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RESEARCH ARTICLE

Fragmentation of China's landscape by roads and urban areas

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Abstract China's major paved road-ways (national roads, provincial roads, and county roads), railways and urban development are rapidly expanding. A likely consequence of this fast-paced growth is landscape fragmentation and disruption of ecological flows. In order to provide ecological information to infrastructure planners and environmental managers for use in landscape conservation, land-division from development must be measured. We used the effective-mesh-size (M_{eff}) method to provide the first evaluation of the degree of landscape division in China, caused by paved roads, railways, and urban areas. Using M_{eff}, we found that fragmentation by major transportation systems and urban areas in China varied widely, from the least-impacted west to the most impacted south and east of China. Almost all eastern provinces and counties, especially areas near big cities, have high levels of fragmentation. Several eastern-Chinese provinces and biogeographic regions have among the most severe landscape fragmentation in the world, while others are comparable to the least-developed areas of Europe and California. Threatened plant hotspots and areas with high mammal species diversity occurred in both highly fragmented and less fragmented areas, though future road development threatens already moderately divided landscapes. To conserve threatened biodiversity and landscapes, we recommend that national and regional planners in China consider existing land division before making decisions about further road development and improvement.

Keywords Fragmentation · China · Effective mesh size · Transportation · Roads

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Introduction

Regional studies of biodiversity threats in China have documented a wide range of ecological attributes and processes, including landscape fragmentation and wildlife movement, desertification, and erosion (Zhang et al. 1998; Fu and Chen 2000; Liu et al.

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2001; Qian et al. 2006; Tang et al. 2006; Xia et al. 2007; Zhang et al. 2007). National-scale studies that compile data about biotic resources, such as species hotspots (Tang et al. 2006; Zhang and Ma 2008) are emerging, but the same scale of studies are needed of the threats, which would allow for improved land change analysis and conservation (Turner et al. 2007). To date, country-wide studies of human impacts have tended to rely on government-derived agency reports that summarize census data and extrapolate to national trends (e.g., Dongjing et al. 2004, but see Yang et al. 2009 for population census techniques). This is not very different from national trend reporting from other countries, except for the tremendous ecological risks associated with China's future development (Grumbine 2007; Liu et al. 2008a, b). Management of these risks requires both the quantification of landscape-scale development and recognition of existing Chinese philosophies regarding human relationships with Nature (Chen and Wu 2009).

While naturally occurring fragmentation can result in greater biodiversity (Quinn and Harrison 1988), habitat fragmentation from human land-uses can threaten plant biodiversity (Honnay and Jacquuemyn 2007) biodiversity in general (Fahrig 2003), and genetic flows (Hilty et al. 2007). Landscape fragmentation by roads, urban construction and other human activities is widely studied outside of China (Forman et al. 2003; Coffin 2006; Shilling 2007; Shilling and Girvetz 2007; Watts et al. 2007; Girvetz et al. 2008; Thorne et al. 2009) and has been used to evaluate human impacts on ecosystem integrity at a landscape scale. Large habitat patches are important to many species (Collinge 1996) and connectivity within and among patches is an important landscape function permitting ecological flows (Beier and Noss 1998). Fragmentation features can also enable the spread of invasive species, negatively impacting native biodiversity (Gelbard and Belnap 2003; Ding et al. 2008). Landscape fragmentation is worsened by development of roads and other barriers (Forman and Alexander 1998; Trombulak and Frissell 2000), that further divide, reduce and isolate habitat patches (Taylor et al. 1993; Forman et al. 2003).

China's road network is growing quickly; with a rapid expansion of expressways from 652 km in 1992 to 65,000 km by 2010 (Planning and Research Institute, Ministry of Communications of China 2004). The length of expressway has placed China second in the world for expressway development, though still largely behind the highway network in the United States. Based on the long-term goals for China's National Expressway Network Planning, the future intensive construction program will build an additional 20,000 km expressway by 2025 for an eventual total of 85,000 km (Planning and Research Institute, Ministry of Communications of China 2004). Transportation infrastructure has been a major focus of China's economic stimulus actions, with $88 billion being spent, or is planned to be spent, annually between 2005 and 2010, compared with $46 billion annually between 2001 and 2005 (Comprehensive Planning Division of Ministry of Communications 2004) China has built 87,182 km^2 of impervious surface areas, including roads and highways, which is more than any other country on the earth (Christopher et al. 2007). One of the Chinese National Government's objectives in road network expansion is to increase rural accessibility and improve economic performance (Fan and Chan-Kan 2005; Seneviratane 2006), with rural roads growing from current 0.59 million km to 3.1 million km by 2010.

Existing road network systems in China are classified and mapped administratively as: (1) national highway (widest and most-developed), (2) provincial roads, and (3) county and township roads (rural roads). In China beside paved roads, there are many paths or cart trails, but these have not so far been systematically mapped. Every class of road is expanding in China, from the eastern plains to the western mountainous regions, and in urban and rural agricultural landscapes (Li 2008). This expansion will cause further loss and fragmentation of habitats and may threaten the survival of terrestrial and aquatic wildlife, especially those already endangered and threatened. However, landscape fragmentation caused by paved roads has never been quantified at the national level in China.

This study provides a first assessment of landscape fragmentation by paved roads and urban areas in China, and provides a basis for additional systematic assessments. Digital nation-wide maps of the national highways, provincial highways, railways, paved county roads, and urban areas were obtained or were digitized from digital datasets, hard-copy maps, and remotely sensed images to construct a comprehensive set of maps for all paved road classes and railways.

The Cross Boundary Effective Mesh Size (CBC M_{eff}) tool in GIS (Jaeger 2000; Moser et al. 2007) was used to measure the spatial distribution and degree of landscape fragmentation in China because it has been proposed as a good single indicator of land division by roads (Jaeger 2000). In addition, patch density in particular ecoregions were calculated using FRAGSTATS (McGarigal et al. 2002) because of the effects of patch size and density on various biota (Hernandez-Stefanoni and Dupuy 2008; Barbaro and van Halder 2009; Klingbeil and Willig 2009; Rossi and van Halder 2010). Results are presented for the country, the 34 provinces and the 2,427 counties. We compare the results to similarly derived fragmentation measures of European countries and California, USA. The results are used to identify the most and least fragmented counties in each of China's 48 ecoregions, to identify the most and least fragmented areas in eight endemic plant hotspots, and to assess the level of habitat fragmentation in areas of varying mammal species richness. The landscape fragmentation metrics provided will for the first time help set the context for ecological conservation and transportation infrastructure planning throughout China.

Methods

Base data

The base data used in the analyses were collected from several sources. The GIS layers of county, province and country boundaries were downloaded from the website of Environmental and Ecological Science Data Center for West China (http://westdc.westgis.ac.cn). Maps of paved roads were purchased by MOE Key Laboratory of Arid and Grassland Ecology, Lanzhou University from the Highway Planning and Research Institute of Ministry of Communications of China in 2005. The locations of roads and highways were verified and enhanced by referencing Google Earth images of China's national, provincial, and county roads, as well as recent hard-copy maps from provincial governments. Editing was done using *ArcMap* editing module and software such as *Raster to Vector* (*R2V*). Many road segments in the road datasets were not connected at their junctions. To correct this, two methods were used. For the provincial roads, we manually added segments complete their intersections with other major roads or urban areas. The county roads had too many gaps for manual re-connection, therefore we used a node snapping tool in ArcMap to connect road ends that were less than 450 m from either another road (national, provincial, or county) or from an urban boundary. Small islands were excluded from the analysis. (All the data images can be obtained from the author by request) Land use and land cover raster data were provided by the China Academy of Science at a 1 km^2 grid cell size. These two datasets were used to locate and map the urban areas. Adjoining urban polygons were combined, resulting in a GIS layer containing 97,250 urban units.

