

Characterizing China's road network development from a spatial entropy perspective

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Research Highlights

1. Spatial entropy is applied to China's road network at the county level.
2. A saturation curve relation exists between road density and entropy.
3. Demographic-economic and topographic factors play a predominant role in shaping the heterogeneity of regional road network development in China.
4. China's counties can be categorized into four development groups based on road network characteristics.

Abstract

Understanding the spatial characteristics of road networks is crucial for the planning of road networks. Although road networks have been frequently evaluated in combination with various socioeconomic factors, the current road network development in developing countries still needs to be better understood. Combining road network density and spatial entropy for 2,728 counties in China, we provide a comprehensive assessment of road networks and their key influencing factors. Our results indicate a significant spatial heterogeneity of the road network development, especially on both sides of the Heihe-Tengchong line. Demographic-economic and topographic variables jointly explained 54.2% and 65.1% of the spatial variations in road network density and entropy, respectively. Road entropy increases with road network density in line with a saturation curve from provincial to national scales, which offers guidance for future road planning. Using a K-means clustering analysis, we categorized China's road networks into four groups corresponding to the

development stages. Our findings improve the current understanding of road network development in China and provide important implications for national road network planning in the future.

Keywords: road density, entropy, influencing factors, saturation curve, development classification, China

1. Introduction

Road network is a fundamental infrastructure that plays a crucial role in a country's economic and social development. Over the past few decades, China has made great efforts to expand and extend its road network (Zhao et al., 2019, Zhao et al., 2017, Li et al., 2019b). Road network development has facilitated rapid economic growth and urban expansion (Iacono and Levinson, 2016, Chakrabarti, 2018, Jiao et al., 2020, Lin, 2017, Sun et al., 2018). It has also caused negative consequences such as landscape fragmentation, traffic congestion and regional disparities in development (Cai et al., 2013, Jiao et al., 2020, Weiss et al., 2018, Mo et al., 2017). A comprehensive understanding of the structure, distribution, and key drivers of current road networks is crucial to ensuring better development of national road networks (Sakar et al., 2022, Zhang et al., 2014).

Road density is a fundamental indicator of road network development that measures the road network concentration or the road quantity per unit area (Coombes et al., 2010, Li et al., 2013, Li et al., 2019b). Higher road network density indicates a more developed regional road network (Li et al., 2013, Li et al., 2019a). Previous studies

suggest that the distribution and expansion of road network density are closely associated with economic development and population dynamics (Jiao et al., 2020, Zhang et al., 2021, Strano et al., 2017, Zhao et al., 2017, Chi, 2010). Road network density is also influenced by natural conditions (Shi et al., 2019). For instance, road construction is more challenging in areas with steep terrain (Eliou and Kehagia, 2007, Cao et al., 2008, Yang et al., 2018). Extreme climates, such as heavy snow and coldness, may increase the road construction costs (Stephenson et al., 2011, Auerbach et al., 1997, Liu et al., 2021a). Heavy precipitation could lead to disruptions to road networks (Qiao et al., 2023). Considerations of vegetation conservation and planning of land uses are essential for road construction (Demir, 2007, Arjmand et al., 2023, Kleinschroth et al., 2019). Previous studies have also explored the relationship between road density and other geographical factors (Riitters et al., 2018, Batisani and Yarnal, 2009, Freitas et al., 2010). Existing studies have mainly explored the consequences of road network development, while rare has elucidated its drivers.

The alignment and structure are vital features of road networks (Barthélemy, 2011, Xie and Levinson, 2007). Spatial analysis techniques, such as morphological spatial analysis (Makse et al., 1998, Suhartini and Jones, 2020), complex networks, and fractal methods (Feng et al., 2007, Domingues et al., 2018, Cardillo et al., 2006, Chan et al., 2011) have been used to assess road network alignment and structural characteristics. Notably, Shannon entropy was proposed (Shannon, 2001) and used to evaluate the complexity of networks (Petrov, 2022, Wilson, 2010). Entropy strongly correlates with the orderliness and complexity of road network. It indicates its

connectivity, diversity, and sustainability (Boeing, 2018, Boeing, 2019), thus providing a straightforward approach to evaluate the complexity of the road network structure (Gudmundsson and Mohajeri, 2013, Mohajeri et al., 2013, Boeing, 2019, Mazzamurro and Guo, 2021, Coutrot et al., 2022).

Previous studies have primarily focused on the entropy of urban streets (Burghardt et al., 2022, Boeing, 2020). The approach might not be directly suitable for assessing road entropy in remote regions where road distributions are less dense than cities. To address this issue, Batty (1974) introduced the concept of spatial entropy, aiming to derive a continuous measure of entropy from a discrete measure in information theory. Since then, several new algorithms for spatial entropy have been proposed by integrating spatial mutual information (Altieri et al., 2018, Altieri et al., 2019, Karlström and Ceccato, 2000). For example, Burghardt et al. (2022) assessed road entropy in both urban and rural regions of the United States at the grid-cell level. Nevertheless, spatial entropy analysis of road networks remains lacking in developing countries.

A previous study on urban road networks suggests a positive relationship between entropy and the density of road networks (Gudmundsson and Mohajeri, 2013). The relationship between entropy and density of road networks may vary across regions with different stages of road network development. Additionally, the drivers of road network entropy also remain poorly understood. Some studies suggest that spatial entropy of road networks is associated with the heterogeneity of regional population distribution (Mazzamurro and Guo, 2021) and topography (Gudmundsson

and Mohajeri, 2013, Mohajeri et al., 2013, Boeing, 2019, Mazzamurro and Guo, 2021). However, investigating the factors influencing road network entropy and its quantitative relationship with road density is essential for understanding the patterns of road development.

