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Integrating Habitat Fragmentation Analysis into Transportation Planning Using the Effective Mesh Size Landscape Metric

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Abstract: Habitat fragmentation due to transport infrastructure and other human development poses a threat to many wildlife species. This threat may differ depending on the species and types of fragmenting elements. There is a need to quantify the level of habitat fragmentation and the impact of habitat fragmentation on different wildlife species for use in transportation planning. Such measures would be useful in assessing the cumulative impacts of multiple road projects on wildlife connectivity and habitat suitability, for long-range wildlife impact mitigation planning for transportation projects, and as an indicator for the environmental monitoring of habitat fragmentation due to roads.

Effective mesh size (m_{eff}) is a biologically relevant landscape metric that quantifies the degree of landscape fragmentation. The definition of the effective mesh size is based on the probability that two randomly chosen points in a region will be located in the same non-fragmented area of land. We calculated effective mesh size to assess the level of landscape fragmentation in the State of California, USA, based on four fragmentation geometries defined by a combination of highways, minor roads, urbanized areas, agricultural areas, and natural fragmenting features (e.g., rivers, lakes, and alpine areas). The effective mesh size for these four fragmenting geometries were calculated for the entire State of California using eight sets of planning units: 1) transportation planning districts, 2) municipal county boundaries, and 3) six levels of watersheds. To demonstrate the methodology, we examined how effective mesh size may impact two species important to transportation planning in California: mule deer (*Odocoileus hemionus*) and mountain lion (*Puma concolor*). The calculated effective mesh sizes were compared with the home range sizes and daily movement distances of the selected focal species to determine the potential impacts of habitat fragmentation and to identify areas where transportation projects will potentially impact these focal species.

Based on the results of this analysis, we suggest that integrating an effective mesh size-based tool into transportation planning frameworks would be valuable to improve identification of potential landscape level impacts early in the planning process. The calculation of effective mesh size will give transportation planners a way to analyze the cumulative impacts of roads in districts, counties, and watersheds and can be used as an environmental indicator for ecological assessment of transportation system impacts.

Introduction

Overview

The impact of landscape fragmentation due to roads, urbanization, and other land uses has been identified as a major impact to wildlife and species of concern (Forman 1995; Forman et al. 2003). Impacts to wildlife include direct mortality (Mazerolle 2004; Riley et al. 2003), behavioral changes (Mazerolle et al. 2005), reduced dispersal abilities (Forman & Alexander 1998), and impediment to gene flow (Riley et al. 2006). Transportation planners have recognized the need to assess landscape fragmentation as a part of the environmental planning process. Recent changes in transportation planning regulations (Federal Transportation HR 3, SAFETEA-LU, Congress 2005) mandate that transportation planning incorporate considerations of wildlife conservation. This is due in part to the economies of scale that may be available through integrated regional planning, and to recognition that roads have cumulative impacts on the ecosystems they pass through that may not be correctly identified if planning and environmental assessment are done on a case by case basis.

There is a need for tools and analyses to assess habitat fragmentation at multiple spatial scales that can be easily used by transportation and land use planners. This is particularly the case in the State of California, a globally ranked hotspot of biodiversity, which is currently undergoing a rapid increase in human population density, urban growth and development of transportation infrastructure. This report presents the first results from applying a custom tool for calculating the effective mesh size to assesses the level of habitat fragmentation due to highways, local roads, rail, urban areas, agricultural areas, and natural fragmenting elements (i.e., rivers, lakes, and high alpine areas) in the State of California. By spatially overlaying different combinations of these fragmenting features, four “fragmentation geometries” were analyzed relative to boundaries relevant to planners: twelve Caltrans districts, 58 counties, and six nested spatial scales of watershed ranging from 9 to 6998 watersheds in the State.

We then examined how landscape fragmentation might impact two focal species that are important in California transportation planning: mule deer (*Odocoileus hemionus*) and mountain lion (*Puma concolor*). Deer are of concern in many states because they are often hit by traffic, making them a high-profile species for transportation planners. Mountain lion are of interest due to their large area requirements, which make them sensitive to ongoing landscape fragmentation. Mountain lion have been used as a focal species for modeling in the identification of important wilderness corridors in California (Beier et al. 2006; Hunter et al. 2003; Shilling et al. 2002; Thorne et al. 2006), and efforts are underway to preserve or restore some of these modeled wildlife corridors in Southern California (Beier et al. 2006).

Landscape Fragmentation Metrics: Effective Mesh Size

The scientific literature suggests a variety of landscape metrics for quantifying landscape fragmentation (e.g., Gustafson 1998; Haines-Young & Chopping 1996; Jaeger 2000; Riitters et al. 2005; Rutledge & Miller 2006). However, few methods have been developed for practical and intuitive assessment of landscape fragmentation by transportation and other land use planners, since most of these metrics can only be applied to specific aspects of landscape fragmentation. Li and Wu (2004) point out that the behaviors of many landscape metrics are not understood in sufficient detail, which may compromise their suitability for planning purposes. Jaeger (2002) compared 22 metrics with regard to their reliability for quantifying landscape fragmentation, and systematically investigated the eight most promising measures based on eight suitability criteria (intuitive interpretation, mathematical simplicity, modest data requirements, low sensitivity to small patches, monotonous reaction to different fragmentation phases (Forman 1995), detection of structural differences, mathematical homogeneity, and additivity). According to these criteria, only the *effective mesh size* (m_{eff})was unreservedly appropriate as a fragmentation measure, while the suitability of the other measures was more or less severely limited (Jaeger 2000).

