
Contribution of Roads to Forest Fragmentation in the Rocky Mountains

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Abstract: *The contribution of roads to forest fragmentation has not been adequately analyzed. We quantified fragmentation due to roads in a 30,213-ha section of the Medicine Bow-Routt National Forest in southeastern Wyoming with several indices of landscape structure using a geographic information system. The number of patches, mean patch area, mean interior area, mean area of edge influence, mean patch perimeter, total perimeter, and mean patch shape identified patch- and edge-related landscape changes. Shannon-Wiener diversity, dominance, contagion, contrast, and angular second moment indicated effects on landscape diversity and texture. Roads added to forest fragmentation more than clearcuts by dissecting large patches into smaller pieces and by converting forest interior habitat into edge habitat. Edge habitat created by roads was 1.54–1.98 times the edge habitat created by clearcuts. The total landscape area affected by clearcuts and roads was 2.5–3.5 times the actual area occupied by these disturbances. Fragmentation due to roads could be minimized if road construction is minimized or rerouted so that its fragmentation effects are reduced. Geographic information system technology can be used to quantify the potential fragmentation effects of individual roads and the cumulative effects of a road network on landscape structure.*

La Contribución de los Caminos a la Fragmentación de Bosques en las Montañas Rocallosas

Resumen: *La contribución de los caminos en la fragmentación de bosques no ha sido analizada adecuadamente. Cuantificamos la fragmentación debida a caminos en una sección de 30,213-ha del Bosque Nacional, Medicine Bow-Routt en el suroeste de Wyoming con diversos índices de estructura del paisaje mediante el uso de Sistemas de Información Geográfica. El número de parches, el área media del parche, la media interior del área, el área promedio del límite de influencia, el perímetro promedio del parche, el perímetro total y la forma promedio de parche identificaron los cambios de parches y los cambios relacionados con los límites del paisaje. La diversidad de Shannon-Wiener, dominancia, contagio, contraste y segundo momento angular indican los efectos en la diversidad y textura del paisaje. Los caminos contribuyeron más a la fragmentación del bosque más de lo hicieron los cortes totales, al disectar parches grandes en pequeñas piezas y al convertir el hábitat interior del bosque en un hábitat borde. El hábitat borde creado por los caminos fue 1.54–1.98 veces el hábitat borde creado por los cortes totales. El área total del paisaje afectada por cortes y caminos fue 2.5–3.5 veces el área ocupada por las perturbaciones mismas. La fragmentación debida a caminos podría ser minimizada si la construcción de caminos se minimiza, o es reorientada de tal forma que sus efectos de fragmentación sean reducidos. La tecnología de los Sistemas de Información Geográfica puede ser usada para cuantificar los efectos potenciales de fragmentación por caminos individuales y los efectos acumulativos de una red de caminos en la estructura del paisaje.*

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Introduction

Increasingly, previously extensive, continuous tracts of forest are being reduced to widely dispersed patches of remnant forest vegetation by logging and road building, but few measures of the effects of roads on forest fragmentation are available. We define fragmentation as a change in landscape structure that typically, but not universally, includes smaller patch sizes, smaller patch perimeter lengths, greater distances between patches, more edge habitat, and less interior habitat (habitat not affected by human-created boundaries). Fragmentation affects animal populations in a variety of ways, including decreased species diversity and lower densities of some animal species in the resulting smaller patches (Arnold et al. 1995; McIntyre 1995).

Roads precipitate fragmentation by dissecting previously large patches into smaller ones, and in so doing they create edge habitat in patches along both sides of the road, potentially at the expense of interior habitat. As the density of roads in landscapes increases, these effects also increase, although road density could conceivably increase without increasing the number of patches and amount of edge habitat, which renders studies based solely on road density (Miller 1994) insufficient. McGurk and Fong (1995) considered the additive effects of clearcuts and roads, but did not measure the amount of associated edge habitat. Thus, a more direct measurement of the impacts of roads on landscapes is needed.

The pre-EuroAmerican landscape in our study area on the Medicine Bow-Routt National Forest (MRNF) in southeastern Wyoming was composed of naturally large patches (Baker 1994). Roads and clearcuts have decreased the size of these patches. We previously documented the severe degree of fragmentation due to clearcutting and its progression from 1950 to 1993 (Reed et al., in press). Subsequent to our initial findings, we became interested in the added effects of roads on the pattern of fragmentation. Here we present a portion of the original findings as reference points, but readers should refer to the earlier work.

The objectives of this study were to (1) determine the area and proportion of the landscape occupied by roads; (2) determine the importance of roads in delineating and quantifying landscape structure, including the proportion of the landscape occupied by edge habitat; and (3) compare the effects of roads and clearcut logging on forest fragmentation.