The development of road networks in China shows significant regional disparities between well-established road networks in certain developed regions and less well-constructed road networks in economically underdeveloped regions (Wang, 2015, Tian et al., 2016). A major ecological and demographic boundary in China is the Heihe-Tengchong line (Hu, 1935), which differentiates the regional imbalances of economic development between its East and West sides (Wang and Zhang, 1995). It remains unclear whether China's road network development is subject to the geographical limitation of the Heihe-Tengchong line. Research efforts are needed to quantify the current patterns of road network development based on road network density and structure and provide guidance for future road planning in China (Liu et al., 2021b, Han et al., 2022).

To fill the aforementioned gaps, we derived road vector data from the National Catalogue Service for Geographic Information (www.webmap.cn/) and assessed the characteristics of road network development in China based on road network density, per capita road length, and gridded entropy. We also analyzed potential factors that affect the road network development, including climate (mean annual temperature, mean annual precipitation, and potential evapotranspiration), topography (mean elevations and its standard deviations, and mean slopes), population and economy

(population, population per area, gross industrial product, gross agricultural product, and gross service product), vegetation (NDVI), and land use (forest, grassland, cropland). Specifically, our study aims to (1) explore the spatial distribution characteristics of road density, per capita road length, and entropy in Chinese counties, along with their influencing factors and interrelationships, (2) investigate the spatial and quantitative relationship between entropy and road density, and (3) classify the development of road network and identify its regional disparities in China.

2. Material and methods

2.1 Data sources

The road vector data (base year 2018) were derived from the databases in the National Catalogue Service for Geographic Information (2021). Our analysis focused on roads that meet specific technical and administrative standards, consisting of expressways, national highways, provincial highways, county highways, and urban roads while excluding rural and urban subways to ensure the comparability of data. Statistical analyses were conducted within 2,728 county-level administrative units, and 147 districts and counties were excluded due to missing data. The road vector data were further converted into raster data with a resolution of 30m, and the length of roads was calculated for each district and county.

This study selected 16 explanatory variables to explore the factors influencing the spatial characteristics of road networks. These variables included three climate factors, three topographic factors, six demographic-economic factors, and four

vegetation indices and land use factors. The specific data sources and data processing methods are described as follows:

(1) Climate variables

Mean annual temperature (MAT), mean annual precipitation (MAP), and potential evapotranspiration (PET) were derived from the China Meteorological Data Service Centre (<http://data.cma.cn/>). These data covered over 2,400 meteorological observation stations across China within the period from 1982 to 2015. Anusplin 4.4 software was used to interpolate observed climate data with a spatial resolution of 8km (Feng et al., 2019). We calculated the mean values of climate variables within each county using the Spatial Analyst Toolbox of ArcGIS 10.3 (<http://www.esri.com/software/arcgis/>).

(2) Topographic variables

Slopes were calculated using the Shuttle Radar Topography Mission Digital Elevation Model (SRTM DEM; resolution of 30m) (<http://www.3decology.org>) via the 3D Analyst toolset in ArcGIS 10.3. Mean elevations (DEM), standard deviations (DEM_{sd}), and mean slopes (Slope) for each county were calculated using the Spatial Analyst Toolbox of ArcGIS 10.3.

(3) Demographic-economic variables

Data on population (POP) and gross domestic product (GDP) were derived from the 2016 China Statistical Yearbook of Counties and Districts (<http://cnki.nbsti.net/CSYDMirror/area/Yearbook/Single/N2017050134?z=D26>).

Gross domestic product per capita (GDP/POP) and population per area (POP/A) were then calculated for each county. The gross industrial product (GDP_{ind}), gross agricultural product (GDP_{agr}), and gross service product (GDP_{ser}) data were obtained from local statistical yearbooks.

(4) Vegetation indices and land use variables

Month-by-month NDVI data from 2013-2015 were derived from the GIMMS NDVI3g.v1 dataset (<https://ecocast.arc.nasa.gov/data/pub/gimms/3g.v1/>). Land use data for 2015 were acquired from the China Land Use Status Remote Sensing Monitoring Database (<http://www.resdc.cn>). We calculated the area shares of forest, grassland, and cropland (Forest, Grassland, and Cropland) for each county using the Spatial Analyst Toolbox of ArcGIS 10.3.

2.2 Quantifying road network characteristics

Road network density (RD) was calculated using the following equation:

$$RD_i = \frac{RL_i}{A_i} \quad (1)$$

Where RD_i represents the road density of county i (km/km²), RL_i represents the total road length of county i (km), and A_i represents the area of county i (km²).

Per capita road length (PRL) was calculated as follows:

$$PRL_i = \frac{RL_i}{POP_i} \quad (2)$$

Where PRL_i represents the per capita road length of county i (km/capita), RL_i represents the total road length of the county i (km), and POP_i represents the resident

population of county i (capita).

Based on the approach introduced by Burghardt et al. (2022), we computed road entropy (S) at a 10km grid-cell level within the county (Figure 1). First, the road network data was segmented based on road intersections and endpoints, and the direction of each discrete road was calculated. Second, the range of 0 to 360 degrees was divided into 36 statistical intervals of 10 degrees each (Coutrot et al., 2022), and the total length of roads within each interval was counted to derive the frequency distribution of roads across different directional intervals. Finally, the road entropy for each $10\text{km} \times 10\text{km}$ grid (pixel entropy) was calculated using equation (3),

$$S_i = - \sum_{\theta=1}^n P(O_\theta) \log_e P(O_\theta) \quad (3)$$

where S_i is road entropy for pixel i , n represents the total number of directions counted, $P(O_\theta)$ denotes the percentage of road lengths within the θ -direction interval. The average value of the 10km resolution road entropy was calculated for each county. A lower entropy value indicates less complexity in road network structure.

2.3 Exploring effects of potential drivers

A multicollinearity test was performed to assess the variance inflation factor (VIF) of climatic, topographic, land use, and demographic-economic variables (Fox and Weisberg, 2019). VIF values less than 10 indicate no strong multicollinearity. Our analysis found no multicollinearity among the variables, with all VIFs below 4 (Table S1). We further conducted a redundancy analysis ordination to explore the effects of

climatic, topographic, land use, and demographic-economic factors on road network characteristics. This approach maximizes the explanation of the variance in multivariate response variables (road characteristics indicators) while mitigating issues related to multicollinearity among the explanatory variables (Chen et al., 2023). Variance Partitioning Analysis was used to quantify the variance explained by climate factors, topographic factors, demographic-economic factors, vegetation, and land use variables. The analysis above was all conducted using the vegan package in the R language (Legendre and Legendre., 2012).