Effective mesh size is an expression of the probability that any two randomly chosen points in a region may be connected, i.e., not separated by barriers such as transportation infrastructure or urban areas (figure 1, Jaeger 2000). This measure has been widely applied in Europe and in several other countries. This includes many states in Germany such as Baden-Wuerttemberg (Esswein et al. 2004; Jaeger 2001; Jaeger et al. *in press-b*) where the resulting time series (1930-2004) have been used for environmental reporting (Ministerium für Umwelt und Verkehr Baden-Württemberg & Landesanstalt für Umweltschutz Baden-Württemberg 2003), Saxony (Walz 2005), Thuringia (Geologie 2004), Hesse (Roedenbeck et al. 2005), and Bavaria (Esswein et al. 2004). The effective mesh size metric was recently selected as one of 24 national core indicators for environmental reporting in the context of sustainability in Germany (Schupp 2005), and the corresponding calculations for the remaining states of Germany are under way. The German Federal Environment Agency has suggested tentative limits to the increase of landscape fragmentation in Germany based on the effective mesh size to start a discussion about environmental goals for the future degree of landscape fragmentation (Penn-Bressel 2005; UBA 2003). The effective mesh size has also been applied in South Tyrol (Italy) for environmental reporting on the level of municipalities (Moser et al. 2007), in Lombardy (Italy) (Padoa-Schioppa et al. 2006), and in Switzerland where it is used as an environmental indicator for monitoring sustainable development (Bertiller et al. 2007; Jaeger et al. 2006; Jaeger et al. in press-a). The European Environment Agency applied the effective mesh size to all European countries, preliminary results are presented in Bertiller et al. (2007), and is planning a more detailed investigation. The method has also been applied outside of Europe (Baldi et al. 2006). Environment Canada uses this measure for environmental reporting in their national report titled "Environmental Signals" (K. Lindsay, pers. comm.).

To analyze landscape fragmentation, it is first necessary to identify which landscape elements are relevant to fragmentation. The specific choice of fragmenting elements defines a so-called "fragmentation geometry". We selected landscape elements shown to impede the movement of animal species, act as sources of emissions, or represent matrix, i.e., non-habitat (Forman et al. 2003; Trombulak & Frissell 2000). These included motorways, roads, railroads, areas of urban development, industrial zones, and agricultural fields. Large rivers and other water bodies also act as barriers to animal movement (Gerlach & Musolf 2000). Therefore, we included rivers and lakes in some fragmentation geometries.

The question of what is an appropriate way of accounting for mountain barriers (which include steep cliffs, rubble slopes, and glaciers) in the effective mesh size was first addressed in Switzerland by Jaeger et al. (in press-a). Holzgang et al. (2001), who in their study of wildlife corridors in Switzerland, considered large areas of rock impassable. This is particularly relevant for species that move along valleys where human activities are focussed. All areas above 2100 m were selected as high mountains (the treeline is between 1600 m and 2300 m in the Swiss Alps, Veit 2002), and this contour applied was applied as a fragmenting element in fragmentation geometries 2 and 3. Here, we present four different fragmentation geometries to allow for various interpretations of landscape fragmentation from different perspectives, and to illustrate the differences and implications of the various assumptions. The four fragmentation geometries were developed by combining highways, local roads, urbanized areas, agricultural lands, and natural fragmenting features (table 1).

The effective mesh size of these four fragmentation geometries is measured relative to different planning units, which may be at different spatial scales. The planning unit boundaries could be political boundaries or they could be based on ecological criteria such as ecoregions, dominant land cover, and watersheds. Planning units occur at a range of spatial scales, and are often hierarchically organized. For example, California Department of Transportation (Caltrans) districts are formulated along county boundaries, and contain from one to several counties. Thus, counties are nested within Caltrans districts, which are nested within the State of California. Similarly, watersheds are nested hierarchical entities with major watersheds containing multiple sub watersheds, which themselves nest watersheds at finer spatial scales, and so on. In California, six nested scales of watersheds have been identified (figure 2).

Methods

Effective Mesh Size Landscape Metric

The m_{eff} expresses the possibility that any two randomly chosen points in the region under observation may or may not be connected. The more barriers (e.g., roads, railroads, urban areas) erected in the landscape, the less chance that the two points will be connected. It can also be interpreted as the ability of two animals of the same species – placed randomly in a region – to find each other (figure 1). The encountering probability is converted into the size of an area called the effective mesh size. The more barriers in the landscape, the lower the probability that the two points will be connected, and the lower the effective mesh size. If a landscape is fragmented evenly into patches all of size m_{eff}, then the probability of being connected is the same as for the fragmentation pattern under investigation.

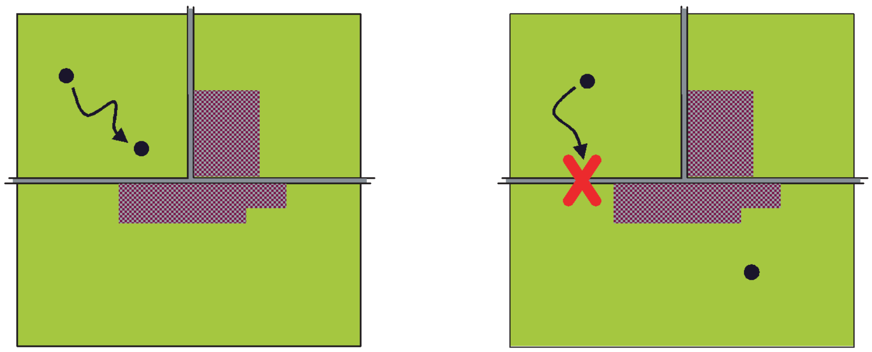

Figure 1. Two randomly chosen points are connected if and only if there are no barriers (e.g., roads, railroads, urban areas) between them (modified after Jaeger et al. *in press-b*).