Methods

Study Area

The study area is located in the Hayden District of the MRNF in Wyoming (lat 41°N, long 106.5°W). It occupies

the Dudley Creek and Blackhall Mountain (7.5', 1:24000 scale, U.S. Geological Survey topographic maps) and is 22.9 km east to west by 15.4 km north to south and 30,213 ha in area (federally owned lands only), representing 15% of the MRNF in Wyoming. Elevation ranges from 2255 to 3346 m. The area is 87% forested, with scattered grasslands and shrublands at lower elevations. Dominant trees include Engelmann spruce (*Picea engelmannii*), subalpine fir (*Abies lasiocarpa*), lodgepole pine (*Pinus contorta*), and aspen (*Populus tremuloides*). The area has been logged since the mid-1800s and has been tie-hacked for railroad ties (Thybony et al. 1985). Cutting patterns in this area from 1950 through 1990 are representative of cutting patterns throughout the forest (Reed et al., in press).

The study area is not atypical of the MRNF, but it is actually less affected by timber harvesting than much of the forest, based on a comparison of landscape structure and fragmentation in 67 watersheds on the Wyoming part of the forest (Baker 1994). Of these 67 watersheds 24 have a greater percentage of watershed area in clearcuts, with the maximum being 32%. Most of the 67 watersheds have a greater percentage of land area considered suitable for logging because our study area contains land designated as wilderness, which is rare in the rest of the forest.

Data Sets

Data sets other than roads were derived from the Resource Information System (RIS) database (U.S. Forest Service 1989). These digital vector maps contain polygons representing homogeneous vegetation stands identified on aerial photographs and partially by ground-truthing. Attributes for each polygon include estimated year of origin, cover type, and forest structure, which is defined by the girth size and percent crown cover of canopy trees (U.S. Forest Service 1993). All maps were converted to raster format and manipulated using the GRASS 4.1 geographical information system (GIS) (USACERL 1993) on a Sun workstation. Each of the maps was 2290 columns by 1544 rows with a 10-m pixel resolution.

The year-origin map consists of numerous stands across the study area classified by the estimated year of their origin (ranging from 1702 to 1992). Stands classified on this map exclude the Encampment River Wilderness (J. von Ahlefeldt, personal communication). Stands predating 1950 had little information on cause of origin; after 1950, all patches originated from clearcut logging.

Twelve cover-type categories included nine vegetation categories: Engelmann spruce/subalpine fir forest, lodgepole pine forest, aspen forest, shrublands (sagebrush [*Artemisia* spp.] and unclassified upland shrubs), willows (*Salix* spp.), tufted hairgrass (*Deschampsia caespitosa*), rushes (*Juncus* spp.) and sedges (*Carex* spp.), bluegrass (*Agropyron* spp.), and unclassified grassland.

Other categories included a reservoir, rocklands, and non-forested land, which together covered 597 ha.

Seven structural categories included "nonstocked," 0-10% crown cover of trees of any diameter at breast height; "seedlings and saplings"; "seed-poletimber 1," DBH's of 3.81-22.86 cm and 11-40% crown cover; "seed-poletimber 2," 3.8 cm < DBH < 22.86 trees with 41-100% crown cover; "sawtimber 1," trees >22.86 DBH, 11-40% crown cover; "sawtimber 2," trees >22.86 DBH, 41-100% crown cover; and "old growth forest." Old-growth forest was defined by Raphael et al. (1992) using an old-growth scorecard based on multiple criteria, including the species diversity of the tree canopy, canopy cover, diameter of canopy trees, and the abundance of snags and downed logs.

Vector road maps were provided by U.S. Fish and Wildlife Service, digitized from 1:24000 scale U.S. Geological Survey topographic maps. Road locations were field-checked using a global positioning system (J. Varner, personal communication). Because the master RIS database did not have sufficient documentation of roads, we needed to take these extra measures. Roads were assigned a width of 10 m after conversion to raster format. We recognize that not all roads constructed by the U.S. Forest Service are the same size: national forest roads vary from narrow jeep tracks to large paved roads with significant cleared rights-of-way. It follows that road edges are probably not the same in magnitude and effect. Information identifying the specific types of roads present in the study area and their locations across the landscape was lacking, however, so all roads and areas of road edge influence had to be treated the same for analysis purposes.

The year origin, cover type, and forest structure maps were combined to create 1950 and 1993 "vegetation/forest structure" maps. The maps were constructed by combining the cover type map, the forest structure map, and the 1950-1993 polygons from the year origin map. The 1950 map portrays the status of the landscape as it was in 1950. The 1950-1993 dates were chosen because of the lack of information on stand origin prior to 1950 and the onset of widespread clearcut logging about 1950. Patches created between 1950 and 1993 were assigned to the nonstocked forest structure category.

