How far to the nearest road?

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Ecological impacts from roads may be the rule rather than the exception in most of the conterminous United States. We measured the proportion of land area that was located within nine distances from the nearest road of any type, and mapped the results for 164 ecoregions and 2108 watersheds nationwide. Overall, 20% of the total land area was within 127 m of a road, and the proportion increased rapidly with distance, so that 83% was within 1061 m of a road, and only 3% was more than 5176 m away. For forest land area only, the proportions differed by less than 2% for all distances. Regions with more than 60% of their total land area within 382 m of a road may be at greatest risk of cumulative ecological impacts from roads. These regions include nearly all coastal zones, as well as substantial portions of the southeast US and the basins of the Ohio, Brazos, Colorado, Sacramento, and San Joaquin Rivers.

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The United States is spanned by an extensive road network that has substantial ecological impacts on the surrounding lands. As of 2001, the conterminous US contained approximately 6.3 million km of public roads of all types, of which 1.6 million km were classified as non-local roads in rural areas (USDT 2002). In comparison, the US Environmental Protection Agency estimated that the same area contained approximately 5.3 million km of streams and rivers (USEPA 2002). Thus, roads approximate streams in terms of their systemic presence in ecosystems.

Recent reviews of the ecological impacts of roads on terrestrial and aquatic systems are provided by Forman and Alexander (1998), Spellerberg (1998), Trombulak and Frissell (2000), and Forman *et al.* (2002). Influence zones extend tens to hundreds of meters from roads, disrupting wildlife movements, modifying habitats, altering water drainage patterns, introducing exotic species, modifying microclimates and the chemical environment, and increasing noise levels. Roads are also precursors to future impacts, because they facilitate land development and the further expansion of the road network itself.

The road network is a novel and pervasive spatial pattern in ecosystems. Whereas ecological processes follow natural constraints, roads follow economic ones. The resulting network is designed to connect places efficiently, in human terms, and because these routes often cross natural boundaries, they create new patterns of communication and movement within ecosystems. The network is also designed to minimize the distance to a road, and this means that road edges and associated influence zones tend to pervade the areas served by roads.

Attention has recently shifted from site-specific road impacts to broader scale impacts on regions (NRC 1997), but there is not much information about roads in relation to ecosystems at that scale. Regional ecological assessments sometimes consider roads (Wickham *et al.* 1999, 2002; Heilman *et al.* 2002), but there are still only approximate national estimates of land area that is affected ecologically by roads. Using total highway length statistics for 1985 and assumptions concerning road density, spatial distribution of roads, traffic volumes, widths of road influence zones, and other factors, Forman and Alexander (1998) and Forman (2000) estimated that 15–22% of the total land area of the coterminous US was ecologically affected by roads.

Here we report map-based measurements of the land area that are close enough to roads to possibly experience an ecological effect. We defined a location as potentially influenced if it was within a specified distance of the nearest road, ignoring differences in types of road, numbers of roads, traffic volumes, topography, and other factors. Recognizing that the effective width of a road influence zone also depends on the specific ecological process involved, we repeated the measurements for nine distances up to 5176 m. We summarized the statistics by watershed and ecoregion to illustrate geographic variation, and made separate estimates for total land area and forest land area, because roads are a key component of the forest fragmentation debate in the US.

Methods

We used four maps of the conterminous US for this analysis. The base map we used for area calculations and identifying forest land was the 1992 NLCD national land-cover map (Vogelmann *et al.* 2001) derived from satellite imagery with a spatial resolution of 0.09 ha per pixel (30 m). Total area calculations were based on all 21 NLCD land-cover types, and the forest land area calculations combined four NLCD forest land-cover types – deciduous forest, evergreen forest, mixed forest, and woody wetland. The national road map (GDT 2002) was a 1995 modification of the Bureau of the Census TIGER/Line files that

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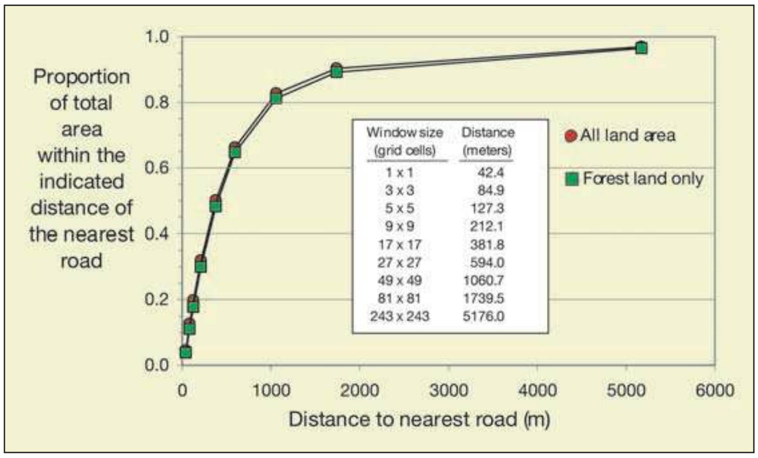