Fragmentation geometries

Calculation of M_{eff} first requires the development of fragmentation geometries (FG), composed of the linear elements identified as fragmenting features on the landscape. This study defined three levels of fragmentation geometry for China based on urban areas, railways, and paved roads. National roads and railway layers were buffered by 100 m to account for both the actual location of the road or rail and their potential near-road effects (Forman et al. 2003; Farhig and Rytwinski 2009); however we did not quantify road effect zones for this study. These two layers were merged with the urban areas layer to create the barriers layer for FG1. Provincial roads were buffered by 60 m because their near-roads effects were assumed to be less than the national roads and railways. After being buffered, the provincial roads were merged with the barrier layer for FG1 to create the barrier layer for FG2. County roads were combined with all other roads and rails to create a network from which to calculate FG3. This network was buffered by 30 m and added to the urban areas layer to create the barriers layer for FG3. Each fragmentation geometry was used in the M_{eff} analysis.

Fragmentation statistics

The effective mesh size metric (M_{eff}) (Jaeger 2000) is based on the probability of 2 points randomly chosen within an area being connected, i.e. not separated by a barrier such as a road. This also could be interpreted as the probability of 2 individuals of opposite sex and same species being able to meet or mate with each other without encountering a fragmenting element, or an animal being able to use any 2 places for food or dispersal on a landscape without crossing a fragmenting element, thus avoiding any possible road mortality or other impacts. Thus, the larger a patch, the greater the probability of co-occurrence; the more barriers within the landscape, the lower the probability of such a co-occurrence.

We used a modification of M_{eff} that incorporates a "cross boundary calculation" (Moser et al. 2007), as follows:

$$M_{eff}^{CBC}(j) = \frac{1}{A_{tj}} \sum_{i=1}^{n} A_{ij} A_{ij}^{cmpl} \quad \text{(I)}$$

in which n is the number of the remaining patches within report unit j, where A_{ij} is the area of patch i in the report unit j and A_{tj} is the total area of the report unit j.

The CBC component of M_{eff} is A_{ij}^{cmpl} which is the sum of the area within report unit j plus the portion of the patch beyond the report unit boundary.

Fragmentation reporting

Landscape fragmentation is reported in four ways: (1) summary CBC Effective Mesh Size (hereafter called M_{eff}) and fragmentation density results for China's provinces and counties; (2) comparison with published values for ten European countries (Jaeger et al. 2007a, b) and the state of California, USA (Girvetz et al. 2008); (3) high and low fragmentation areas of each major geo-ecoregion (Du et al. 2008) of the country were mapped; (4) the relative fragmentation of endangered plant hotspots (Zhang and Ma 2008) was mapped; and (5) M_{eff} values by county were compared to mammal species richness by county, which was derived from mammalian species distribution downloaded from the web site of the International Union for the Conservation of Nature (http://www.iucn.org).

The geo-ecoregions (ecoregion) map used (Du et al. 2008) is a widely used national-scale map that demarcates the broad patterns of climate and vegetation types for 48 regions in continental China (Appendix 1 in supplementary material). County-level measures of landscape fragmentation using FG3 M_{eff} were used to examine the range of fragmentation by ecoregion. The highest and lowest 20% of rates of fragmentation among counties in each ecoregion were identified and mapped to portray the areas potentially at greatest threat and highest conservation opportunity of each climate/vegetation combination. Because of the importance of patch size and density and edge density in fragmentation effects on various biota, patch density, delineated by paved roads, within each ecoregion was determined using FRAGSTATS and expressed as number of patches per 10,000 km^2 (McGarigal et al. 2002). Although ecological attributes are correlated with this metric, we recognize that it has the limitation of being sensitive to small patches (Jaeger 2000).

We assessed the level of landscape fragmentation in eight diversity hotspots of threatened plants (Zhang and Ma 2008), that had been mapped to the county level. We used M_{eff} to identify the most and least fragmented counties in each hotspot, which represent the highest threat and best conservation opportunities by hotspot.

Mammalian species richness was calculated for all counties by summarizing the number of species occurrences from range maps downloaded from the International Union for the Conservation of Nature's (IUCN) website (http://www.iucn.org), and combined to rank mammal hotspots by county. Mammal species richness values were compared to M_{eff} values per county.

Results

County and province fragmentation

M_{eff} was quantified at province and county scales. The lowest values (greatest fragmentation) in China's eastern counties and provinces for all three fragmentation geometries (Fig. 1). The 10 most fragmented counties (FG3) have a mean M_{eff} of 10.7 km^2 (SD 5.5 km^2). The most fragmented 10% of counties (FG3) have mean M_{eff}s of less than 110.5 km^2, and are found in the provinces of Tianjin, Beijing, Hebei (north), Shangdong, Jiangsu, Shanghai, Zhejiang, and parts of Sichuan, Henan, and Anhui provinces. The least-fragmented county (FG3) is Gaize County in Tibet Autonomous Region, with a M_{eff} of 676,623 km^2. The ten least-fragmented counties (FG3) have an average M_{eff} of 570,691 km^2 (SD 74,412 km^2).