The importance of roads in delineating and quantifying landscape structure was examined by overlaying the road map on the vegetation/forest structure maps. Roads cut existing patches into pieces; one patch intersected by a road becomes two or more patches. The effect of roads on edge habitat was examined by placing 50- and 100-m depth-of-edge influences along the roads on each combined map. Introducing a depth-of-edge influence into a patch bordered by a road separates the patch into two sections, an area of edge influence and an interior area. These edge depths were chosen because Vaillancourt (1995) found that edge effects were

evident approximately 50 m or more into the surrounding forest habitat in this area. In addition, Chen et al. (1992) showed that edge effects in conifer forests in the Pacific Northwest were evident up to 137 m into the surrounding old-growth Douglas fir forests.

Analyses

Landscape structure measurements fell into four categories: (1) density-related indices (number of patches, mean patch area [including interior area, area-of-edge influence, and edge:interior ratio]), (2) edge-related indices (mean patch perimeter and total perimeter), (3) shape-related indices (mean patch shape), and (4) diversity-related indices (Shannon-Wiener diversity index, dominance, contrast, contagion, and angular second moment).

We analyzed landscape structure using the r.l.e programs (Baker & Cai 1992). Structure was quantified using measures and indices detailed above. The interior area of a patch is the area that remains after removing the area of edge influence, which is defined by buffering the patch with a depth-of-edge influence distance inward from the patch boundary. The mean patch perimeter is the mean, for all patches, of the distance around the border of each patch, whereas total perimeter sums this distance across all the patches. Generally, as the number of patches increases and mean patch area decreases, mean patch perimeter declines and total perimeter rises.

Mean patch shape is the mean, for all patches, of the corrected perimeter/area index (Baker & Cai 1992). Lower shape-index values indicate patches with rounder, more simply shaped boundaries, whereas higher values indicate more complex patch boundaries. Shannon-Wiener diversity and dominance are related measures of combined richness and evenness of patch types in the landscape. Because patch richness is essentially constant in these analyses, both increases in diversity and decreases in dominance indicate greater evenness of patch types across the landscape. Contagion, contrast, and angular second moment are measures of texture obtained by tallying the co-occurrence of patch types within 3×3 -pixel windows moved across the landscape. Lower contagion values indicate greater landscape heterogeneity and less clumpiness, whereas greater contrast results from greater local variation in the landscape.

Results

Constraints on Logging

The 30,213-ha study area contains 9713 ha (32% of the study area) that cannot be logged because of legal constraints that prevent cutting within 100 feet (30.5 m) of stream boundaries, on slopes with grades greater than 10%,

