during the studied period mostly came from the county and rural roads, which was probably the result of the 'All Village Accessible' (AVA) road construction project launched for the remote mountainous regions across China in the 10th 'Five Year Plan' period (2000–2005). The spatial pattern of RSC increment (Fig. 6c) suggested that more rapid road development in 1989–2005 occurred at the areas of low RSC, and the spatial unbalance of road service was reduced during this time, mostly by the extension of lower level roads. Given the dominance of agricultural population, and the small-sized settlements scattered across the mountains of high elevation, the AVA policy might be helpful in meeting daily traffic demands, reducing the technical and economic thresholds of road construction in this unique region. However, the low level roads can only support traffic load of low intensity and short distance, thus contribute more road service at local rather than regional scale. Therefore, the regional road service capacity in the studied area mainly depended on the national and provincial roads, which played a major role in the traffic and transportation services within and outside the region.

Corridor networks are the landscape elements with the strongest spatial processes and the flows of organisms, materials, energy and information (Forman *et al.*, 2003). The quantification of network effect can be an effective way to understand landscape functions and predicting landscape dynamics. The KDE algorithm provides a feasible way to measure the road effect in a 2-dimensional space (Okabe *et al.*, 2009), and has been applied in the evaluation of regional traffic conditions (Eckley and Curtin, 2012; Shiode and Shiode, 2012; Cai *et al.*, 2013), but the algorithm did not take the effect difference of road levels into account. By involving the differences of effect range and intensity between road levels, the modified KDE algorithm proposed in this study provided a more comprehensive and reasonable estimate to RSC of a road network with a multi-level structure. This estimate is obviously different from that indicated merely by road density (Fig. 4). The spatial patterns of road development priority estimated with the two approaches had no significant correlation ($r = 0.048$, $p = 0.545$), suggesting that the modified KDE algorithm provides additional information, which is necessary to be involved for estimating road service capacity.

Although the modified KDE algorithm takes the difference in the effect range and intensity between road levels into account, there is still space of improvement for a more reasonable evaluation of the service capacity of a road network:

(1) The effect of RSC is amplified differentially by connecting roads of different levels. Given two identical rural roads, one is connected with a national road and the other is connected with a county road. Their service capabilities should have a big difference, because of the different inputs from the higher level road.

(2) The RSC is not only determined by road level, but also restricted by the quality of neighboring environmental condition, such as topographic slope, land use/ cover types. A realistic estimate of road service needs to take into account the interaction between road corridor and the landscape matrix.

(3) Connectivity is a critical measure of network structure, as well as the intensity and efficiency of network functions (Lämmer *et al*., 2006; Erath *et al*., 2009; Rosvall and Bergstrom, 2011; Li and Li, 2012). Combining the measures of network connectivity and RSC estimated with modified KDE algorithm in evaluating the function of road network would be a challenging while promising direction.

Level-related range and intensity of road effect are critical parameters in the modified KDE model, influenced not only by the geometric features of the road network, but also by the road quality and type of traffic tools (Wang *et al*., 2010). However, as the experimental tests or empirical records about these parameters are very lack in literature, the parameterization of this model would require further empirical observation or experiments.

Based on evaluation of population burden and economic efficiency per unit RSC at town level, this study provided an estimate of spatial RDP in the Three Parallel River Region on account of socio- economic demands. This result is useful as a reference in the planning of road network in this region. Nevertheless, a comprehensive evaluation of investment plan for road construction needs more information, including technique requirements and environmental limitations (Li *et al*., 2003). Specifically for the Three Parallel River Region, the identity of global natural heritage, the fragile geologic context and the rugged topography are all critical factors in determining the plan of road development, and therefore to be included in a realistic RDP evaluation model for eventual implementation.

5 Conclusions

In this study, we modified KDE algorithm by involving the level related differences of road effect range and intensity, and estimated the spatial pattern and dynamics (1989–2005) of town scale road service capacity in the Three Parallel River Region. Focusing on the social-economic demands for road development in this region, we estimated the spatial pattern of priority for future road development. Although further work is needed for parameterizing the modified KDE model and improving the estimate of RDP, the estimating procedure of this study can serve as a useful framework for a plan of regional road network optimization, with solid consideration of the critical factors.

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