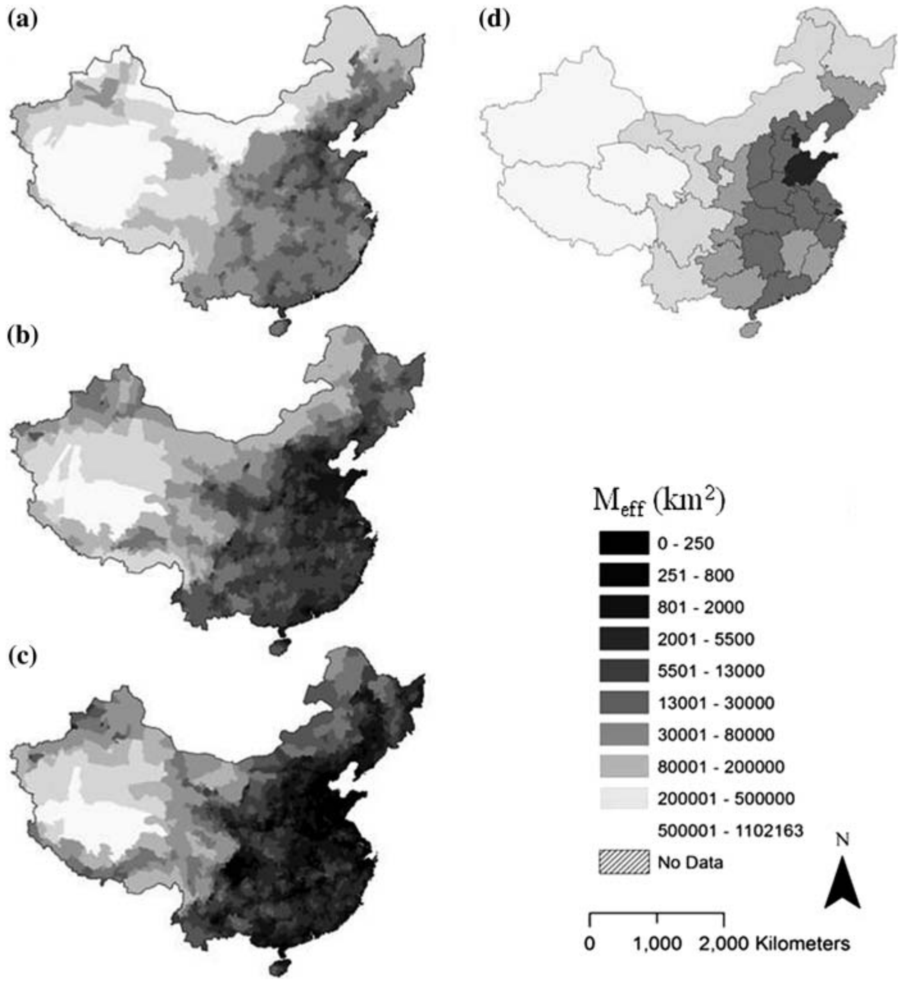

Fig. 1 China's fragmentation spatial distribution based on 3 fragmenting geometries: **a** FG1, National highways, railways, and urban areas; **b** FG2, areas in FG1 + provincial highways; and **c** FG3, areas in FG2 + county paved roads. The reporting unit is the county in each of the provinces. **d** Province-level fragmentation

Province-level fragmentation using all paved roads (FG3) ranges from $M_{eff} = 29.9$ km^2 (Hong Kong), to $M_{eff} = 304{,}491$ km^2 (Tibet) (Fig. 1d). The greatest landscape fragmentation by paved roads is primarily in the eastern Provinces with Hong Kong, Hebei (north), Shanghai and Tianjin all having province-level M_{eff} values of less than 100 km^2. The provincial roads and county roads are primarily responsible for the degree and geographic scope of fragmentation (Fig. 1c).

When the provincial fragmentation is viewed from the perspective of their component counties (Fig. 1a–c), the most fragmentation from paved roads is near Beijing and the surrounding lands within the Huabei Plain, in coastal areas especially the Shandong Peninsula, and around the major metropolitan regions of China, such as Pearl River Delta, Beijing, Tianjin and Bohai Bay Area, down reaches of Yangtze and Yellow River Valleys, and southeast of Sichuan Basin. M_{eff} of counties at the boundary between pastoral-based agriculture and field-based agriculture may serve as indicators for monitoring the progression of fragmentation caused by the roads in China (Fig. 1c). Western provinces (such as Tibet, Xinjiang, Qinhai and Gansu, west Sichuan etc.) are much less fragmented. There is an obvious dividing line from northwest Inner Mongolia southward through Gansu, Sichuan, reaching southwest Guangxi, Yunnan province (Fig. 1d, lightest grey areas), which contains potential conservation opportunities during highway and railroad planning.

Nationally, parts of nine western and northern provinces contain areas in the least fragmented class (Fig. 1d). This is likely because China's basic highway network originally developed in a pattern radiating outward from Beijing in the east to promote national unity. After 1980, fast developing areas such as Yangtze River Delta, and Pearl River Delta started to play similar roles. The combination results in the observed concentration of fragmentation in the East. Moderate levels of fragmentation are found in the central part of the country where agriculture predominates.

International comparison

For the province reporting units, FG3 M_{eff} size varied between 30 km^2 and 304,491 km^2. A first calculation of comparable FG3 M_{eff} values for 10 European countries show that none has a larger M_{eff} than Sweden (7,156 km^2), while Belgium (150 km^2) and the Netherlands (299 km^2) are the most fragmented (Fig. 2). Based on FG3 M_{eff}, four Chinese provinces are more fragmented than any measured European Country, while eight western and northern provinces are less fragmented than the least-fragmented European country.

Ecoregion analysis

Ranking of the top and bottom 20% of county M_{eff} values per ecoregion permits view of where the best land conservation opportunities are, and most

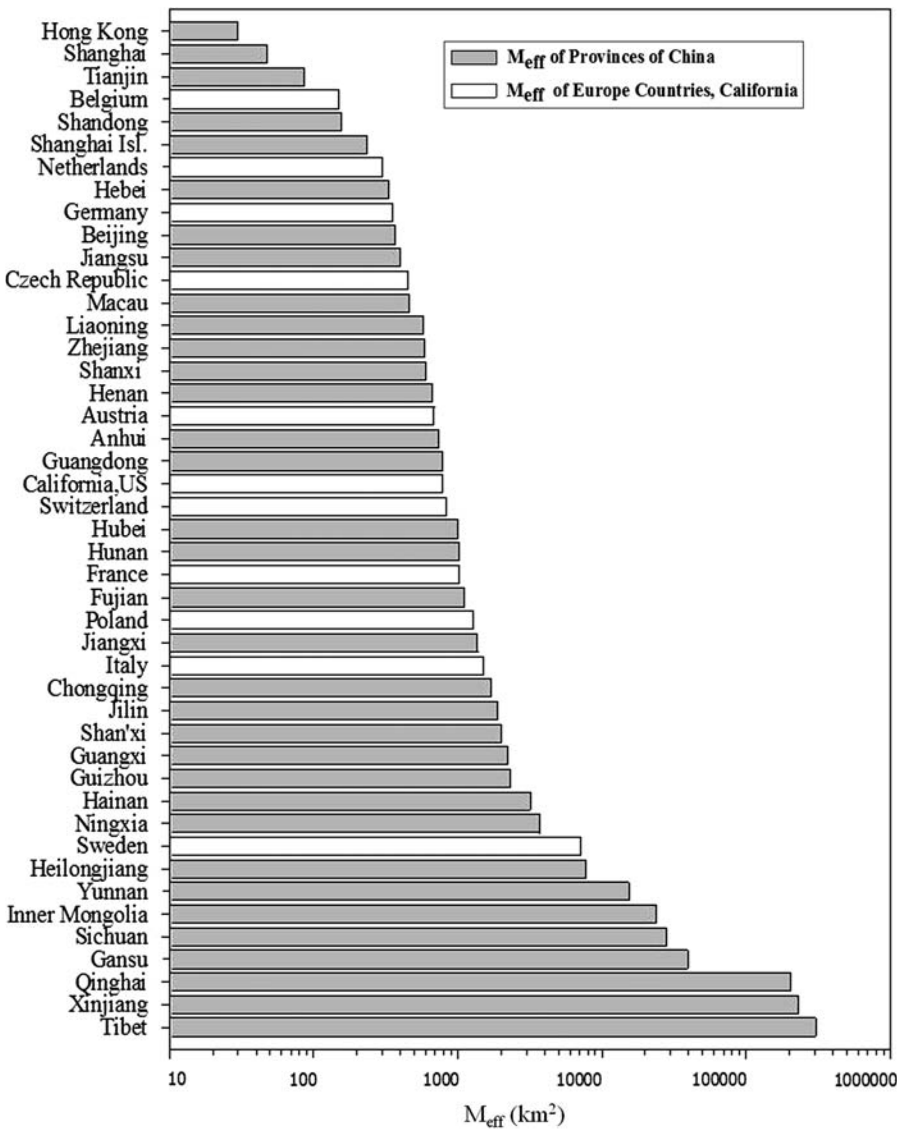

Fig. 2 Fragmentation (M_{eff} FG3) in Chinese provinces compared to other countries. Values for China are from the current study, those for European countries were from Jaeger et al. (2007a, b) and for the state of California, USA, from Girvetz et al. (2008)

threatened localities (Fig. 3, Appendix 1 in supplementary material). The most fragmented ecoregion is IIIB1(deciduous broadleaf forest and cultivated vegetation area of central Shandong province), with a mean county-FG3 M_{eff} of 147 km^2, and with mean a M_{eff} of 220 km^2 for the least fragmented 20% of counties. Three other ecoregions also fall into this ecoregion's climate definition (Warm-temperate zone, sub-humid region). They rank 3rd, 5th and 10th most fragmented (Appendix 1 in supplementary material), with the least fragmented having a FG3 M_{eff} of 1,530 km^2, indicating that this entire climatic zone is highly disturbed. The Kunlun high mountain/plateau, alpine desert ecoregion is the least fragmented, with FG3 M_{eff} of 473,140 km^2.