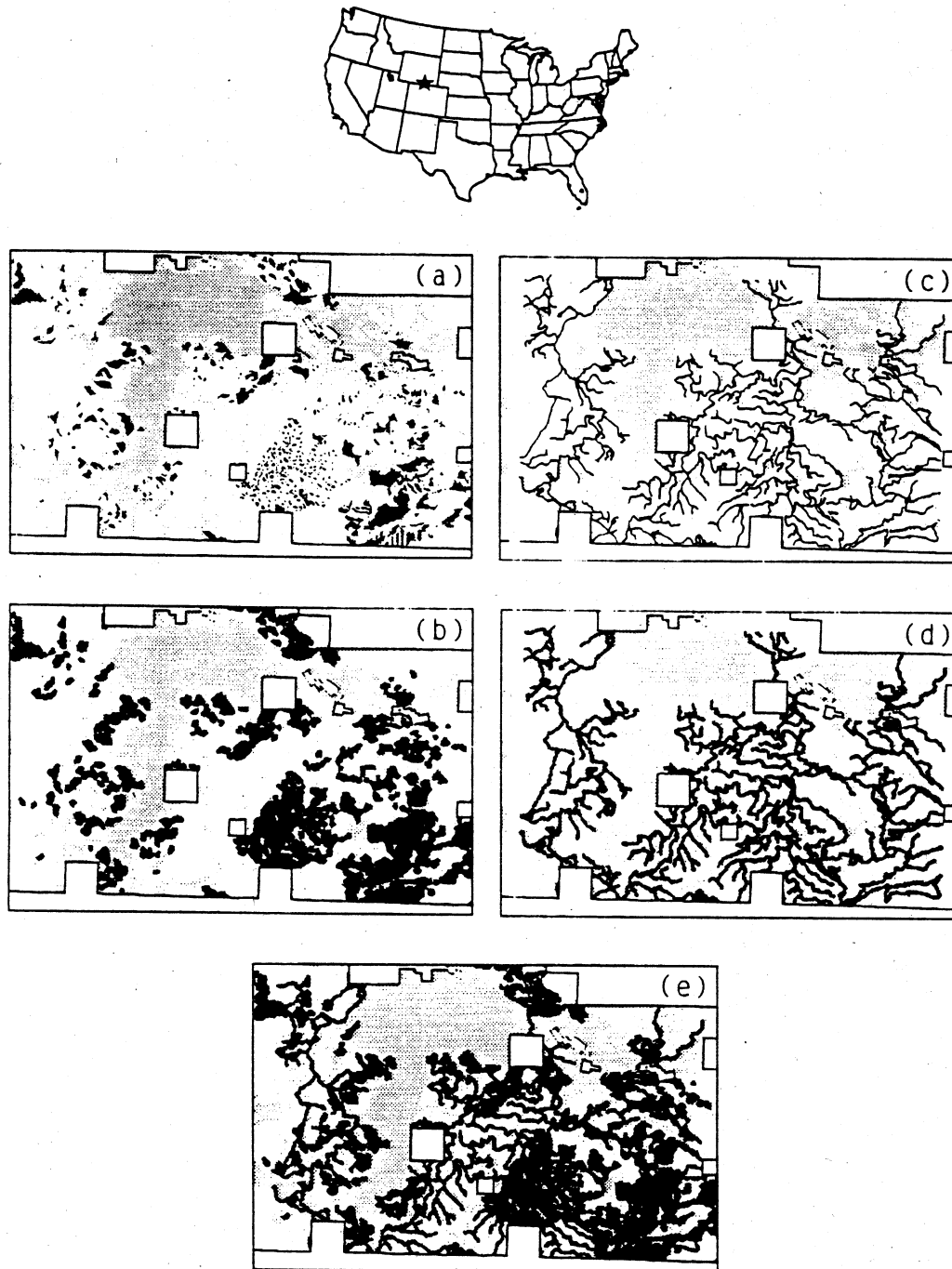


Figure 1. Maps of the study area in 1993, with the road network, 1950-1993 clearcuts, and 100-m depth-of-edge influence shown: non-federal lands are shown in white adjoining the north and south boundaries and as squares or rectangular polygons inside the study area; gray areas are forested areas unsuitable for logging; white areas are available for logging; clearcuts 1950-1993, black (a); clearcuts 1950-1993 plus a 100-m area-of-edge influence around the clearcuts, black (b); all roads as of 1993, black (c); all roads as of 1993 plus a 100-m area-of-edge influence around the roads, black (d); and clearcuts, roads, and a 100-m area-of-edge influence around the clearcuts and roads, black (e).

within wilderness boundaries, or within areas that lack forest. If roads are added to this amount, the area increases to 10,012 ha (33% of the study area). This leaves 20,201 ha (67%) of the land still legally available for logging.

Landscape Area Affected by Roads and Clearcuts

Clearcuts, roads, and area-of-edge influences created by clearcuts and roads affect 42% of the study area and 62%