One problem with this landscape metric, as pointed out by Moser et al. (2007), is that it assumes the unfragmented patches of land stop at the boundary of the planning unit (i.e. county, Caltrans district, or watershed), when in fact, the unfragmented area may extend far beyond the boundary of the planning unit. The effective mesh size described above uses the "CUT" procedure. An alternative implementation of the effective mesh size calculation to account for this is the effective mesh size based on the cross boundary connection (CBC) procedure, which accounts for the area of connected unfragmented areas that extend beyond the boundaries of a given planning unit that the effective mesh size is being calculated for.

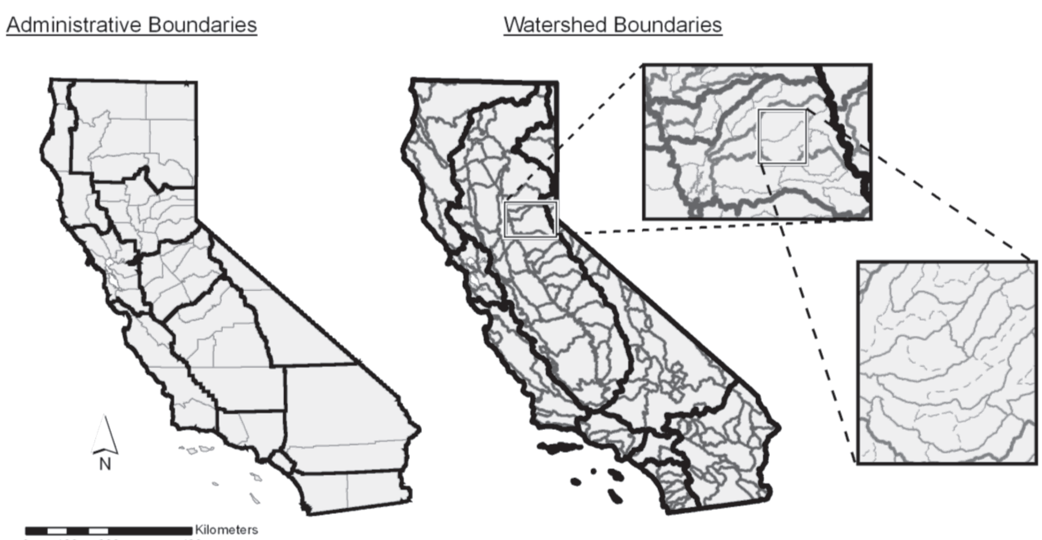

Figure 2. Administrative and watershed boundaries used as planning units to calculate effective mesh size for the State of California. Two spatial scales of administrative boundaries are shown on the left: counties (thin grey lines) nested within Caltrans districts (dark lines). Six spatial scales of watershed used in this analysis are shown on the right: hydrologic regions (thick black lines) and hydrologic units (thinner grey lines) zoomed-in to show hydrologic areas (medium thickness grey lines) and hydrologic sub-areas (thin grey lines), and zoomed-in finer to show super-planning watersheds (thin grey lines) and planning watersheds (dashed lines).

Automated Effective Mesh Size Calculation Tool

A geographic information systems (GIS) automated tool for calculating effective mesh size was developed for use in ArcGIS 9.1 (ESRI 2005). This tool calculates both the effective mesh size CUT procedure and the CBC procedure based on GIS maps of a given fragmentation geometry and planning unit boundaries. This tool was written as a visual basic 6.0 .dll using the ArcObjects programming library, and can be obtained from the authors upon request.

The tool calculates the effective mesh size by first calculating the area of each planning unit from the planning unit layer and the area of each unfragmented patch from the fragmentation geometry layer. These two layers are then intersected while retaining the information about the area of each original planning unit and unfragmented area.

The CUT effective mesh size calculation was then calculated for each planning unit *j* using the formula as follows (Jaeger 2000):

$$m_{\text{eff}}(j) = \frac{1}{A_{tj}} \sum_{i=1}^{n} A_{ij}^{2}$$

where *n* = the number of unfragmented patches in planning unit *j*, A_{ij} = size of patch *i* within planning unit *j*, and A_{tj} = the total area of planning unit *j*.

The CBC effective mesh size calculation was also calculated for each planning unit *j* using the following formula (Moser et al. 2007):

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

where *n* is the number of unfragmented patches intersecting patch *j*, A_{tj} is the area of planning unit *j*, A_{ij} is the area of unfragmented patch *i* inside of patch *j*, and A_i^{cmpl} is the complete area of unfragmented patch *i* including the area outside the boundaries of planning unit *j*.

Planning Units

The effective mesh size using only the CBC procedure was calculated for four fragmentation geometries (described below) for every Caltrans District (12 total), county (58 total), and five spatial scales of watersheds: river basin (RB, 9 total), hydrologic unit (HU, 189 total), hydrologic area (HA, 578 total), hydrologic sub-area (HSA, 1040 total), super-planning watersheds (SPWS, 2309 total), and planning watersheds (PWS, 6998 total).

Fragmentation Geometries

Four fragmentation geometries were created from the GIS database (Table 1). Fragmentation geometry 1 (FG 1) includes highways, major connector/arterial roads, railroads, and urban areas. Fragmentation geometry 2 (FG 2) includes all fragmenting elements in FG 1 plus all minor roads. Fragmentation geometry 3 (FG 3) included all elements from FG 2 plus agricultural areas. Fragmentation geometry 4 (FG 4) includes all elements from fragmentation geometry 3 plus natural fragmenting elements.

GIS Database

Transportation Infrastructure

A GIS database of base layers was assembled in order to create four different fragmentation geometries. A 1:100,000 scale GIS data set of all roads for the State of California for 2005 was obtained from the California Department of Transportation (Caltrans). This data set included attributes distinguishing between highways, major connector/artery roads, and minor local roads. For the fragmentation geometries, major highways were buffered by 10 meters (on either side), major roads were buffered by 5 meters, and minor roads were buffered by 3 meters. A 1:100,000 scale GIS dataset of railroads was obtained from the California Spatial Information Library (CASIL) and were buffered by 3 meters for the fragmentation geometries.