Figure 1. *The proportion of total area located within a certain distance from the nearest road increases rapidly with distance. These statistics for the conterminous US were compiled by evaluating road proximity to approximately 8.6 billion locations. Inset: window sizes and corresponding distances used in the analysis.*

identified public roads ranging from interstate highways to four-wheel drive vehicular trails. We used national maps of 2108 watersheds (USGS 1999) and 164 ecoregions (Bailey 1995) to summarize the measurements that were made on the road and land-cover maps.

The road map was converted to a grid format with 0.09 ha per pixel spatial resolution; a given 30-m grid cell was considered a "road" cell if it contained at least one road segment of any class. We converted the gridded road map to a set of nine road proximity maps by placing square windows around each grid cell. Nine window sizes from 1 x 1 to 243 x 243 cells were used. For each window size, a cell value on a road proximity map recorded whether the window of the given size contained at least one "road" cell. The nine road proximity maps were then combined into a single road distance grid, in which each cell recorded the smallest window size that contained a road. It is a road-distance grid because the size of the smallest window that contains a road defines the maximum distance the grid cell can be from the nearest road. We conservatively measured the distance from the outside corner of a grid cell in the corner of a window to the opposite corner of the grid cell in the center of the window. (A less conservative measurement between the centers of the two cells would be 42.4 m less for all window sizes.) Data summaries were prepared by overlaying the road-distance grid with the land-cover, watershed, and ecoregion maps and tabulating the road distances by land-cover type, watershed, or ecoregion. A total of ~8.6 x 10^9 grid cells, including ~2.8 x 10^9 forest land cells, were used in the analysis.

Results

Approximately 4.5% of the grid cells contained at least one road, and the proportion of total land area that was