Patch size and density and edge density have been shown to affect animal and plant distribution (Hernandez-Stefanoni and Dupuy 2008; Barbaro and van Halder 2009; Klingbeil and Willig 2009; Rossi and van Halder 2010). At the same time, it is a metric that is sensitive to the presence of small patches (Jaeger 2000). To augment the M_{eff} method of comparing fragmentation among ecoregion types, we also calculated patch density (delineated by roads) per ecoregion. The alpine desert region of the Kunlun high mountain plateau (H1D1) had the lowest patch density (least fragmented), while the cultivated vegetation region of the Huabei plain (IIIB2) had the highest patch density (most fragmented, Fig. 3b).

Threatened plant hotspot analysis

Zhang and Ma's (2008) eight threatened plant diversity hotspots are in central and southeastern China. M_{eff} values of the hotspots' counties shows the four eastern most hotspots have high levels of fragmentation (Fig. 4; Table 1). The least fragmented hotspot is #I, the Central and southern Hengduanshan mountainous area, with mean M_{eff} of 88,421 km^2. The most fragmented hotspot located in the western mountains of Guangdong (#VIII), with county M_{eff} values ranging from 263 to 1,580 km^2 (mean 872 km^2).

Mammal species richness analysis

Mammals are negatively affected by fragmentation from urban roads and paved roads (Hilty et al. 2007). We compared mammal species richness (Fig. 5a) with fragmentation, measured using M_{eff} (Fig. 1c). The greatest number of species occurred in the moderately fragmented southern and central counties (Fig. 5a). Counties with the least number of species occur both in areas that are highly fragmented (eastern provinces) and least fragmented (western provinces, Fig. 5b). Comparison of mammal species richness with fragmentation at the county scale (Fig. 5c) provides one tool to measure threats to biodiversity and potential sites of conservation action, including that associated with future transportation planning. We found a wide range of mammal species richness values across the similarly wide range of M_{eff} values (Fig. 5c). We posited that counties with the lowest fragmentation and highest mammal species richness (black box) provided the greatest opportunity for developing conservation areas, counties with high mammal richness and high fragmentation (grey, solid-line box) were areas needing remedial action to reduce threats, and counties with high fragmentation and low species diversity (grey, dotted-line box) may contain individual species needing special protection.

Discussion

The challenge of maintaining biodiversity and ecological sustainability while accommodating an increasing population's search for economic security is perhaps nowhere as daunting as in China. China contains over 10% of the world's plant and animal species (Liu et al. 2003), of which about 50% are endemic, about 10% of the world's wetlands, major river systems, extensive grasslands, and a highly diverse set of environments (Liu and Diamond 2005). At the same time, as we show here, much of China's landscape is fragmented by paved roads, with eastern provinces containing field agriculture and urban areas among the most fragmented regions in the world. In contrast are some of the least fragmented areas in the world, the western provinces (e.g., Mongolia), which are mountainous, arid, and semi-arid regions.

History and topography

China's highway and paved road network originally developed in a pattern radiating from Beijing. This pattern is evident in that paved roads are most

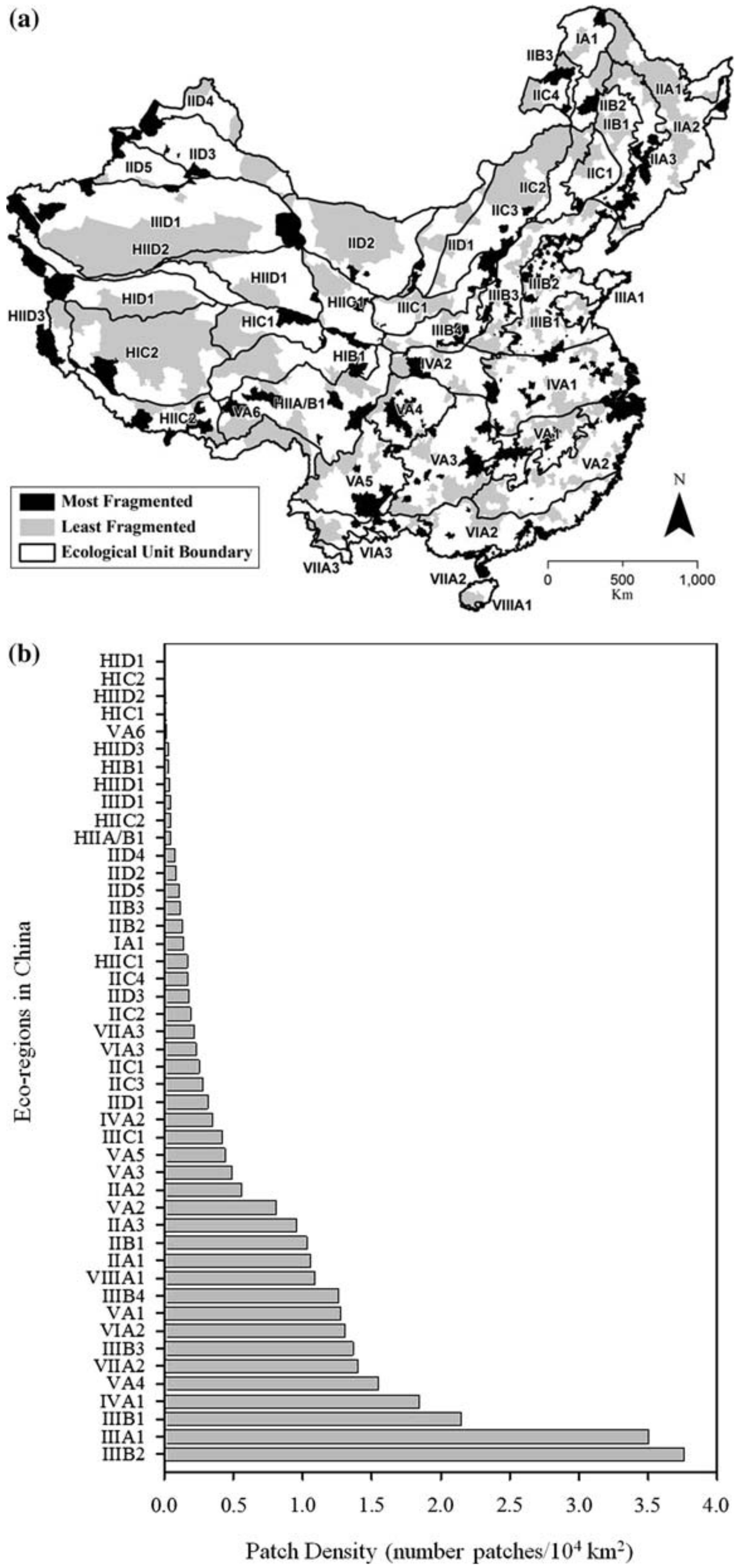

Fig. 3 **a** The least and greatest 20% of county M_{eff} values per eco-geographical region in China, the black color indicates the most fragmented 20% counties (smallest M_{eff} values) and the light grey indicates the least fragmented 20% (largest M_{eff} values) within each of the 48 climate and vegetation types regions in continental China. **b** Patch density (number per 10,000 km^2) in each major eco-region of China