2.4 Exploring the relationship between entropy and road network density

Road entropy is expected to increase gradually to approach its theoretical upper limit as road density increases in line with a saturation curve (Michaelis-Menten hyperbola) (Srinivasan, 2022),

$$S = \frac{S_m \cdot RD}{k + RD} \quad (4)$$

where S_m represents the theoretical maximum entropy, and k is the road network density at which the entropy reaches $\frac{1}{2} \cdot S_m$ (Johnson and Goody, 2011). We used a threshold corresponding to 90% of the maximum entropy and estimated the corresponding road density. Road entropy increases slowly with road density when exceeding the threshold, highlighting a diminishing marginal return of road network construction (Cho and Lim, 2018, Cade et al., 1999). However, the fitted saturation curve itself does not have a reachable threshold. We thus used a threshold corresponding to 90% of the maximum entropy and estimated the corresponding road

density. The critical road network density corresponding to 90% of the maximum entropy was estimated to be 1 km/1 km², commonly regarded as the standard for determining urban areas (Wu et al., 2020). The relationships between entropy and road network density were analyzed separately at provincial scales and for regions west and east of the Heihe-Tengchong line.

2.5 Classifying road network development

We combined road network density and entropy for a spatial classification of China's road network development. A redundancy analysis ordination was used to transform these two variables into linearly disjoint principal components (Chen et al., 2023). We then employed the K-means clustering analysis using the two principal components (Sinaga and Yang, 2020). The dissimilarity of the counties' road characteristics was quantified based on the squared Euclidean distance. The loss function T was calculated and minimized.

$$T = \frac{1}{2} \left(\sum_{h=1}^k \left[\sum_{i \in h} \sum_{j \in h} d_{ij} + \sum_{i \in h} \sum_{j \notin h} d_{ij} \right] \right) \quad (5)$$

The first term of T is the total dissimilarity within cluster h , and the second is the total dissimilarity between cluster h and other clusters. Additionally, the number of clusters is determined using the variance ratio criterion (VRC) (Caliński and Harabasz, 1974). A higher VRC index suggests more vital intra-category linkage and more dispersed linkage between categories, indicating better clustering results for the model. The VRC index is calculated using equation (6):

$$VRC_k = \frac{SS_B}{SS_W} * \frac{N - k}{k - 1} \quad (6)$$

SS_B represents the variance between categories, SS_w denotes the variance within categories, N is the number of samples, and k is the number of classifications. Based on the principle of minimum divisions and considering the VRC index synthesis, the optimal number of categories for spatial clustering was determined to be 4 (Figure S1).

3. Results

3.1 Spatial characteristics of the road network

Road network characteristics in China showed strong spatial variations with distinct patterns occurring on either side of the Heihe-Tengchong line (Figure 2, S4). The road density exhibited a spatial divergence in China (Figure 2a) with an average of 0.76 km/km² (median 0.68 km/km², Figure 2b). High road density mainly occurred in the Northeast Plain, North China Plain, Yangtze River Delta, Sichuan Basin, and Pearl River Delta. Notably, the central plain area of the Sichuan Basin, the Bohai Rim, the Yangtze River Delta, and the Pearl River Delta exhibited exceptionally high road density, with some urban clusters exceeding 1 km/km². In contrast, road density mainly was below 0.2 km/km² in the northwest, southwest, and Qinghai-Tibet Plateau.

The per capita road length showed a distinct pattern compared to road density (Figure 2c). The northwest region, with a sparse population, had a relatively higher per capita road length, while per capita road length was lower in the densely populated eastern region. Specifically, Haixi in Qinghai Province had the highest per

capita road length (78.9 km/capita), while the lowest value was found in Yangquan in Shanxi Province (0.005 km/capita).

Road entropy exhibited contrasting values between the southeast and northwest regions of China (Figure 2e). The mean road entropy in China was estimated to be 2.26 (Figure 2f), with the highest entropy (2.86) occurring in Jinping District, Guangdong, and the lowest entropy (0.53) in Ruqiang County, Xinjiang. Road entropy in northwest China was mostly below 1.8, while in eastern China, its value was generally larger than 2.0.

3.2 Factors influencing road network characteristics

Multivariate redundancy analysis indicated that road density was positively associated with population per area, gross service product, and gross industrial product, while it was negatively associated with slope (Figure 3). Conversely, per capita road length was positively correlated with mean elevations and negatively correlated with mean annual precipitation, NDVI, and gross agricultural product (Figure 3). Road entropy was positively correlated with population, mean annual precipitation, and mean annual temperature and negatively correlated with mean elevations and standard deviations (Figure 3).

The results of variance partitioning analysis suggest that climate, topography, demographic-economic factors, and vegetation/land use variables jointly explained 56.0% of the regional variation in road density, 53.6% in road entropy, and 24.9% in per capita road length, respectively (Figure 4). Topographic (13.3%) and demographic-economic factors (9.2%) are the primary contributors to the variations in road density (Figure 4a). As for entropy, topography is the main influencing factor (explaining 16.3% of the variance). The interaction between topography and climate

and demographic-economic factors accounts for 8.6% of the variance. The interaction between topography, demographic-economic, and climatic factors contributes 6.1%, suggesting that in addition to topographic factors, demographic-economic and climatic factors also play a significant role in entropy, mainly through their interaction with topographic factors (Figure 4b). For per capita road length, the impact of topography is the most significant (20.7%), but the overall explanatory power across categories is relatively low (Figure 4c).