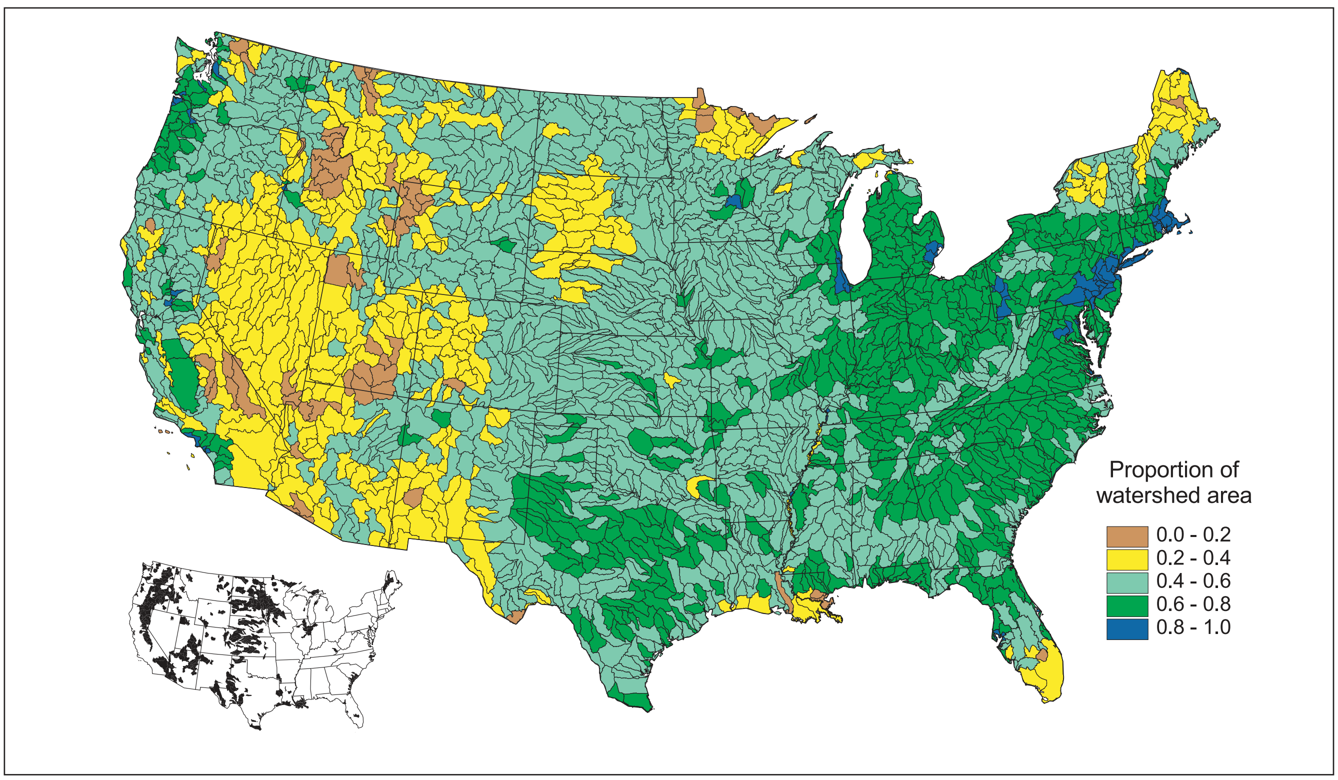

Figure 2. *The proportion of total area in a watershed that is within 382 m of the nearest road exhibits substantial geographic variation. Inset: Watersheds where roads are closer to forest land, in comparison to all land-cover types. States are shown for geographic reference.*

within a defined distance from the nearest road increased rapidly with distance (Figure 1). Twenty percent of all land area was located within 127 m of the nearest road, and 50% was within 382 m. Only ~18% of all land area was more than 1000 m from a road, and ~3% was more than 5000 m away. Overall, forest land was slightly more remote from roads than other land-cover types, but the trend line was similar and the area differences were less than 2% for all distances (Figure 1).

Figure 2 illustrates the geography of the area-distance relationship using watersheds to show the local proportion of all land within 382 m of a road. Similar geographic patterns were obtained for other distances. The inset map identifies watersheds in which roads are closer to forest land than to other land-cover types. In many Western and Great Plains watersheds, roads are closer to forest land, because trees and roads often follow rivers, while upland areas have less forest. Forest land is also closer to roads in watersheds that contain a high proportion of area covered by water (eg Minnesota's Lake of the Woods, Florida's Lake Ocheechobee, and Louisiana's Lake Pontchartrain).

More than 60% of the total land area of 32 of the 164 ecoregion sections is within 382 m of a road (Figure 3). This includes most of the ecoregion sections comprising the Eastern Broadleaf Forest and Southeastern Mixed Forest provinces (Bailey 1995). Also included are ecoregion sections in the Cascade Mixed Forest–Coniferous Forest–Alpine Meadow province, the Southwest Plateau and Plains Dry Steppe and Shrub province, the Pacific Lowland–Mixed Forest province, the California Coastal Chaparral Forest and Shrub province, and the Outer Coastal Plain Mixed Forest province. Only 5 of 164 ecoregion sections have less than 20% of their total land area within 382 m of a road.

Discussion

Imagine that the conterminous US has been subdivided into 8.6 billion parcels the size of a baseball diamond infield, and then consider standing on home plate in each one. According to our data model, in one out of 22 cases you will find a road no farther away than second base (~43 m). In one out of every five cases, the road is no further away than the center-field fence in Yankee Stadium (~125 m). This alone is a compelling reason to consider the possible systemic impacts of roads on ecosystems.

Forman's (2000) estimate of 22% of total land area affected ecologically by roads assumed effect distances of 100 m near secondary roads, 305–365 m near primary roads, and 810 m near some roads in urban areas. By comparison, our analysis shows that 16% of total land area is within 100 m of a road of any type, 22% is within 150 m, and 73% is within 810 m (Figure 1). These results generally support Forman's (2000) suggestion that 22% is a minimum estimate of land area affected by roads. Apart from the ecological effects, few places are likely to be immune from all road-mediated human influences. Humans can drive to within a kilometer of 82% of all land in the con-