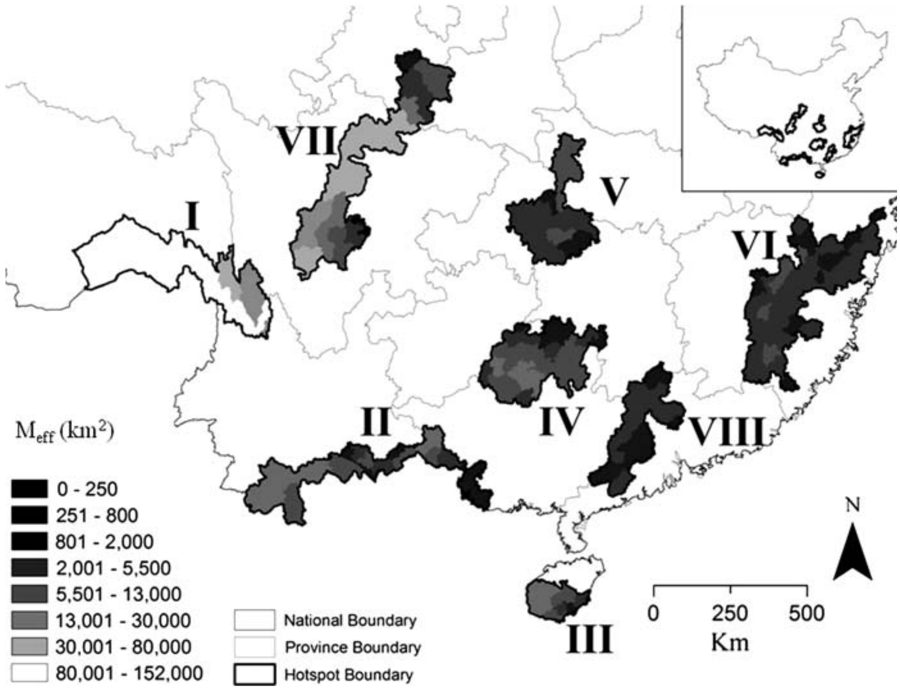

Fig. 4 Endangered plants hotspots in southern China. Specific identified areas are indicated with Roman numerals. M_{eff} values for each county in the hotspots regions are indicated ranging from black (least values, most fragmented) to white (greatest values, least fragmented)

Table 1 The Effective mesh size (M_{eff}) values, based on FG3, for eight threatened plant hotspots

Hotspot ID number	Mean county M_{eff} (km^2)	Hotspot name	Least fragmented county	M_{eff} (km^2)	Most fragmented county	M_{eff} (km^2)
I	88,421	Central and southern Hengduanshan mountainous area	Medog County	154,086	Lijiang City	16,601
II	3,304	Xishuangbanna region, southeastern Yunnan and southwestern Guangxi	Funing County	11,199	Pingxiang City	181
III	4,335	Southern Hainan island	Dongfang City	8,770	Lingshui Li Autonomous County	704
IV	2,758	Border mountains of Guizhou, Guangxi and Hunan provinces	Congjiang County	7,935	Huitong County	273
V	1,658	Mountainous area of southwestern Hubei and northern Hunan	Shennongjia Conservation Zone	4,009	Zhangjiajie City	430
VI	1,177	Southwestern Zhejiang and western Fujian	Guangze County	2,867	Tiantai County	359
VII	15,124	Central Sichuan and southern Gansu	Lixian County	73,864	Jiajiang County	220
VIII	872	Western mountains of Guangdong	Lianzhou City	1,580	Yunfu City	263

The hotspots are the same as those mapped in Fig. 4. Each hotspot is comprised of multiple counties. The most and least fragmented county for each hotspot and the corresponding county M_{eff} values are indicated

extensive in Beijing and eastern China and decrease in prevalence toward the central and western provinces. The very great difference in fragmentation between east and west China may also be related to the long history of transportation development in the eastern and southern parts of the country, to serve the

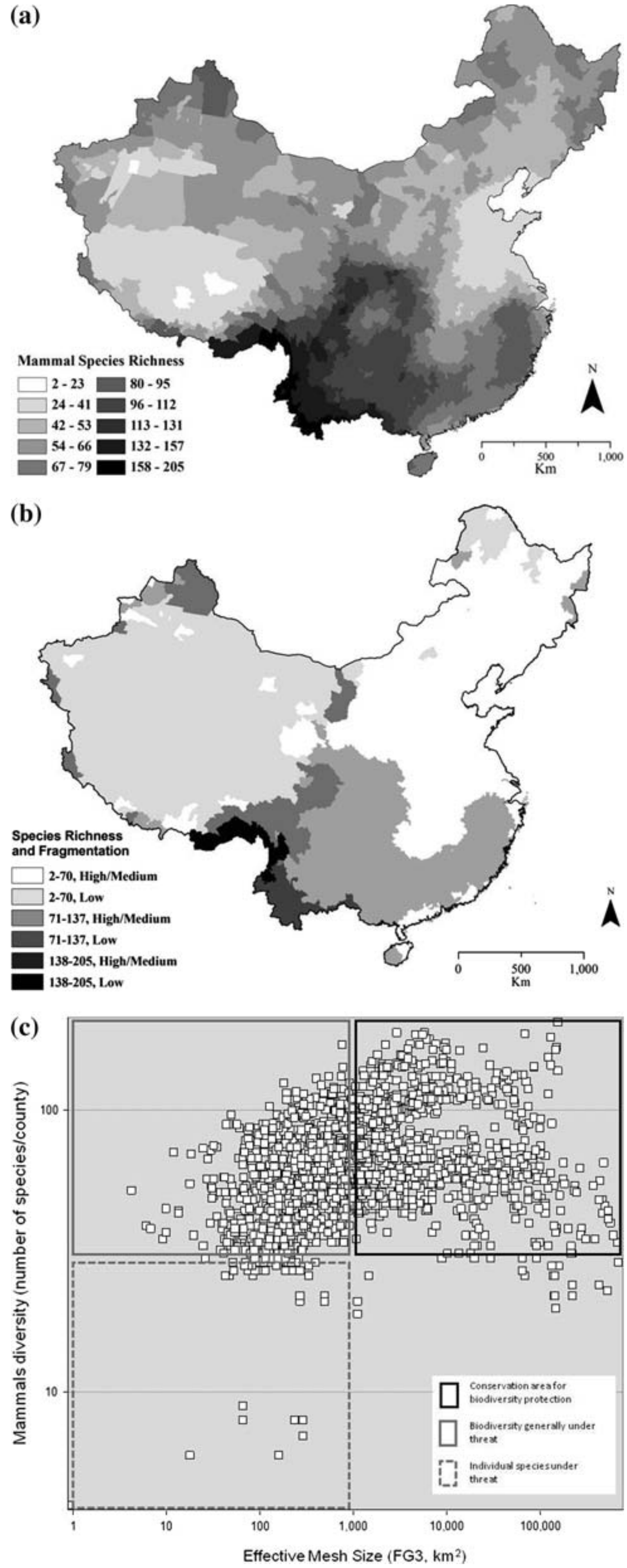

Fig. 5 **a** Mammal species richness for each county in China. The number of mammals occurring in an area were summarized to counties. Data for mammal species distributions were obtained from the web site of the International Union for the Conservation of Nature. **b** Comparison of categories of mammal species richness with fragmentation for counties in China. Number of mammal species is indicated in numeric categories (e.g., 2–70) and fragmentation in descriptive categories (e.g., high/medium). **c** Number of mammal species likely to occur in a county compared to M_{eff} for the same county. Boxes were drawn to group counties according to relative threats to biodiversity and conservation opportunities

numerous population centers and extensive agriculture in this part of the country.