3.3 Relationships between road network density and entropy

Road entropy increased significantly with road network density in line with a saturation curve ($R^2=0.80$; Table S3; Figure 5a). The road network density corresponding to the threshold of 90% maximum entropy was 1.0 km/km² (Figure 5a). Currently, counties exceeding this critical road network density were mainly distributed in the central and eastern parts of China (Figure 2a). The relationship between road entropy and road network density followed a similar curve for each province (Figure S2). However, the critical road network density varied across different provinces, showing the highest value of 3.12 in Guangxi. Additionally, we found a similar relationship between road entropy and road density for the regions on the east and west sides of the Heihe-Tengchong Line (Figure 5b, 5c). Overall, the critical road network density in the west region is 0.82 km/km², which was lower than that in the eastern region (1.15 km/km²).

3.4 Road network development levels

Based on the K-means clustering analysis of the principal component of road characteristics, we classified China's road networks into four development groups (I,

II, III, and IV; Figure 6). Roads of group I had the lowest road density and entropy (on average 0.14 km/km^2 , 1.41, respectively) and accounted for about 51.4% of the national territory, mainly in western China and the Inner Mongolia and Daxing'anling area in the north (Figure 6d). However, the road length of group I was $32.8 \times 10^4 \text{ km}$, only accounting for 7.6% of the national total. Roads of group II were mainly distributed in the secondary terrain of China and had a total length of $258.2 \times 10^4 \text{ km}$, accounting for 59.9% of the national total (Figure 6d). The average road density and the average entropy of group II were 0.44 km/km^2 and 2.09, respectively. Roads of group III accounted for 28.1% of the total road length ($121.2 \times 10^4 \text{ km}$) and were mainly distributed in the eastern plains, hilly areas, and the Sichuan basin (Figure 6d), showing average road density and an average entropy of 0.82 km/km^2 and 2.44, respectively. Roads of group IV had a low share of total road length (4.4%; $19.1 \times 10^4 \text{ km}$) and were mainly distributed in the plains, urban or urbanizing areas (Figure 6d), showing high values of road network density and entropy (1.60 km/km^2 , 2.60).

4. Discussion

4.1 Relationship between road network density and entropy

Previous studies have found both positive spatial correlations between road network density and entropy (Burghardt et al. (2022), Gudmundsson and Mohajeri (2013)).

Our results indicate a non-linear relationship between road network density and road entropy in line with a saturation curve. As road density increases, the road network structure stabilizes after reaching a certain threshold, transitioning from insufficient to relatively well-developed (Figure 5). Secondary roads, ring roads, and connecting roads are built as the road density rises to maintain the integrity and continuity of the

network. As a result, the road network becomes more complex, and thus, the entropy rises. This frequently occurs in developed urban regions featured with high entropy (Boeing, 2018, Boeing, 2019). Therefore, regions with higher entropy generally have a more complicated road network, a higher degree of regional road development, and an established road network. Once a certain threshold point is achieved, a further increase in road density will result in a limited increase in entropy. In that case, better road planning is needed to improve and optimize the road network structure (Figures 5, S2).

The non-linear relationship between road network density and road entropy was also found for provinces (Figure S2). Road network development has surpassed the national average in Tianjin, Shanghai, and Jiangsu (Maximum entropy > 3 , critical road network density $> 2 \text{ km/km}^2$), whereas it is below the national average in Shanxi, Liaoning, Anhui, Henan, Hainan, Sichuan, Tibet, Shaanxi, Gansu, Qinghai, and Xinjiang (Maximum entropy < 3 , critical road network density $< 1 \text{ km/km}^2$). Notably, there are distinct regional and spatial disparities in road development (Figure S2). Besides, lower curve fitting values ($R^2 < 0.3$) are produced in the northern plains of China, specifically in the provinces of Beijing, Hebei, and Henan, because the entropy remains largely fixed or only slightly increases with the growth of road density (Figure S2). These regions are featured with flat topography and a grid-like road network layout resulting from earlier urban road development (Figure S3). Future efforts could focus on optimizing the road network structure in these regions. Due to topography, population, and economic circumstances, the road network is more

developed in East China and South China. Many provinces have high critical road network density, and in some counties, road entropy values have reached the regional fitted maximum entropy (Figure S3). Additionally, in the western regions of China, such as Gansu, Xinjiang, and Inner Mongolia Autonomous Region, critical road network density are low, and most counties have not reached the regional fitted maximum entropy, indicating significant development potential in the road network construction in these areas (Figure S2).

4.2 Key regulators of the road network development

Our results showed a pronounced regional imbalance in road network development in China (Figure 2, 5, 6). Topographic and demographic-economic factors were found to be the most important regulators of the spatial variations in road characteristics.

Consistent with findings from earlier studies (Yang et al., 2018, Cao et al., 2008, Eliou and Kehagia, 2007), high road density was found in regions with a mild climate and flat topography (Figures 2a, 3, 4a), while lower road density was found in regions with steep and complex topography. A densely inhabited and economically developed area is likely to have a higher road density and entropy (Figure 2a, 2c, 3, 4a, 4b), potentially due to strong human demand for improved road networks (Jiao et al., 2020, Zhang et al., 2021, Strano et al., 2017, Zhao et al., 2017, Chi, 2010). In metropolitan regions, previous studies have found a strong relationship between entropy and local terrain, road length, and population density (Gudmundsson and Mohajeri, 2013, Mohajeri et al., 2013, Boeing, 2019, Mazzamurro and Guo, 2021). The results of the current study are generally consistent with earlier studies (Figure

2c, 3, 4b).

Furthermore, our analysis indicates that vegetation and climatic factors also play a role in influencing road characteristics (Figure 3, 4). This result aligns with the findings of previous studies (Auerbach et al., 1997, Liu et al., 2021a, Demir, 2007, Arjmand et al., 2023, Kleinschroth et al., 2019), which suggested a significant association between roads and land use change (Batisani and Yarnal, 2009, Riitters et al., 2018, Chomitz and Gray, 1996). However, the results of the current study indicate that, for both individual indicators and different regions, the impact of land use on road characteristics is relatively weak (Figure 3, 4). Overall, more research efforts are needed to understand the relationships between topographic, demographic, and other contributing factors and the potential policy implications of entropy in the context of regional road network planning in China.