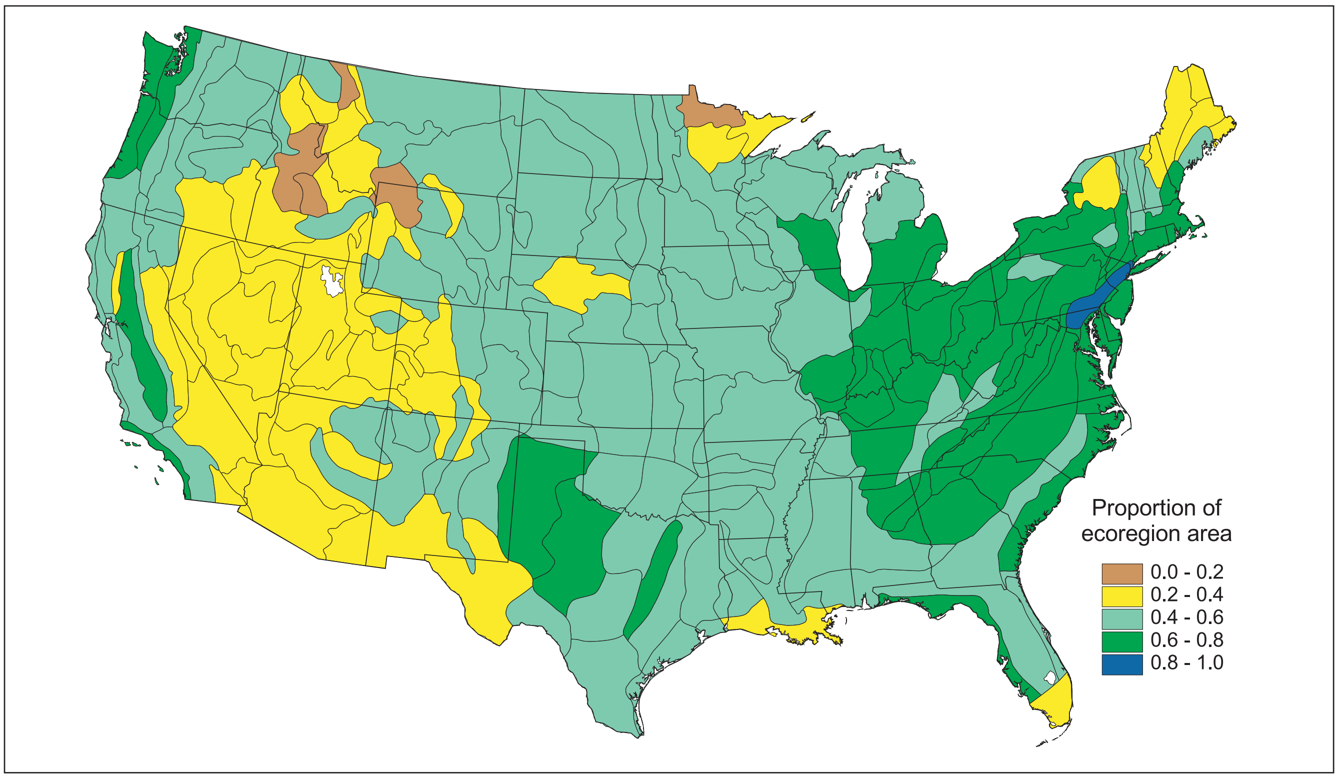

Figure 3. *The proportion of total area in an ecoregion section that is within 382 m of the nearest road varies nationwide from less than 20% to more than 80%. Ecoregion provinces mentioned in the text are aggregations of several ecoregion sections (Bailey 1995) and are not shown here. States are shown for geographic reference.*