China has a long history of transportation system development. During thousands of years prior to the twentieth century, gravel and dirt roads were built and maintained, including township roads and cart trails. These roadways were built for local transport of crops from fields to storage, or from one village to another, or even for trans-regional business purposes, for example the Silk Road. Some of them have disappeared or have been replaced by paved roads, but some still remain and are used by the local people, especially in the countryside. Although these roads likely have relatively lower impacts on the ecosystems because of lower frequency of use than modern paved highways, they are densely occurring and have generally been used by local farmers and pedestrians. Many rural communities have established along such roads and tracks in the past and recently, it has become part of the national strategy to widen and pave these routes, which will increase their contribution to fragmentation.

The substantial decrease in M_{eff} values from west to east (Fig. 1d) coincides with the dividing zone between China's pastoral and agricultural regions (Wenuan 1989), as well as the new urban development over the last 20 years in the coastal agricultural areas (Long et al. 2009). This zone also marks the transition from humid to arid climate, and from sparsely to densely populated, and from minority nationality settlements (such as Tibetan, Mongolian and many others in the Southwest area) to Chinese settlements. The change in M_{eff} values may therefore be the result of a field-farming culture with a greater need for the accessibility provided by the roads than the pastoral culture and life-styles of the people in the west. China's road fragmentation pattern also roughly coincides with topographic features, from plateaus in the west to basins in the east, as well as coinciding with economic zones developed by the Chinese government (Cole et al. 2008).

Planned expansion

China's existing paved road network has fragmented eastern China to a degree found in the highly developed European and US regions, but western China remains free of this fragmentation. However, with the rapid expansion of China's economy and China's objectives of rapidly developing the "Grand West Development Campaign", "Integrity of Urban and Countryside" the western areas and vast countryside will experience more transportation system construction; such as the Tibet railway which was opened to the public in 2007 and has already impacted Tibetan wildlife migrations (Xia et al. 2007).

There may be particular opportunities to integrate the landscape impacts measured here with ongoing road and highway expansion. China has plans to spend billions of dollars on trunk road development and rural accessibility (Senevirtane 2006; Cole et al. 2008). Much of this road development is anticipated for the less-fragmented regions posing a new conservation concern. The national availability of M_{eff}-based measures of landscape fragmentation, which can easily be incorporated into GIS databases, may help to guide plans for new road projects away from less fragmented regions, which could help maintain un-fragmented and less-fragmented spaces for many endangered species such as giant panda and snow leopard which require large ranges. This is similar to the approach used by Vasas et al. (2009) to recommend alternative alignments for a highway to reduce fragmentation effects.

M_{eff} maps and conservation

The M_{eff} statistic is a landscape-scale measure of threat or impact to species and habitats of conservation concern. As such, a nationally comprehensive M_{eff} map allows for multiple types of comparisons that rank conservation opportunity and level of threat. This paper showed three national applications of the use of the FG3 M_{eff} statistic for natural resources that others had already mapped: ecoregions, threatened plant hotspots, and areas of high mammal species richness. This type of integration of anthropogenic threats with baseline biodiversity and conservation data is widely needed for conservation priority setting (Beardsley et al. 2009).

The integration of M_{eff} with China's ecoregions allows for the comparative assessment of road fragmentation in major different habitat types. Systematic conservation planning (Margules and Pressey 2000) suggests that representation of each major habitat type (and by extension the species which inhabit it) should be included in protected lands portfolios. The M_{eff} maps are particularly useful in this context for the highly developed ecoregions, as they permit identification of potentially the few remaining suitable spaces for conservation (Fig. 3). However, it should be noted that the effects of roads in different habitats may vary, a road in the steppe may have different impacts from a road in tropical habitats, so the M_{eff} maps should be used in conjunction with other biodiversity data and conservation planning tools (Thorne et al. 2009). Patch density, where patches are delineated by paved roads, varied among ecoregions. Effects of landscape fragmentation on animals and plants vary depending on the landscape structure variable and the taxonomic group and behavior or life-cycle requirements (Hernandez-Stefanoni and Dupuy 2008; Schindler et al. 2008; Barbaro and van Halder 2009; Klingbeil and Willig 2009; Rossi and van Halder 2010). An important step in planning for biodiversity conservation in the face of future paved road expansion in China, will be to combine fragmentation metrics such as M_{eff} with others that indicate other aspects of landscape structure.

Zhang and Ma (2008) identified eight threatened plant diversity hotspots in China where there are currently low levels of conservation management lands. Threatened plants are by definition already subject to anthropogenic impacts in most cases. By using the county-level M_{eff} values in each hotspot (Fig. 4) it is possible to rapidly get a view of which hotspots are most at risk, and which have remaining relatively roadless regions. Many of these hotspots are located in mountainous areas, likely due to increased habitat heterogeneity, higher rates of endemism often in such areas, and potentially lower human activity. Assessments of biodiversity such as Zhang and Ma (2008) or Tang et al. (2006) have more detailed analyses than is possible to integrate with M_{eff} results in this introductory paper. It is our hope that the M_{eff} maps will prove useful for integration with such biodiversity of studies in the future.

The IUCN mammal species range maps permitted calculation of mammal species richness by county. A simple three-tier classification of richness against either low, medium, or high levels of fragmentation (Fig. 5b) shows that about 80% of the area of moderate species richness (71–137 species) is in medium to high levels of fragmentation in the south east, and less than 70 species occur in the highly fragmented central and north east. This type of analysis also opens the door for classifications such as Fig. 5c, which defines individual counties according to their level of threat or conservation opportunity (upper left and right), and counties that may have only a few species, but which may be threatened by fragmentation effects. Counties that are both rich in mammal diversity and highly fragmented will require careful planning by transportation and land-use officials to avoid greater impacts and threats to mammalian biodiversity.

Environmental conservation practice in China has been critiqued for not being proactive or adequately enforced (Liu et al. 2008a, b). China is relatively unique compared with another developed countries in the degree to which planning is centralized. Maps produced in this study enable provincial and regional assessments of what areas are still least impacted by paved roads. The identification of low-fragmentation counties may potentially be combined with measures of biotic or ecological importance to help with further national-scale conservation planning and with design of new road networks that attempt to minimize impacts in those areas.

Advantages and limitations of M_{eff}

Effective mesh size has been used to trace the growth of fragmentation through time (Jaeger et al. 2007a), to inform transportation planning (Jaeger et al. 2007b), and as a metric for monitoring sustainable development (Jaeger et al. 2008). M_{eff} can be calculated for a variety of spatial reporting units, including watersheds, counties, highway maintenance districts, single segments of highways (buffered by some distance) or other political and natural units (Girvetz et al. 2008). We used M_{eff} based on county units because it offers the possibility of informing county planners about fragmentation at the scale of their decision-making. One of its greatest utilities is that it can be used in the study of specific vertebrate species, if the movement requirements of that species are known. This permits assessment of the level of fragmentation within the range of the species.