Land Use: Urban and Farmlands Data

A GIS layer of urbanized areas was created by combining two data sets. The first data set is the Department of Forestry Fire Resources and Assessment Program statewide GIS layer of Footprint of Development derived from 2000 Census (housing density) and USGS National Land Cover Data (land use) at 30 m resolution. Since there has been a substantial amount of urbanization that has occurred in California since 2002—especially due to agricultural and rangeland conversion to urban areas—this map was updated using the California Farmlands Mapping and Monitoring program GIS dataset from 2004, which identifies urbanized areas, but only for agricultural counties. These two datasets were intersected using ArcGIS 9.1 and any area identified in either of the datasets as being urbanized, was assumed to be urbanized for the fragmentation geometry.

Table 1: Summary of the fragmenting elements used to define each fragmentation geometry. Note that each higher level of fragmentation geometry builds on the previous fragmentation geometry by adding additional fragmenting elements, as signified by the bold fragmenting elements

Fragmentation Geometry	Fragmenting Elements Included
FG 1	**Highways, major roads, railroads, urbanized areas**
FG 2	**FG 1 and add minor roads**
FG 3	**FG 2 and add agricultural areas**
FG 4	**FG 3 and add lakes, major rivers, alpine areas above 3000 m**

Natural Fragmenting Features

Lakes and major rivers were identified from the National Hydrologic Dataset. All lakes and permanently flooded areas were included in the fragmentation geometries. Only major rivers were included in the fragmentation geometries. Areas greater than 3000 m elevation were identified using a 30 m digital elevation model including all areas above 3000 m, the approximate elevation at which treeline begins in California.

Focal Species

Large mammals are a primary concern to California transportation planners because of the dangers of animal vehicle encounters. We selected Mule Deer (*Odocoileus hemionus*) and Mountain Lion (*Puma concolor*) to illustrate how modeling the effective mesh size can inform planners about the extent to which landscape fragmentation may already be affecting wildlife. Range maps of each species were obtained from the California Wildlife Habitat Relationships Model (CWHR, CDF&G 2003). These range maps were spatially intersected with the effective mesh size maps calculated for planning watersheds based on fragmentation geometry 4. We used fragmentation geometry 4 because these species will react to fragmentation due to roads, rail, urbanized areas, agricultural areas, and natural fragmenting features. These maps were then analyzed based on thresholds for effective mesh size that relate to daily movement distances, home range sizes, and juvenile dispersal distances based on values estimated from the literature as described below.

A study of female mule deer with fawns in northern coastal California identified home ranges of on average 3 km^2, with a maximum of 5 km^2 (Taber & Dasmann 1957). Similar results were found in the central coast mountains of California. Eberhardt et al. (1984) reported juvenile movement distances were 14 km, and thus a squared area based on this estimates would be 14 km x 14 km = 196 km^2. Based on this information we selected a daily movement effective mesh size threshold of 5 km^2 and a dispersal movement threshold of 196 km^2.

Mountain lions have variable home range size and daily movement distances depending on the density of prey items, and are most abundant where prey densities are high. Home range for an adult male in California is often over 260 km^2 (Torres & Bleich 2000). A study in southern California identifies average nightly mountain lion movement to be 10 km (Beier et al. 1995). Squaring the nightly movement distance gives a 10 km x 10 km = 100 km^2 square area. Thus, effective mesh size thresholds for mountain lion used in this analysis were 100 km2 for daily movements, and 260 km^2 for home ranges.

Results

Fragmentation Geometries

Maps of the four fragmentation geometries show the spatial distribution of patch sizes bounded by fragmenting elements throughout the State of California (figure 3). Some similarities among the four maps can be seen. The spine of the Sierra Nevada, north coastal mountains and south eastern desert areas constantly have larger patch sizes, while the Los Angeles, San Francisco, and Sacramento metropolitan areas have consistently smaller patch sizes. However, many differences exist between these maps. The largest difference can be seen in the reduction in patch sizes throughout the State when adding minor roads to the fragmenting elements in fragmentation geometry 2. On the other hand, changes in patch size due to the addition of agricultural areas in Fragmentation Geometry 3 predominantly occur in the Central Valley region, where many of the agricultural areas in the State are located.

Effective Mesh Size for Administrative and Watershed Planning Units

The effective mesh size within the entire State of California for FG 1 is 2962 km^2 (figure 4). By adding minor roads to the fragmenting elements, Fragmentation geometry 2 results in m_{eff} decreasing to 1128 km^2. Adding agricultural areas to the fragmenting elements in fragmentation geometry 3 results in only a slight decrease in m_{eff} to 1116 km^2. This slight decrease is due to the fact that the agricultural areas are covered by a dense network of minor roads. Finally, with the addition of natural fragmenting elements, m_{eff} decreases to 789 km^2.

The effective mesh size was also calculated for each fragmentation geometry within each of the eight sets of planning units. The complete results for all these combinations are too massive to present completely, so summary statistics of the effective mesh sizes calculated are provided (table 2). The complete results may be obtained by contacting the authors.

Table 2 shows that by using finer and finer planning units the range of m_{eff} increases for all fragmentation geometries. For example, for FG 1, the range of m_{eff} for large river basins is 5,142 km^2, while the range for the much smaller planning watersheds is 20,885 km^2. This pattern holds true for all planning units and all fragmentation geometries.

Table 2: Planning unit area and effective mesh size summary statistics for the two nested administrative planning unit boundaries--Caltrans Districts and Counties--and six nested watershed planning unit boundaries--River Basins (RB), hydrologic units (HU), hydrologic areas (HA), hydrologic sub-areas (HSA), super planning watersheds (SPWS), and planning watersheds (PWS). For each of the boundaries the mean, standard deviation, median, minimum, and maximum planning unit area, and effective mesh size for the four fragmentation geometries (FG) are given. All values given in km^2. The m_{eff} for the entire State of California for FG 1 is 2962 km^2, for FG 2 is 1128 km^2, for FG 3 is 1116 km^2, and for FG 4 is 789 km^2. Note that some planning units have an area of zero because they are located at the edge of the State and have an area less than 0.5 km^2.