4.3 Road network development classification

Based on cluster analysis of road network density and entropy, we categorized China's road networks into four groups (Figure 6). Previous research on road development and its influencing factors has predominantly focused on urban areas (Gudmundsson and Mohajeri, 2013, Mohajeri et al., 2013, Boeing, 2019, Mazzamurro and Guo, 2021, Zhao et al., 2017), with only a few studies in non-urban areas (Burghardt et al., 2022, Boeing, 2020). Our study broadens the scope by including various major road types and enabling a comprehensive assessment of road network development in China.

Previous studies indicate that higher entropy is associated with more evenly distributed roads in all directions, as shown in the rose diagram (Batty et al., 2014). Our result thus serves as a reference for road planning in China. In the western region, it is crucial to enhance road density and prioritize the construction of roads in the dominant direction while considering the development of roads in non-dominant directions to ensure orderliness and connectivity of county roads. The gradual transition observed in the rose diagram of provinces also demonstrates the road development gaps among provinces, with a predominant focus on the north-south and east-west directions for most developed provinces (Figure S3). This implies a potential to improve the road network structure for these regions further.

Based on the analysis of the road networks in China, we found that road development exhibited significant geographical variations and unevenness, which aligned with previous studies (Wang, 2015, Tian et al., 2016). Notably, the boundary between Group I and the other Groups generally aligns with the Heihe-Tengchong line (Hu, 1935), suggesting that the geographic limit is also reflected in road network development (Figure 6d). Our study also found that the spatial divergence in road network development between both sides of the Heihe-Tengchong line was primarily constrained by topographical and demographic factors (Figure 3, 4). Road construction is more challenging and costly in regions characterized by complex topography. Sparsely populated areas may have underutilized roads, limiting road benefits and accessibility. These findings further underscore the significance of the natural environment in shaping road development patterns.

Despite China's infrastructure investments and initiatives like the Western Development (Shiu et al., 2016), road network development shows distinct features on the west and east sides of the Heihe-Tengchong line. Some researchers suggest that there is a possibility that the demographic pattern of the Heihe-Tengchong Line will be broken in the future by a dramatic change in climatic conditions due to future global warming (Chen et al., 2016). However, proactive policy guidance and strategic spatial planning can promote comprehensive road development in the central and western regions, potentially bridging the East-West divide. These findings offer new perspectives and methodologies for road network development research and provide valuable references for road network planning.

5. Conclusions

Our study provided a comprehensive assessment of China's road network development and explored the factors influencing the features of road networks. We found a significant spatial heterogeneity of the road network development, especially differentiated by the Heihe-Tengchong line. Demographic-economic and topographic factors both had a notable impact on the development of road networks. Our results elucidated the spatial correlations between road entropy and road density in line with a saturation curve from provincial to national scales, offering potential guidance for national road network development. More efforts should be made to improve road network structure when road density exceeds 1 km/km². Utilizing K-means clustering analysis, we categorized China's road networks into four groups, providing a reference for future road network planning. Future research efforts should combine

more features of road networks to gain a better understanding of the dynamics of road network development.

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Figures

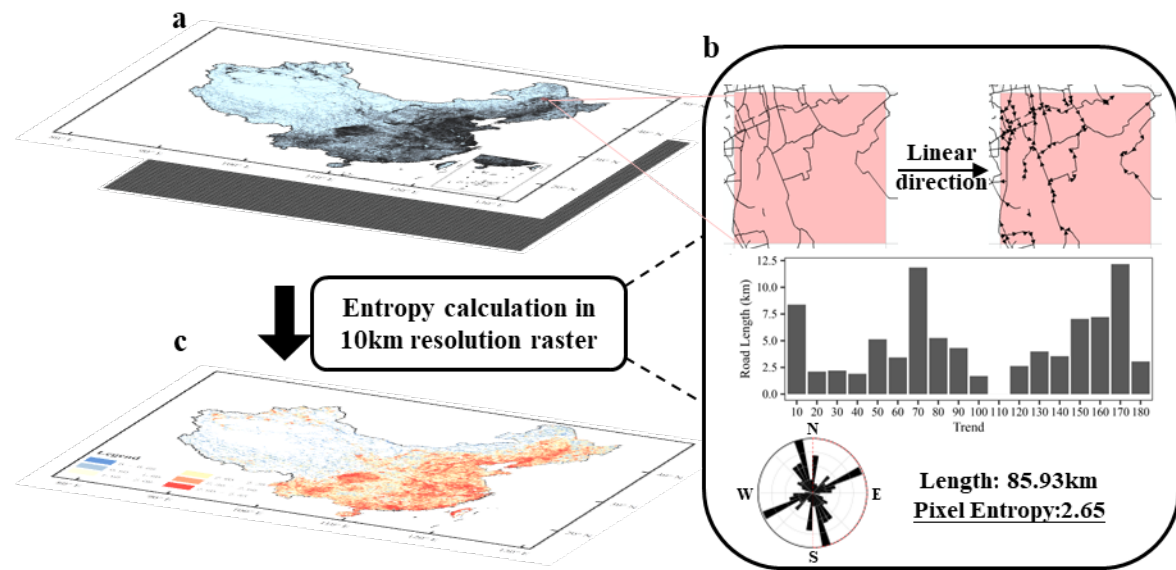


Figure 1 Schematic diagram of the road entropy calculation process. Road distribution map and 10 km resolution grid map (a). The entropy calculation process within the grid cell includes the road vector map, the percentage of road length in each direction, and its rose diagram, where N, W, S, and E stand for North, West, South, and East, respectively (b). Road entropy distribution map with a resolution of 10 km (c).