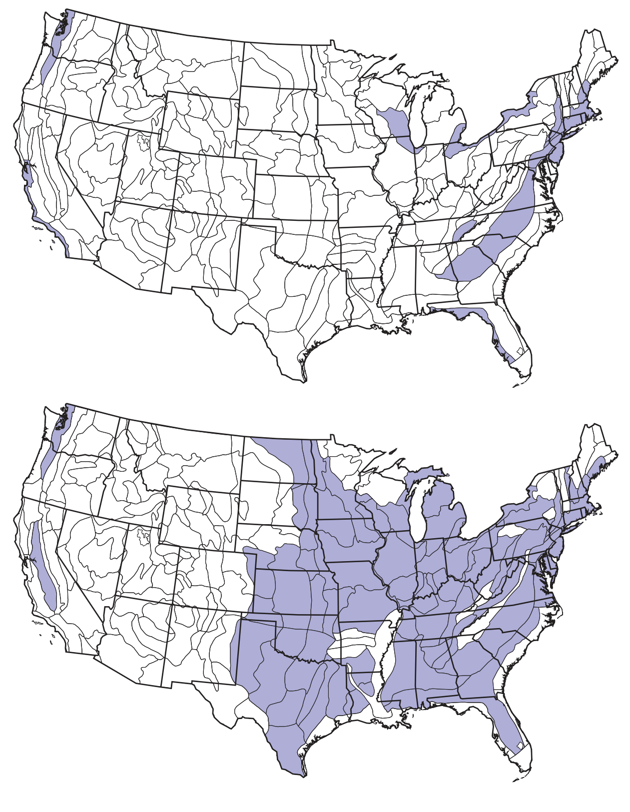

Figure 4. *(top) Ecoregion sections with more than 20% of their total area within 85 m of the nearest road. (bottom) Ecoregion sections with more than 90% of their total area within 1061 m of the nearest road. States are shown for geographic reference.*

terminous US (Figure 1), and to within 382 m of 40% of total land area in the majority of watersheds (Figure 2).

The steep slope of the area–distance curve in Figure 1 means that a better quantification of actual road effect distance is an important research goal. Forman (2000) cites actual effect distances up to 810 m, and our estimates of land area that may be ecologically affected ranged from less than 5% to more than 70% as the distance increased to 800 m (Figure 1). Fixed-width influence zones are less realistic than asymmetric and convoluted zones, and actual effects depend on the local context and the ecological processes involved (USFS 1999; Forman and Deblinger 2000). A given ecological process may be more or less affected by roads depending on location, even within the same ecoregion section (compare Figure 2 and Figure 3).

In comparison to the eastern regions of the US, western parts of the country have smaller proportions of land area close to roads, but the typical western watershed still has more than 20% of its total land area within 382 m of a road, and many have more than 40% (Figure 2). Nationwide, many of the watersheds with the highest proportions of road proximity are coincident with major urban areas, but some watersheds with high proportions do not contain major urban areas, such as western Texas and the Pacific Northwest coast. In contrast, the south Florida and Mississippi Delta regions contain large human populations, but have roads concentrated on dry land over small portions of their watersheds. Large geographic concentrations of watersheds with more than 60% of their land area within 382 m of a road are located in coastal regions in the Northeast, the lower Great Lakes, and the Pacific Northwest and Southwest; on the southeast Piedmont and coastal plain; and in parts of the basins of the Ohio, Brazos, Colorado, San Joaquin, and Sacramento Rivers (Figure 2).

Spatially explicit measurements of road proximity are needed to predict where ecological effects are likely to occur. We can speculate that the cumulative impacts of relatively short-range (<100 m) effects are most probably manifested in ecoregion sections with a relatively high proportion of their total area within 85 m of a road (Figure 4, top). By the same rationale, with some exceptions, the cumulative impacts of relatively long-range (>1000 m) effects are more likely to be found in eastern ecoregion sections than in western ecoregion sections (Figure 4, bottom).

Forest fragmentation by roads is an important and contentious issue. Using the same land-cover map that was used here, Riitters *et al.* (2002) estimated that 43.5% of all forest land was located within 90 m of a forest edge, excluding edges with roads and the water, ice/snow, and bare rock/sand/clay/talus land-cover types. Also, using the same map, Heilman *et al.* (2002) looked at fragmentation by all land-cover types as well as by roads, and estimated that 65.7% of the forest land within large forested regions was within 90 m of a road or a forest edge. In comparison, we found that 11.1% of all forest land was located within 85 m of a road (Figure 1), suggesting that most of the overall fragmentation measured in previous studies was the result of the juxtaposition of forest and non-forest land-cover types. However, the relative contribution of roads to fragmentation is much higher in mostly forested regions with high road density, such as the Pacific Northwest coast and the Appalachian Mountains.

Our estimates of potentially influenced regions are based on physical proximity only. The estimates would be larger if effect distance were compounded by traffic volume, cumulative road density, or land use along roads, or if private roads, transmission lines, railroads, and other linear features were included in the analysis. The estimates would also be larger if we had used the less conservative measurement protocol. Furthermore, ecologically important characteristics such as habitat patch size and distance between patches are not reflected in our measurements. For these reasons, our results represent minimum estimates of land area that may be ecologically affected by roads.

In summary, a remarkably high proportion of the conterminous US is located within a short distance of the nearest road. Ecological impacts from roads may be the rule rather than the exception in many regions, and few places are likely to be immune from all road-mediated impacts. When combined with evidence of actual road impacts on ecosystems, the sheer pervasiveness of roads should encourage ecologists to include them in their thinking about ecological processes and ecosystem sustainability.

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