		Caltrans District	County	RB	HU	HA	HSA	SPWS	PWS
planning unit area	**mean**	34,022	7,054	45,459	2,165	709	395	177	58
	stdev	22,036	8,073	48,314	2,791	861	585	324	193
	median	28,541	4,017	29,715	1,129	422	193	109	32
	min	2,052	118	7,235	28	0	0	0	0
	max	72,240	52,061	46,525	18,219	8,282	7,871	6,692	6,692
FG 1	**mean**	2,237	1,714	1,782	2,615	2,176	1,845	2,649	3,423
	stdev	2,216	2,338	1,698	3,904	3,888	3,715	4,854	5,718
	median	1,604	920	1,619	1,143	673	502	830	1,256
	min	171	0	259	0	0	0	0	0
	max	6,620	12,092	1,606	18,436	20,885	20,885	20,885	20,885
FG 2	**mean**	869	689	660	909	715	607	1,028	1,478
	stdev	966	1,146	606	1,505	1,639	1,622	2,738	3,572
	median	470	242	394	354	153	103	143	181
	min	50	0	84	0	0	0	0	0
	max	2,829	5,064	571	10,447	14,891	14,891	14,900	14,900
FG 3	**mean**	857	676	649	895	703	597	1,019	1,471
	stdev	966	1,147	605	1,508	1,640	1,623	2,739	3,572
	median	455	221	376	332	133	94	134	173
	min	43	0	78	0	0	0	0	0
	max	2,813	5,058	569	10,445	14,889	14,889	14,898	14,898
FG 4	**mean**	610	466	521	716	554	452	666	890
	stdev	560	644	456	983	1,024	978	1,503	1,945
	median	420	175	366	258	117	74	112	147
	min	43	0	78	0	0	0	0	0
	max	1,722	2,615	425	4,821	7,883	9,097	10,137	10,175

Relating Effective Mesh Size to Focal Species Movement Needs

For mountain lion, 57% of its range in California has an effective mesh size that requires the animals to cross fragmenting elements on a daily basis or within their home ranges, leaving only 43% of the range with a large enough effective mesh size that they do not necessarily have to cross fragmenting elements within their home range (table 3). Fifteen percent of the mountain lion range is in the medium effective mesh size class, where individuals are less likely to encounter fragmenting elements with daily movements, although home ranges are very likely cross fragmenting elements. This leaves 42% of the mountain lion home range in the low effective mesh size class, where individuals would be expected to encounter fragmenting elements on a daily basis.

For mule deer, 44% of the range is has an effective mesh size larger than the threshold where deer would be expected to encounter fragmenting elements by dispersing juveniles or daily adult movements (table 3). Another 49% of its range is in the medium effective mesh size threshold category where deer would be expected to encounter fragmenting elements by juveniles, but adult daily movements would be less likely to encounter fragmenting elements. The remaining 7% of the range has an effective mesh size small enough that adult daily movements would likely encounter fragmenting elements.

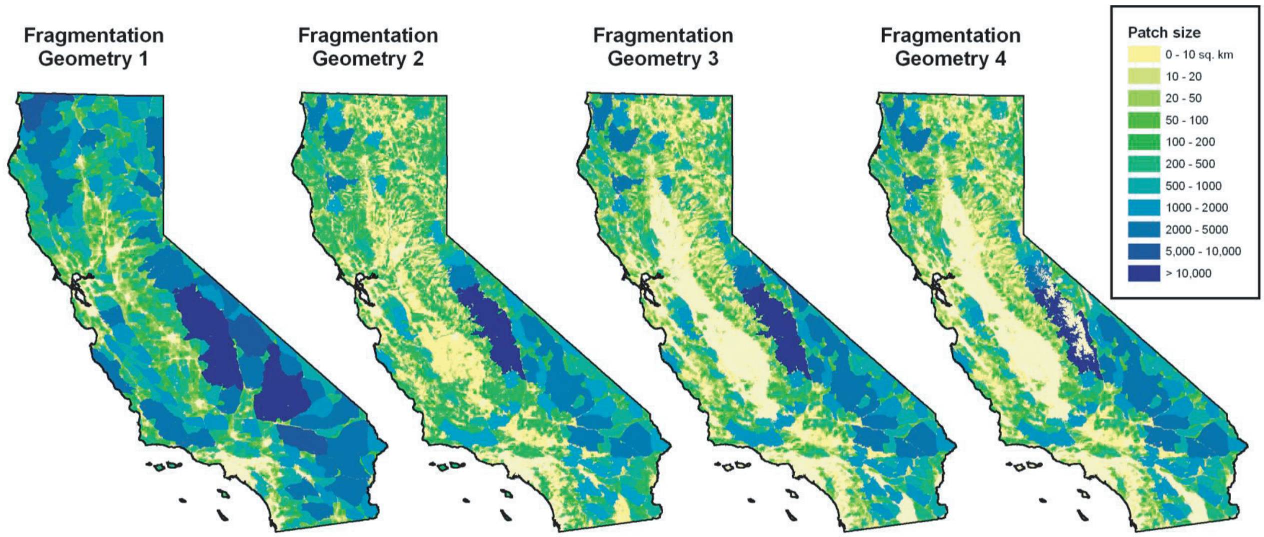

Figure 3. The four fragmentation geometries: (1) highways, major roads and urban areas; (2) highways, major roads, minor roads and urban; (3) highways, major roads, minor roads, urban and agriculture; (4) highways, major roads, minor roads, urban, agriculture, rivers, lakes and areas above 3000 m elevation (table 1). The categories show the sizes of the remaining patches.