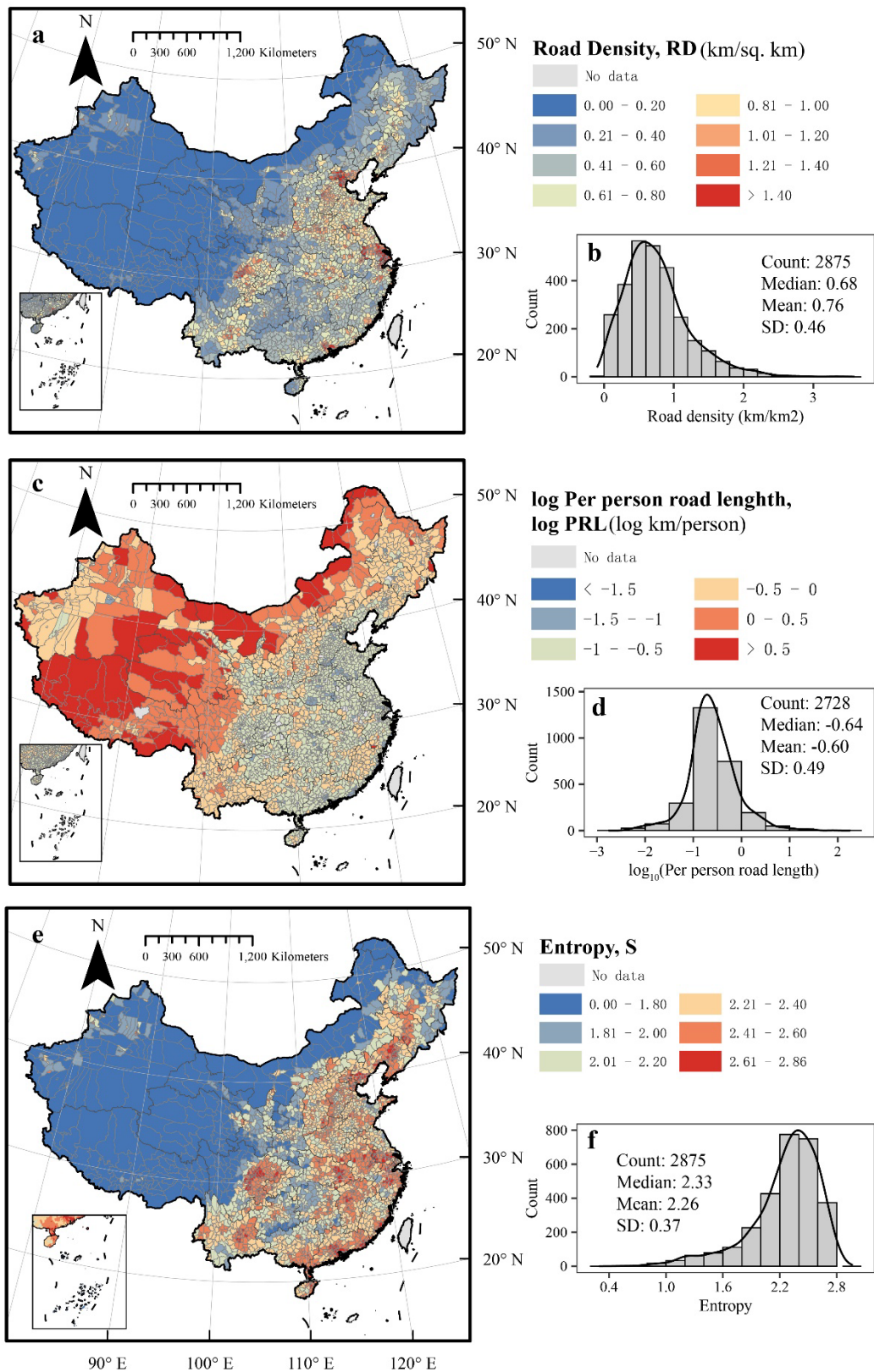


Figure 2 China spatial distribution of road density, per capita road length, and road entropy at the county level (a, c, e) and frequency distribution of road density, per

capita road length, and road entropy at the county level (b, d, f).

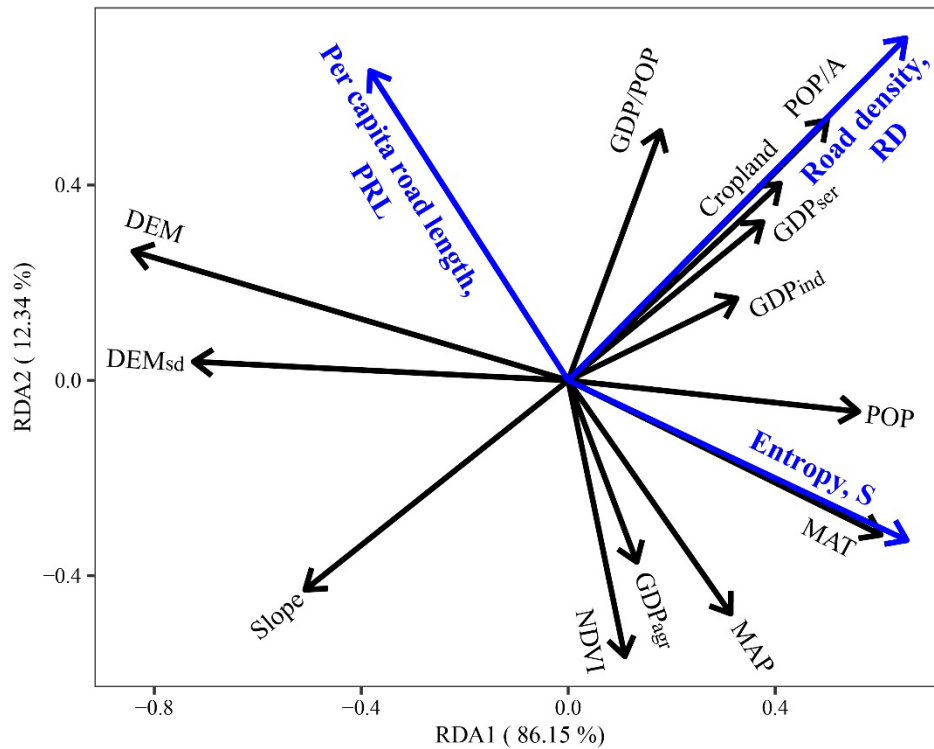


Figure 3 Redundancy analysis shows the relationship between road characteristics (blue arrows, response variables) and thirteen influencing factors (black arrows, explanatory variables). Response variables are road density (RD), entropy (S), and per capita road length (PRL). Explanatory variables include climate factors (MAT, MAP), topographic factors (DEM, DEM_{sd}, Slope), demographic-economic factors (POP, POP/A, GDP/POP, GDP_{agr}, GDP_{ind}, GDP_{ser}), vegetation indice (NDVI), and land use factor (Cropland). Effects of all explanatory variables and the first two canonical axes are significant at $P < 0.001$. The percentage of variation explained by each canonical axis is shown in parentheses. Influencing factors abbreviations see 2.1.