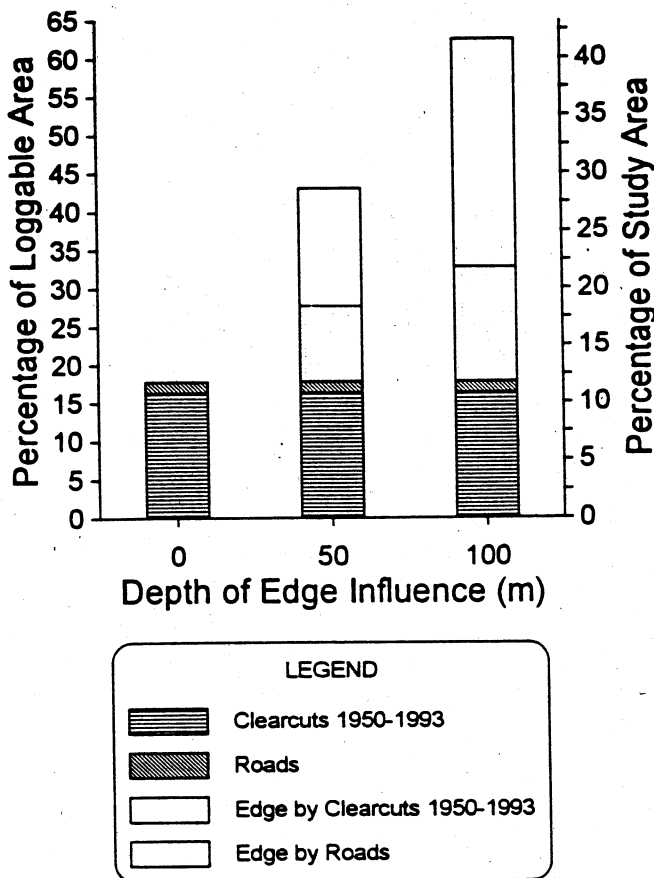


Figure 2. The percentage of the landscape occupied by clearcuts, roads, and edge habitat. "Depth-of-edge influence" indicates the width of the zone bordering clearcuts and roads designated as edge habitat. "Percentage of loggable area" is defined as the percentage of area suitable for logging that is occupied by clearcuts, roads, and edge habitat. "Percentage of study area" is defined as the percentage of the study area as a whole that is occupied by these landscape elements.

of the loggable area, assuming a 100-m depth-of-edge influence (Figs. 1e & 2). Clearcuts alone occupy 3268 ha or 16% of the loggable area (Figs. 1a & 2). If area-of-edge influences along just the clearcuts are considered, edge habitat occupies 1995 ha (10%) of the loggable area assuming a 50-m depth-of-edge influence and 3022 ha (15%) with a 100-m depth-of-edge influence (Fig. 1b).

There are 760 km of roads with an average road density of 2.52 km of roads per km². Assuming a 10-m width, roads themselves occupy 299 ha of the study landscape (2% of the loggable area) (Fig. 1c). If areas-of-edge influence along the roads are considered apart from areas-of-edge influence adjoining clearcuts, edge habitat occupies 3079 ha (15%) of the loggable area assuming a 50-m depth-of-edge influence and 5986 ha (30%) with a 100-m depth-of-edge influence (Fig. 1d). If

the depth-of-edge influence along both the clearcuts and the roads is considered, edge habitat occupies 5074 ha (25%) of the landscape suitable for logging with a 50-m depth-of-edge influence and 9008 ha (45%) with a 100-m depth-of-edge influence (Fig. 1e). The amount of edge created by roads is 1.54 times that created by clearcuts assuming a 50-m depth-of-edge influence and 1.98 times that created by clearcuts with a 100-m depth-of-edge influence (Fig. 2).

Effects of Roads on Landscape Structure Analyses

Combining the roads with the 1950 map shows the effects of roads on the structure of a landscape relatively unaffected by clearcut logging; merging the roads with the 1993 map shows the effects of roads on the structure of a landscape significantly affected by clearcut logging (Fig. 1 for a simplified map of the study landscape). Introduction of roads onto the 1950 and 1993 landscapes increased the number of patches by 179 and 158%, respectively, (Fig. 3a) and decreased the mean patch area by 65 and 62%, respectively (Fig. 3b). Mean patch-interior area decreased from 17.7 to 5.7 ha and 12.6 to 4.3 ha, mean patch area-of-edge influence decreased considerably, and the ratio of area-of-edge influence to interior area increased by 29 and 23%, respectively (Fig. 3b). Mean patch perimeter decreased from 3.9 to 1.7 km in 1950 and from 3.3 to 1.5 km in 1993 with the addition of roads, whereas total perimeter increased by 24 and 21%, respectively (Fig. 3c). These measures indicate that roads cause a degree of fragmentation even greater than that caused by clearcutting alone.

Mean patch shape decreased from 2.2 to 1.8 and from 2.0 to 1.8, respectively, with the introduction of roads onto the 1950 and 1993 landscapes (Fig. 3d). There was little effect of roads on the Shannon-Wiener diversity, dominance, or angular second moment of the landscape, but contrast increased from 3.8 to 5.9 in 1950 and from 3.6 to 6.3 in 1993 (Fig. 3e) and contagion decreased by 2% both years (Fig. 3f).

Road Edge Habitat

The introduction of roads onto the 1993 landscape resulted in 12.8% (3833 ha) of the vegetation as a whole becoming road edge habitat assuming a 50-m depth-of-edge influence and 24.5% (7331 ha) assuming a 100-m depth-of-edge influence (Fig. 4a). Similar proportions of forest vegetation as a whole, lodgepole pine forest overall, lodgepole pine old growth, and spruce/fir forest became road edge habitat given the two depths-of-edge influences (Figs. 4a & 4b). In the spruce/fir, old-growth forest 8.6% (70 ha) became road edge habitat with 50-m depth-of-edge influence and 17.1% (139 ha) with 100-m depth-of-edge influence (Fig. 4c). In the aspen forest