However, M_{eff} only captures one aspect of fragmentation and does not indicate variable intensities of fragmentation from different road types, traffic patterns on these roads, or patch-specific characteristics. It also only captures fragmentation by roads completely bisecting a patch and not roads intruding into patches without bisecting. Other landscape metrics should be used where available for development of a more complete understanding of the effects of fragmentation on specific areas and regions and on biodiversity (Schindler et al. 2008), such as we did by assessing the density of patches for the ecoregions of China (Fig. 3b). We recommend using other patch-specific metrics (e.g., patch morphology, size, and isolation) in conjunction with M_{eff}, while recognizing that each will also have limitations when used in isolation.

Conclusion

Currently in China's economic development, roads and highways are planned based on Environment Impact Assessments associated with specific projects and roads/highways. The ecology of fragmentation has never been integrated into transportation plans across national to county scales. Based on our study this is a serious shortcoming, having resulted in high levels of fragmentation in the eastern third of the country. We strongly recommend that evaluation of ecological fragmentation be integrated into road system planning at various scales, from the national scale to the smallest planning units.

The structure of the road network (roads braided together or sparsely distributed) and the corresponding fragmented landscape requires the planner to think at a landscape scale instead of the finer scale of the transportation corridor. This may create a meaningful role for conservation in future road planning, as well as for road maintenance plans which can change (add, remove) segments in the existing road network.

If a structured program of connectivity evaluation can be applied to all the roads planning, design, and maintenance, this may reduce future fragmentation pressure on China's landscape. One example could be concentrating traffic onto fewer existing and/or new roads, allowing less-used roads to be closed and their impacts on ecosystems reduced. Based on the M_{eff} analyses described in this study, planners should (1) carefully align roads in the west, taking action to conserve the existing non-fragmented areas, (2) amplify the value of less-fragmented areas in the east and the south of China by improving connectivity within and among them, and (3) avoid any further fragmentation of existing natural areas, such as woodlands, wetlands, and other existing connected habitats in China.

Future planning and studies

Paved roads are a critical fragmenting element in Chinese landscapes, as in other countries. Because of the prevalence of un-paved roads and agricultural tracks in at least the agricultural areas of China, analysis of paved road land-division is only the first step. The next step of developing comprehensive maps of these unpaved road systems has been initiated (Li, unpublished observations). The addition of these mapped roads and improved resolution of the existing paved road maps will greatly improve local, regional, and national assessments of landscape fragmentation by roads in China.

There are local and regional efforts to decrease road impacts in China, including planting trees and shrubs along highways (Lu et al. 2008), assessing the prospects for transit-oriented development (Thomas and Deakin 2008), and building wildlife crossing structures (e.g., for Tibetan antelope, Xia et al. 2007). However, many recent road planning publications are focused on improving the economic condition of rural communities through the development of roads, (Plessis-Fraissard 2008), on the political context of transportation decision making (Yang et al. 2008), and on impacts of increasing numbers of motor vehicles (Cai and Xie 2007; Huo et al. 2008), with little or no mention of ecological effects. Transportation studies should also make assessment of biodiversity and ecosystem process preservation an integral part of their process. We hope that this assessment of the paved roads will help China's government to put into practice their proposal for lower-impact road systems and urban development strategies.

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Citations

Barbaro L, van Halder I (2009) Linking bird, carabid beetle and butterfly life-history traits to habitat fragmentation in mosaic landscapes. Ecography 32:321–333

Beardsley K, Thorne JH, Roth NE, McCoy M (2009) Impact of rapid human population growth on biological resources in the San Joaquin Valley of California. Landsc Urban Plan 9:172–183

Beier P, Noss RF (1998) Do habitat corridors provide connectivity? Conserv Biol 12:1241–1252

Cai H, Xie S (2007) Estimation of vehicular emission inventories in China from 1980 to 2005. Atmos Environ 41:8963–8979

Chen X, Wu J (2009) Sustainable landscape architecture: implications of the Chinese philosophy of "unity of man with nature" and beyond. Landscape Ecol. doi:10.1007/s10980-009-9350-z

Christopher DE, Benjamin TT, Paul CS, Kimberly EB, Ara TH, Cristina M, Budhendra LB, Ramakrishna N (2007) Global distribution and density of constructed impervious surfaces. Sensors 2007(7):1962–1979

Coffin AW (2006) From roadkill to road ecology: a review of the ecological effects of roads. J Transp Geogr 15:396–406

Cole D, Furst T, Daboin S, Hoemann W, Meyer M, Nordahl R, Parker M, Penne L, Stoner N, Tang T (2008) Freight mobility and intermodal connectivity in China. Report of the Federal Highway Administration (FHWA-PL-08-020), 52 pp

Collinge SK (1996) Ecological consequences of habitat fragmentation: implications for landscape architecture and planning. Landsc Urban Plan 36:59–77

Comprehensive Planning Division of Ministry of Communications (2004) Outline of highway and waterway development plan for the 11th 5 years plan, Beijing

Ding J, Mack RN, Lu P, Ren M, Huang H (2008) China's booming economy is sparking accelerating biological invasions. Bioscience 58:317–324

Dongjing C, Guodong C, Zhongmin X, Zhiqiang Z (2004) Ecological footprint of the Chinese population, environment and development. Environ Conserv 31:63–68

Du Z, Bingyuan L, Wu G (2008) China's eco-geographical region map, in hierarchical system of eco-geographical regions, 2008. Commercial Press, Beijing

Fahrig L (2003) Effects of habitat fragmentation on biodiversity. Ann Rev Ecol Evol Syst 34:487–515

Fan S, Chan-Kan C (2005) Road development, economic growth, and poverty reduction in China. Research Report 138. International Food Research Policy Institute, Washington, DC

Farhig L, Rytwinski T (2009) Effects of roads on animal abundance: an empirical review and synthesis. Ecol Soc 14:21 URL: http://www.ecologyandsociety.org/vol14/iss1/art21/

Forman RTT, Alexander LE (1998) Roads and their major ecological effects. Ann Rev Ecol Evol Syst 29:207–231

Forman RTT, Sperling D, Bissonette JA, Clevenger AP, Cutshall CD, Dale VH, Fahrig L, France R, Goldman CR, Heanue K, Jones JA, Swanson FJ, Turrentine T, Winter TC (2003) Road ecology: science and solutions. Island Press, Washington, DC

Fu B, Chen L (2000) Agricultural landscape spatial analysis in the semi-arid hill area of the Loess Plateau, China. J Arid Environ 44:291–303

Gelbard JL, Belnap J (2003) Roads as conduits for exotic plant invasions in a semi-arid landscape. Conserv Biol 17:420–432

Girvetz EH, Thorne JH, Berry AM, Jaeger JAG (2008) Integration of landscape fragmentation analysis into regional planning: a statewide multi-scale case study from California, USA. Landsc Urban Plan 86:205–218

Grumbine RE (2007) China's emergence and the prospects for global sustainability. Bioscience 57:249–253

Hernandez-Stefanoni JL, Dupuy JM (2008) Effects of landscape pattern on species density and abundance of trees in the tropical subdeciduous forest of the Yucatan Peninsula. For Ecol Manag 255(11):3797–3805

Hilty JA, Lidicker WZ, Merenlender AM (2007) Corridor ecology. Island Press, Washington, DC