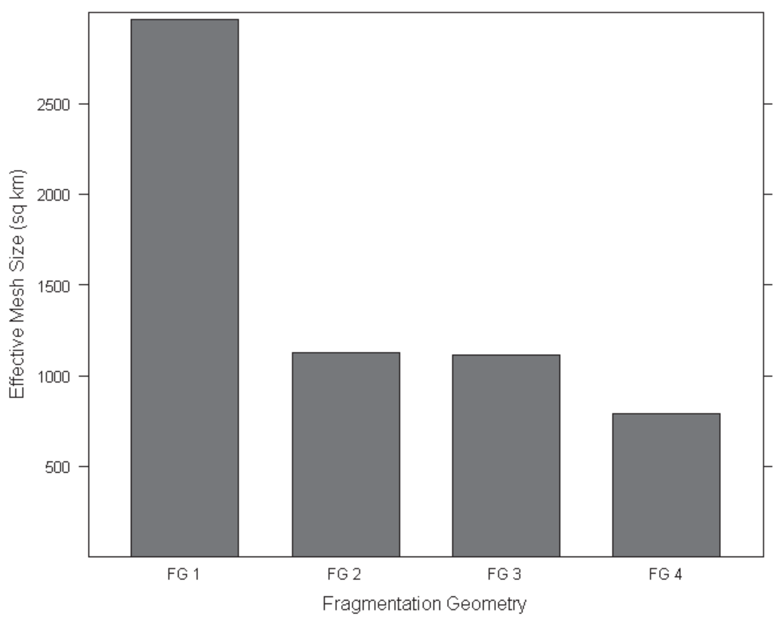

Figure 4. Effective mesh size within all of California for the four fragmentation geometries.

Discussion

Overview

Effective mesh size provides an easy to use and reliable method for quantifying landscape fragmentation useful for transportation planning. The metric produces a map of the spatial distribution of fragmentation, as well as quantitative data on the level of fragmentation present in different planning areas relevant to planners. Using effective mesh size as a landscape index permitted an assessment of the degree to which two species important to transportation planners are affected by roads in California. Such analytical techniques and tools are needed to improve the biological mitigation planning process.

The project took a multi-scale approach to assessing habitat fragmentation, which is important for both transportation planning and biological reasons. Different transportation planning efforts occur at different spatial scales. That is, a small road improvement project may only affect a fraction of a hectare of the landscape, but a major road project may affect tens to hundreds of hectares, while regional transportation planning efforts may affect thousands to millions of hectares. In addition, multi-scale analysis is important biologically because different animals respond to landscape characteristics at different spatial scales (Kotliar & Wiens 1990). A mountain lion will respond to habitat fragmentation at a much broader scale than will a small mammal. We recommend that tools developed for environmental assessment be flexible enough to allow for the analysis of potential impacts at a range of spatial scales (Thorne et al. 2007). The method described here allows for the flexibility to identify and analyze habitat fragmentation at scales that are relevant to a wide range of transportation planning efforts and animals that may be impacted.