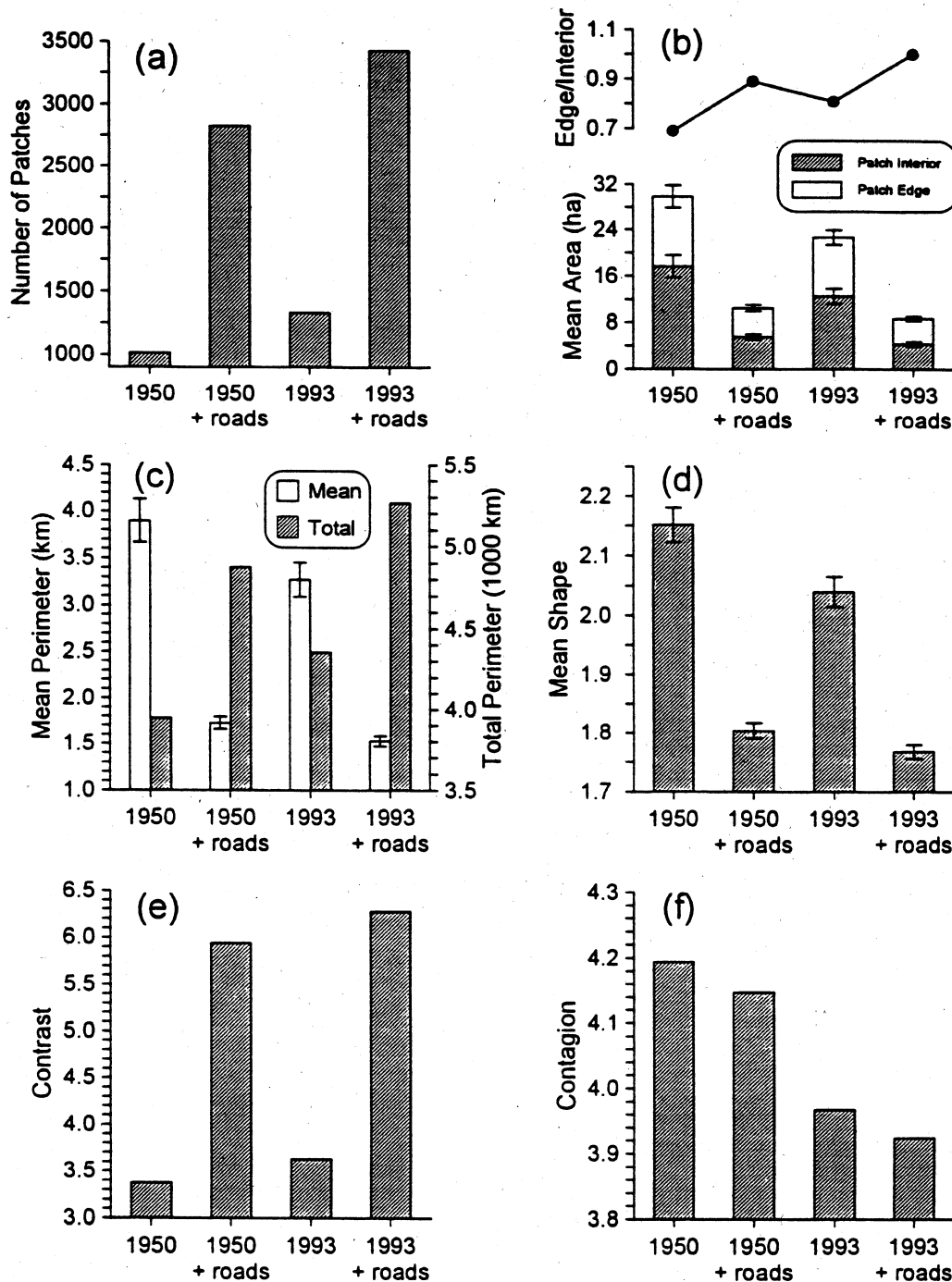


Figure 3. Patch density-, edge-, shape-, and diversity-related landscape structure measurements for the 1950 and 1993 landscapes, with (+ roads) and without roads: number of patches (a); mean patch area (b), showing the proportion of patch areas occupied by interior and edge habitats and the edge:interior habitat ratios; mean patch perimeter and total perimeter (c); and mean patch shape (a); contrast (e); and contagion (f). Error bars indicate ± 1 SE.

4.2% (45 ha) overall became road edge habitat with 50-m depth-of-edge influence and 8.3% (90 ha) with 100-m depth-of-edge influence (Fig. 4c), whereas 6.8% (7 ha) of the old growth became road edge habitat with 50-m depth-of-edge influence and 12.8% (13 ha) with 100-m depth-of-edge influence (Fig. 4d).