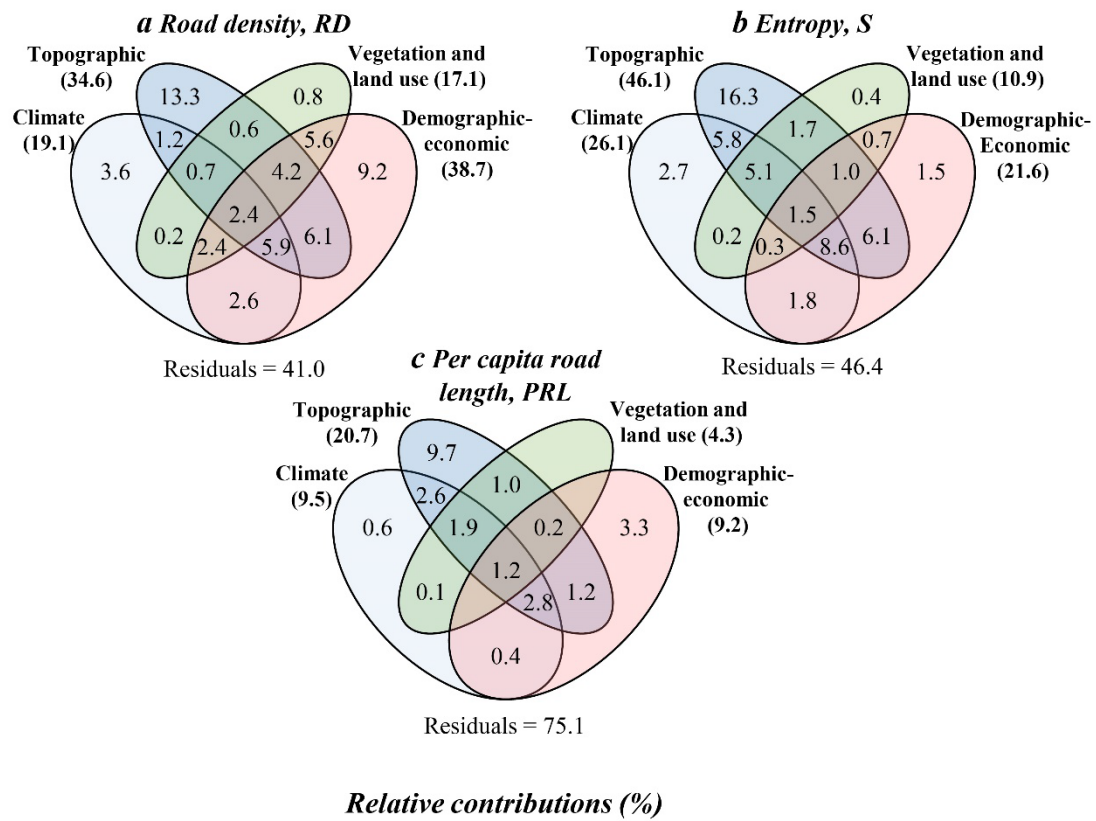


Figure 4 Variance Partitioning Analysis for road characteristics explained by climate factors, topographic factors, demographic-economic factors, vegetation, and land use variables. Road density (a). Entropy (b). Per capita road length(c).