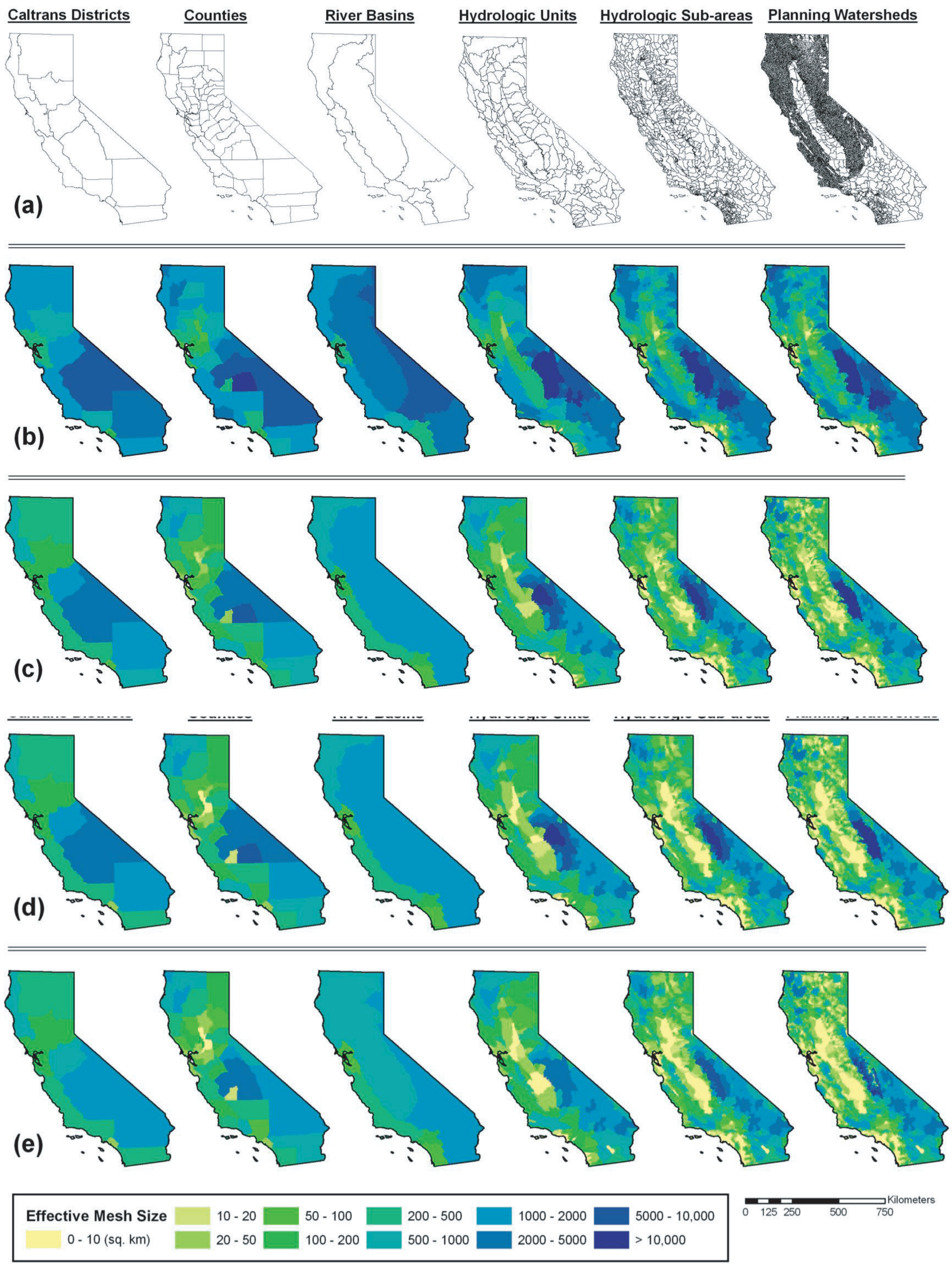

Figure 5. Effective mesh size within six different planning units for the four fragmentation geometries. (a) The two administrative planning units and four levels of watershed maps are shown and labeled across the top. The effective mesh size CBC metric is calculated for the different planning units (labeled across the top) based on: (b) Fragmentation Geometry 1, (c) Fragmentation Geometry 2, (d) Fragmentation Geometry 3, and (e) Fragmentation Geometry 4.

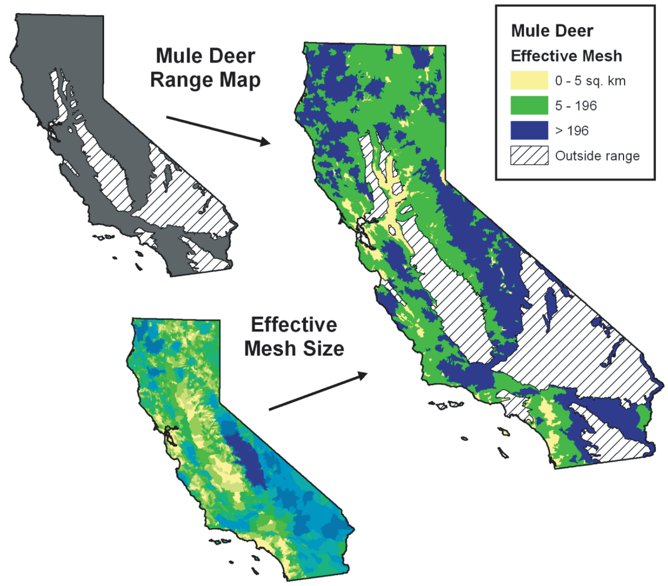

Figure 6. Mule deer range map overlaid with planning watershed level of effective mesh size (Fragmentation Geometry 4), show areas deer are more or less likely to encounter fragmenting elements (see also table 3).

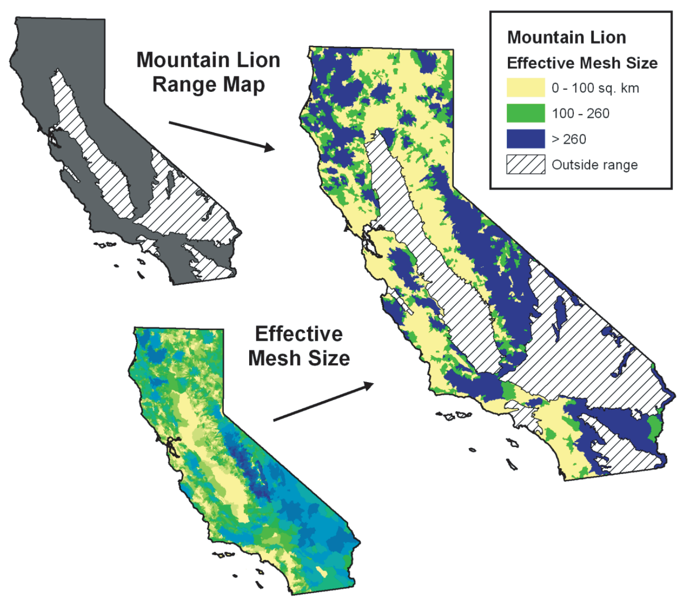

Figure 7. Mountain lion range map overlaid with planning watershed level of effective mesh size (Fragmentation Geometry 4), show areas mountain lion are more (0 - 100 km^2) or less likely (> 260 km^2) to encounter fragmenting elements (see also table 3).

Table 3: Effective mesh size suitability for mountain lion and mule deer ranges in the State of California. The area within and percent of the total range area for each of the suitability categories are given for each species. For mountain lion, high suitability has an effective mesh size greater than 260 km^2, medium is 100 – 260 km^2, and low is less than 100 km^2. For mule deer high suitability has an effective mesh size greater than 196 km^2, medium is 5 – 196 km^2, and low is less than 5 km^2. For these species high suitability relates to dispersal distances, medium relates to daily movement requirements, and low is generally unsuitable for the species.

Effective Mesh Size Suitability	Mountain Lion		Mule Deer	
	Area (sq km)	Percent	Area (sq km)	Percent
High	116,783	43%	123,708	44%
Medium	40,484	15%	139,244	49%
Low	115,940	42%	20,110	7%
Total	272,758		283,062	

Relating m_{eff} to Focal Species

Once landscape fragmentation has been quantified, any species for which there is a range map, and for which movement patterns can be obtained, can be assessed in similar fashion to the two presented here. The effective mesh size can be used to classify the landscape into regions where particular species are no longer able to move without encountering a fragmenting element. Depending on the species being studied, a different fragmentation geometry may be the most appropriate to use. In California, there are 294 terrestrial vertebrate species excluding birds, for which range maps are available (CDF&G 2003) and which can now be analyzed from the perspective of the landscape fragmentation indices, a future research goal of this group.