Discussion

Interpretation of Patch-related Effects

The landscape structure measurements demonstrate a clear pattern of fragmentation of the landscape by roads

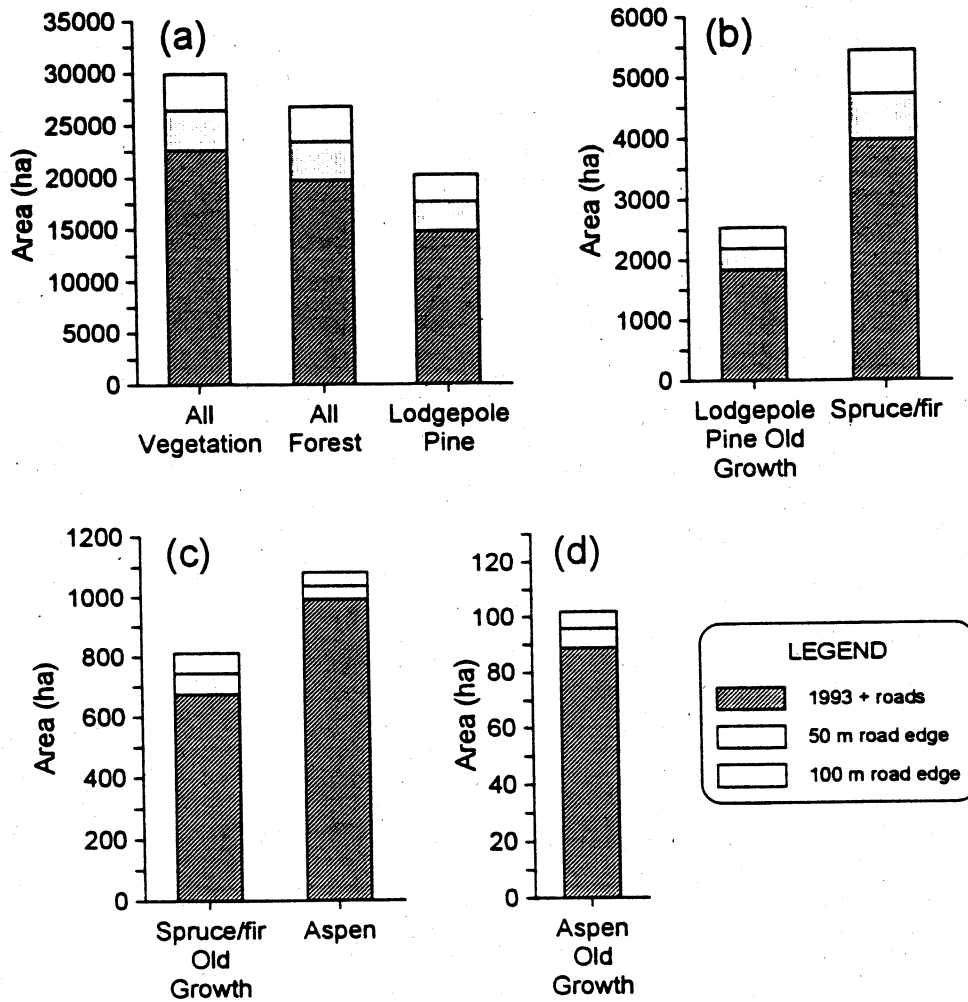


Figure 4. The area of the landscape occupied by various vegetation types in an unaffected state and in road edge habitat designated with 50- and 100-m area-of-edge influences.

and a greater fragmentation effect from roads than clearcuts. Such effects are illustrated by the increase in number of patches, which occurs as roads dissect large patches of vegetation into smaller fragments (Fig. 2). The number of patches approximately tripled due to road dissection even in a landscape (1993) that has had heavy clearcut logging activity (Fig. 3). A greater number of patches corresponds with the decrease in mean patch area to about one-third of that if roads were absent. The implications of decreasing mean patch area are manifested largely in the substantive decrease in mean patch-interior area and the coinciding increase in the ratio of area-of-edge influence to interior area. Such trends indicate a significant reduction in the amount of interior forest habitat available to requisite interior species, such as pine martens (*Martes americana*) (Shultz & Joyce 1992) and Brown Creepers (*Certhia familiaris*) (Keller & Anderson 1992) in this area, or gray wolves (*Canis lupus*) (Thiel 1985; Mladenoff et al. 1995) or Northern Spotted Owls (*Strix occidentalis caurina*) (Lehmkuhl &

Raphael 1993) in areas to the north and west, as well as greater distances between suitable interior habitat patches. Larger distances may make migration between patches more difficult for individuals in a population and could ultimately lead to isolation of subpopulations within patches or small areas of the landscape, possibly endangering the survival of the species (Saunders et al. 1991).