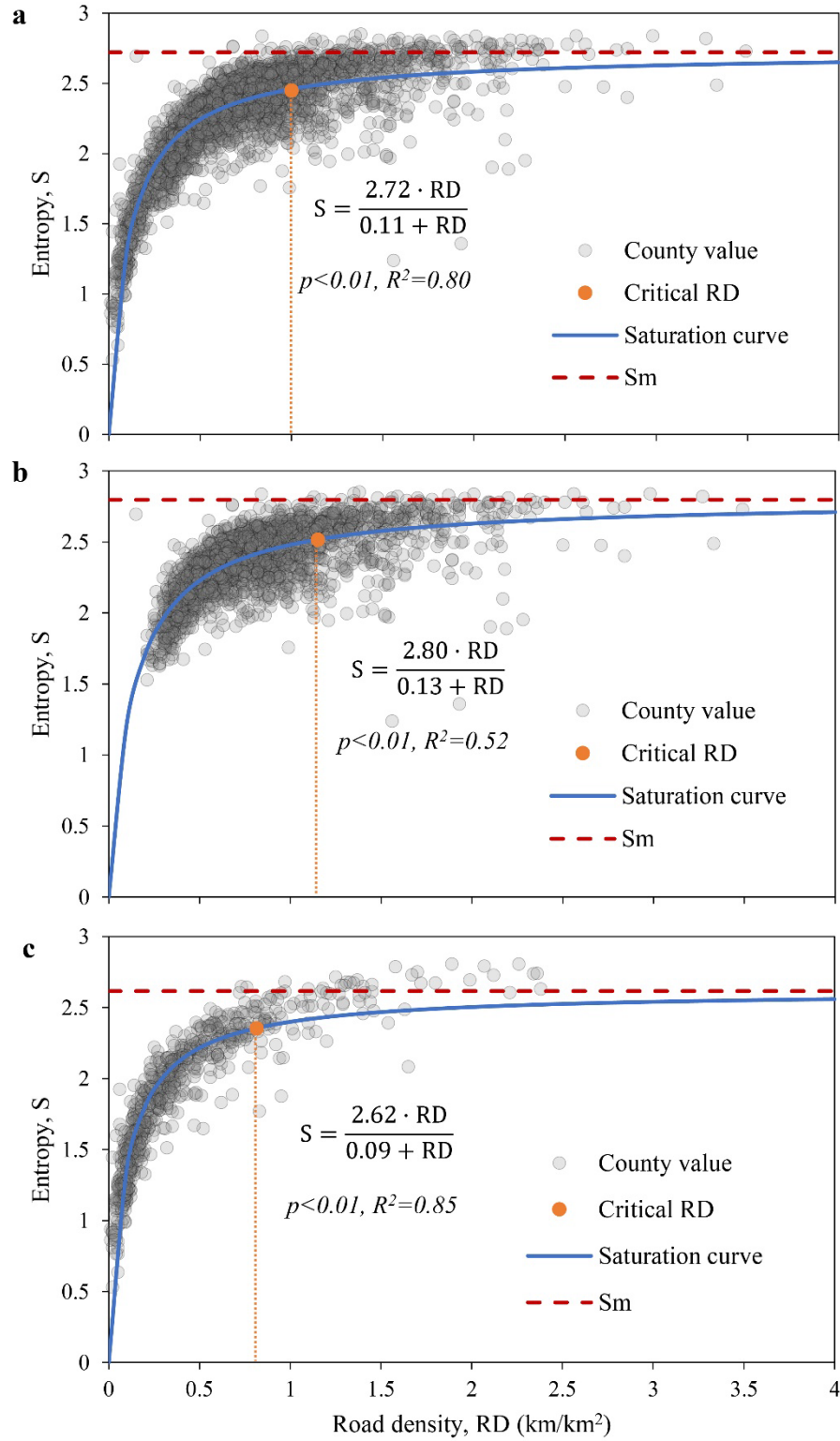


Figure 5 Relationship between entropy and road density of all China counties (a) and the counties on the east and the west side of the Heihe-Tengchong line, respectively

(b, c). The grey dots represent county values, the dark blue line represents the saturation curve, and the red dashed line represents the fitted maximum entropy (S_m). The orange point on the curve indicates the critical road network density corresponding to the 90% threshold of maximum entropy (b).

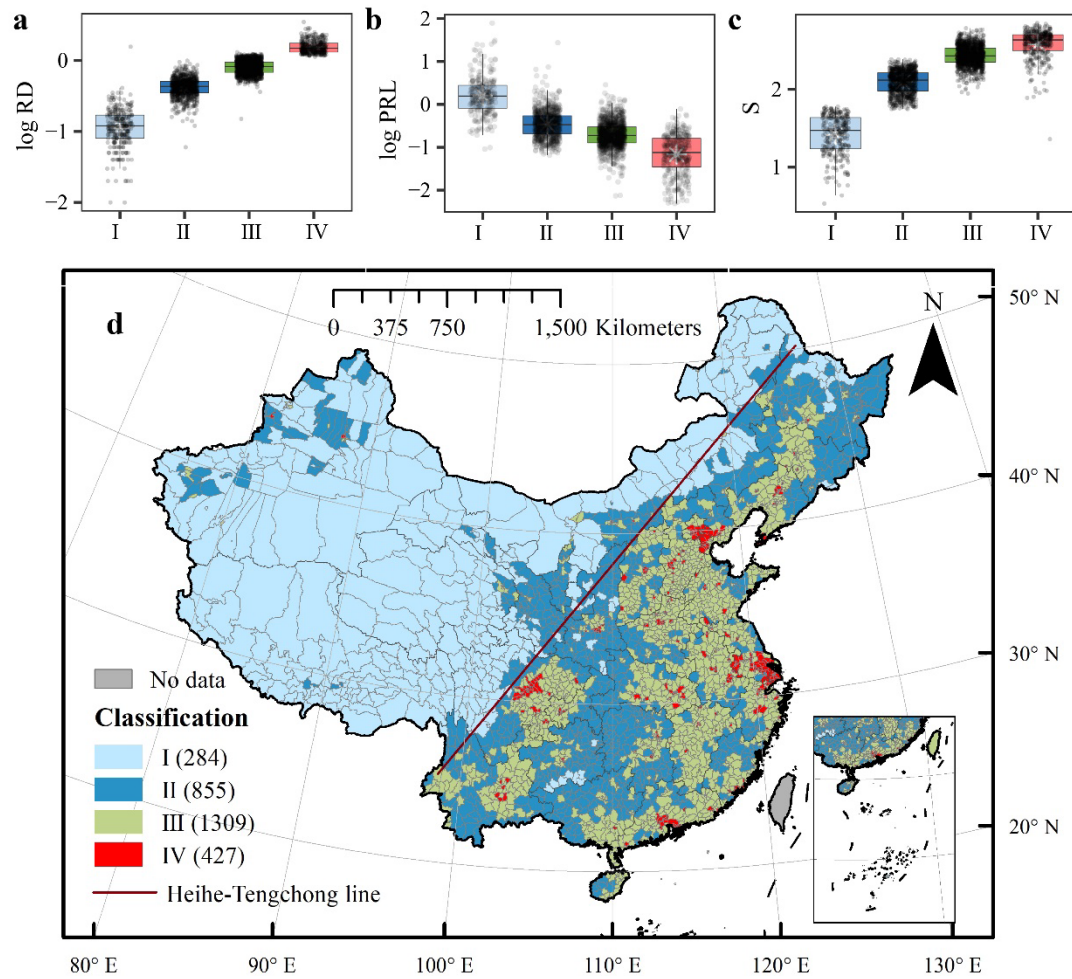


Figure 6 China road development classification at the county level based on K-means clustering analysis, including four development levels: I, II, III, and IV. Box plots of road density (RD), per capita road length (PRL), and entropy (S), relatively (a, b, c). Spatial distribution of road development classification and parentheses indicate the number of counties (d).



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