Animals exhibit different movement patterns, which can coarsely be classed into four categories: daily movement, home range, seasonal movement, and juvenile dispersal. We used this information to assess the "effective mesh size suitability" which relates m_{eff} to the movement patterns for a particular species (table 3). In this case the daily (nightly) movement of mountain lion in southern California had been measured using radio collars, and the home range size estimate came from a study of desert mountain lion (Beier et al. 1995), which was potentially a larger estimate of area needed, and therefore a more conservative one. By classing the effective mesh sizes calculated for nearly 7000 watersheds in California into those below the daily movement patterns, those above the home range, and those in between, we were able to determine the level of habitat degradation imparted to mountain lion by roads in California. The results showed that 42% of the entire range is now below the threshold for daily movement patterns for this animal. We would expect mountain lion populations in this part of their California range to be in decline due to the necessity of frequent road crossings (table 3).

Effective mesh size could be used to identify areas that are prone to wildlife/vehicle collisions. Areas with very high meff would be expected to exhibit no fragmentation effects on deer populations, and not be prone to wildlife/vehicle collisions. Areas within the deer range that have very low m_{eff} (< $5km^2$) are likely to have low deer populations because the level of fragmentation is so high, and may be less prone to collisions. However, the areas with moderate levels of fragmentation (5 – 225 km^2) are likely to support viable deer populations, but these population are more likely to encounter roads. Thus, it is the areas that are large enough for the daily movement, but smaller than the dispersal movement requirements where there will be the highest possibility for wildlife collisions, and of greatest concern to transportation planners.

Another set of biological questions arises around a species' response to roads. Some species may have stronger road avoidance behavior, or may be less sensitive than others to roads (Jaeger et al. 2005). Many roads have some drainage structures, which may permit some species to move while the surface level roads prevent others from using the same landscape. Now that methods for quantifying effective mesh size have been developed, many road ecology research questions can be revisited using this landscape fragmentation index.

Population viability as impacted by increasing fragmentation exhibits critical thresholds, below which populations are prone to a much higher risk of extinction (Jaeger & Holderegger 2005; With & King 1999). As a consequence, better policies, decision-making procedures, and planning tools are needed that are based on the precautionary principle and on prospective simulation models, e.g., quantitative environmental standards limiting the degree of landscape fragmentation and precautionary assessment criteria.

Once the thresholds are crossed and the populations are declining, in most cases it is in practical terms impossible to return to the situation before the thresholds were crossed. Even in cases when it is in principle possible to reverse the trend and return to the situation before the thresholds were crossed, this is typically very difficult and much more expensive to implement the measures necessary for a recovery than before the thresholds were crossed.

Implications of m_{eff} for Transportation Planners

The results illustrate the utility of the effective mesh size metric, and raise questions about how to incorporate estimates of habitat degradation into transportation planning. This type of analysis can potentially be useful to identify contiguous suitable habitats split by roads which could become candidate locations for crossing structures. The data presented here represent an important step forward in analyzing and interpreting the current situation in California and other states, especially for comparative analyses of similar types of ecoregions. The results of this research are being provided to Caltrans for incorporation into a statewide database being developed to identify potential biological impacts due to planned future transportation projects (Thorne et al. 2007). This would then provide another metric for assessing the impact of these future transportation projects on habitat fragmentation and connectivity.

The long-term goal is to create comparative data for the whole of North America. These would serve as a basis for drawing up agreements about environmental standards such as limits, norms, and targets, and for creating measures towards limiting landscape fragmentation (Jaeger 2001; Penn-Bressel 2005; SRU 1994; UBA 2003). For this purpose, it is useful to establish time series for making comparisons with previous conditions, including comparisons with/without increase in traffic volume, and to identify changes in trends. The method used here is well suited for this purpose.

Incorporation of environmental indicators into environmental impact reports is potentially a major application for the type of data we report. A noteworthy example is the report on "The State of the Nation's Ecosystems – Measuring the

Lands, Waters, and Living Resources of the United States" which aims at using seven indicators of fragmentation and landscape pattern but suffers from the lack of data on these indicators (Center 2002; O'Malley et al. 2003), which could be partially addressed using m_{eff}. Assessing landscape fragmentation through time using meff is another application, and has already been implemented in the state of the environment report by the State Institute for Environmental Protection Baden-Württemberg (Ministerium für Umwelt und Verkehr Baden-Württemberg & Landesanstalt für Umweltschutz Baden-Württemberg, 2003) and in the report on the status of sustainable development in Baden-Württemberg (Renn et al. 2000), providing examples of how to measure and interpret time series of landscape fragmentation.

Conclusions

Analyses of correlations between the degree of fragmentation and the presence of species can provide valuable information on the effects of transportation infrastructure. In the future, relationships with the absence or decreasing tendencies of species, especially listed species, may indicate to what degree the amount and loss of unfragmented areas reflect the situation of a species. Further refinements of the effective mesh size method should include the potential of mitigating fragmentation effects by crossing structures (Forman et al. 2003; Jaeger 2007; van der Grift 2005).

It has been called a cruel irony in road ecology that "the more important the question, the more uncertainty is associated with the answers that road science will be able to provide" (Roedenbeck et al. 2007). That is, while there is a large body of experience on how to study the project level effects, the effects on the larger scales are much more difficult to analyze and assess. The methods and results presented in this report provide a tool that is convenient to use for an assessment of the effects of road network on landscape fragmentation and connectivity on the regional and state scale, which can be applied in different places.

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