Honnay O, Jacquuemyn H (2007) Susceptibility of common and rare plant species to the genetic consequences of habitat fragmentation. Conserv Biol 21(3):823–831

Huo H, Wang M, Johnson L, He D (2008) Projection of Chinese motor vehicle growth, oil demand, and CO_2 emissions through 2050. Transp Res Rec: J Transp Res Board 2038:69–77

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

Jaeger JAG, Schwarz-von Raumer HG, Esswein H, Müller M, Schmidt-Lüttmann M (2007a) Time series of landscape fragmentation caused by transportation infrastructure and urban development: a case study from Baden-Württemberg (Germany). Ecol Soc 12(1):22. [online] URL: http://www.ecologyandsociety.org/vol12/iss1/art22/

Jaeger JAG, Bertiller R, Schwick C (2007b) Degree of landscape fragmentation in Switzerland: quantitative analysis 1885–2002 and implications for traffic planning and regional planning. Condensed Version. Swiss Federal Statistical Office, Neuchâtel, 36 pp. Online: http://www.bafu.admin.ch/publikationen/index.html?action=show_publ&lang=D&id_thema=20&series=DIV&nr_publ=8409

Jaeger JAG, Bertiller R, Schwick C, Muller K, Steinmeier C, Ewald KC, Ghazoul J (2008) Implementing landscape fragmentation as an indicator in the Swiss Monitoring System of Sustainable Development (MONET). J Environ Manage 88(4):737–751

Klingbeil BT, Willig MR (2009) Guild-specific responses of bats to landscape composition and configuration in fragmented Amazonian rainforest. J Appl Ecol 46:203–213

Li Y (2008) China's economy has no declining trend after Olympic Games. People's Daily, February 25th, 2008

Liu J, Diamond J (2005) China's environment in a globalizing world. Nature 435:1179–1186
Liu J, Linderman M, Ouyang Z, An L, Yand J, Zhang H (2001) Ecological degradation in protected areas: the case of Wolong Nature Reserve for Giant Pandas. Science 292:98–101
Liu J, Ouyang Z, Pimm SL, Raven PR, Wang X, Miao H, Han N (2003) Protecting China's biodiversity. Science 300:1240–1241
Liu J, Li S, Ouyang Z, Tam C, Chen X (2008a) Ecological and socioeconomic effects of China's policies for ecosystem services. Proc Natl Acad Sci 105:9477–9482
Liu SL, Cui BS, Dong SK, Yang ZF, Yang M, Holt K (2008b) Evaluating the influence of road networks on landscape and regional ecological risk- a case study in Lancang River Valley of Southwest China. Ecol Eng 34:91–99
Long H, Liu Y, Wu X, Dong G (2009) Spatio-temporal dynamic patterns of farmland and rural settlements in Su-Xi-Chang region: implications for building a new countryside in coastal China. Land-Use Policy 26:322–333
Lu J, Yuan L, Ge Q (2008) Development of a model for freeway green landscape evaluation. Transp Res Rec: J Transp Res Board 2025:63–71
Margules CR, Pressey RL (2000) Systematic conservation planning. Nature 405:243–253
McGarigal K, Cushman SA, Neel MC, Ene E (2002) FRAGSTATS: spatial pattern analysis program for categorical maps. University of Massachusetts, Amherst, MA, USA. http://www.umass.edu/landeco/research/fragstats/fragstats.html
Moser B, Jaeger JAG, Tappeiner U, Tasser E, Eiselt B (2007) Modification of the effective mesh size for measuring landscape fragmentation to solve the boundary problem. Landscape Ecol 22:447–459
Planning and Research Institute, Ministry of Communications of China (2004) National Expressway Network Planning, Beijing
Plessis-Fraissard M (2008) Planning roads for rural communities. Transp Res Rec 1989(1):1–8
Qian J, Wang G, Ding Y, Liu S (2006) The land ecological evolution patterns in the sources areas of the Yangtze and Yellow Rivers in the past 15 years, China. Environ Monit Assess 116:137–156
Quinn JF, Harrison SP (1988) Effects of habitat fragmentation and isolation on species richness—evidence from biogeographic patterns. Oecologia 75:132–140
Rossi J-P, van Halder I (2010) Toward indicators of butterfly biodiversity based on multiscale landscape description. Ecol Indic 10:452–458
Schindler S, Poirazidis K, Wrbka T (2008) Toward a core set of landscape metrics for biodiversity assessments: a case study from Dadia National Park, Greece. Ecol Indic 8:502–514
Senevirtane PN (2006) Road sector development in China and India. Transp Res Rec 1954:15–21
Shilling FM (2007) Repairing road impacts on landscape connectivity. Trans Western Section Wildlife Soc 43:11–18
Shilling FM, Girvetz E (2007) Barriers to implementing a wildland network. Landsc Urban Plan 80(1–2):165–172
Tang Z, Wang Z, Zheng C, Fang J (2006) Biodiversity in China's mountains. Front Ecol Environ 4:347–352
Taylor PD, Fahrig L, Henein K, Merriam G (1993) Connectivity is a vital element of landscape structure. Oikos 68:571–573
Thomas A, Deakin E (2008) Land use challenges to implementing transit-oriented development in China. Transp Res Rec 2077:80–86
Thorne JH, Girvetz EH, McCoy M (2009) Evaluating aggregate terrestrial impacts of road construction projects for advanced regional mitigation. Environ Manage 43:936–948
Trombulak SC, Frissell CA (2000) Review of ecological effects of roads on terrestrial and aquatic communities. Conserv Biol 14:18–30
Turner BL, Lambin EF, Reenberg A (2007) The emergence of land change science for global environmental change and sustainability. Proc Natl Acad Sci 104:20666–20671
Vasas V, Magura T, Jordan F, Tothmeresz B (2009) Graph theory in action: evaluating planned highway tracks based on connectivity measures. Landscape Ecol 24:581–586. doi:10.1007/s10980-009-9346-8
Watts RD, Compton RW, McCammon JH, Rich CL, Wright SM, Owens T, Ouren DS (2007) Roadless space of the conterminous United States. Science 316:736–738
Wenuan N (1989) The discriminatory index with regard to the weakness, overlapness, and breadth of Ecotone. Acta Ecological Sinic 02:20–21
Xia L, Yang Q, Li Z, Wu Y, Feng Z (2007) The effect of the Qinghai-Tibet railway on the migration of Tibetian antelope Pantholops hodgsonii in Hoh-xil National Reserve, China. Oryx 41:352–357
Yang J, Feng C, Cao G (2008) Land and transportation development. Transp Res Rec 2038:78–83
Yang X, Huang Y, Dong J, Liu H (2009) An updating system for the gridded population database of China based on remote sensing, GIS and spatial database technologies. Sensors 9:1128–1140
Zhang Y, Ma K (2008) Geographic distribution patterns and status assessment of threatened plants in China. Biodivers Conserv 17:1783–1798
Zhang X, Quine TA, Walling DE (1998) Soil erosion rates on sloping cultivated land on the Loess Plateau near Ansai, Shaanxi Province, China: an investigation using 137Cs and rill measurements. Hydrol Process 12:171–189
Zhang W, Hu Y, Chen B, Tang Z, Xu C, Qi D, Hu J (2007) Evaluation of habitat fragmentation of giant panda (Ailuropoda melanoleuca) on the north slopes of Daxiangling Mountains, Sichuan province, China. Anim Biol 57:485–500