The diversity-related indices that did respond to the introduction of roads also reflect the aforementioned trends in fragmentation. Increased contrast (Fig. 3e) indicates an increase in the local variation across the landscape, and decreased contagion (Fig. 3f) reflects increased landscape heterogeneity and decreased clumpiness, both of which result from the dissection of landscape patches by roads.

Interpretation of Edge-related Effects

The decrease in mean patch perimeter (Fig. 3c) supports the trend of increasing fragmentation due to roads

and reflects the dissection by roads of many large patches to form a much greater number of new patches. This effect is corroborated by the corresponding decrease in the mean patch shape index (Fig. 3d), which indicates a trend toward more round, simply shaped patch boundaries. The edge-related effects of roads that contribute to landscape fragmentation are also clearly illustrated by the whole-landscape measurement of total perimeter, which is increased considerably by roads (Fig. 3c). Greater total perimeter indicates an overall increase in edge habitat across the landscape, which is expected with greater fragmentation and reflects the dissection caused by roads (Krummel et al. 1987).

The apprehension concerning the introduction of edges onto landscapes results from potentially detrimental microclimatic and biological changes, relative to intact forest, which occur along edges (Noss and Cooperrider 1994). Edge habitats along roads and clearcuts experience microclimatic changes, including increased evaporation, increased temperature, increased incident solar radiation, and decreased available soil moisture (Kapos 1989; Chen et al. 1992, 1993; Vaillancourt 1995). Road edges and clearcut edges are not necessarily equal in magnitude and impact, however. For some effects, such as wind and associated environmental changes, clearcut edges may have greater depth and impact than road edges due to greater wind fetch.

Road edge habitat is unique in many respects from natural edges or edges produced by clearcuts. Whereas natural and clearcut edges will become progressively less defined as the forest regenerates in a patch, road edges tend to exist long-term and be disturbed more frequently. Road edges increase air pollution (Santelmann & Gorham 1988), soil erosion (Hodgson & Dixon 1989; Fahey & Coker 1992; Douglas et al. 1993), noise (Reijnen et al. 1995), direct vehicular fatalities (Wilkens 1982; Rosen & Lowe 1994), disturbance by human activity (Stankey 1980; Buckley & Pannell 1990), and exotic species introductions (Amor & Stevens 1976; Tyser & Worley 1992), and may induce population changes (McLellan & Shackleton 1988; Eaglin & Hubert 1993) in the vegetation and animal communities included in the areas of edge influence. These factors combine to create particularly deleterious habitat situations, and endanger the existence and perpetuation of all native species (interior and edge species alike) on the landscape.

The simple appearance of the landscape, the actual area in clearcuts and roads (McGurk & Fong 1995), and the density of roads (Miller 1994) are incomplete indicators of the impacts of logging. Even though roads occupy a small fraction of the landscape in terms of land area, their influence extends far beyond their immediate boundaries. We have illustrated that a large proportion of the vegetation on the landscape, 13–25% in this study, and a large percentage of the loggable area, about 41–62% in this study (Figs. 1e & 2), is exposed to edge

conditions. The amount of land area that is edge habitat created by clearcuts and roads is 1.5–2.5 times the land area actually occupied by the clearcuts and roads (Fig. 2), so the cumulative area affected is approximately 2.5–3.5 times the actual area of clearcuts and roads.

Applications to Forest Management

We provide strong evidence that roads occupy a substantial proportion of land area in the forest, which can have potentially detrimental impact not only on wildlife habitat but also on timber harvesting. More landscape area in roads leads to less area available for trees, which is significant from a forest management and economic perspective. With these considerations in mind, we recommend a forest-wide program of systematic obliteration and revegetation of roads. This measure would reclaim land for a variety of resources, including wildlife and timber production. Not only should existing old, little-used logging roads be revegetated, but road obliteration and revegetation should become part of the overall harvesting process.

Timber harvests should be planned to minimize impact on the landscape and exacerbation of the current landscape fragmentation problem on the forest. Proposed clearcuts (or other harvesting activities, including shelterwood cuts) and roads should be entered into a geographical information system along with the information currently available in U.S. Forest Service databases and the resulting effects on landscape structure examined quantitatively. An analysis of the effects of an individual timber sale and its roads is useful, but the effects of roads are more cumulative than are the effects of timber cutting because, currently, many roads are not closed and vegetation does not reestablish on them. An adequate assessment of present and future fragmentation in forests subject to timber harvest should include an analysis of (1) harvested and roaded area, (2) the edge created by these activities, and (3) the dissection of patches by roads. Roads must be mapped as accurately as possible, for example by using global positioning systems. Otherwise, road length and the impacts of roads on the landscape may be significantly underestimated. A cumulative effects analysis of proposed roads over several decades should become part of the environmental assessment process required of extractive activities.

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