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Decision Support for Road System Analysis and Modification on the Tahoe National Forest

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ABSTRACT / The United States Forest Service is required to analyze road systems on each of the national forests for potential environmental impacts. We have developed a novel and inexpensive way to do this using the Ecosystem Management Decision Support program (EMDS). We used EMDS to integrate a user-developed fuzzy logic knowledge base with a grid-based geographic information system to evaluate the degree of truth for assertions about a road's environmental impact. Using spatial data for natural and human processes in the Tahoc National Forest (TNF, California, USA), we evaluated the assertion "the road has a high potential for impacting the environment." We found a high level of agreement between the products of this evaluation and ground observations of a TNF transportation engineer, as well as occurrences of road failures. We used the modeled potential environmental impact to negatively weight roads for a least-cost path network analysis to 1573 points of interest in the forest. The network analysis showed that out of 8233 km of road analyzed in the forest, 3483 km (42%) must be kept in a modified road network to ensure access to these points. We found that the modified network had improved patch characteristics, such as significantly fewer "cherry stem" roads intruding into patches, an improved area-weighted mean shape index, and larger mean patch sizes, as compared to the original network. This analysis system could be used by any public agency to analyze infrastructure for environmental or other risk and included in other mandated analyses such as risks to watersheds.

Road networks pose a variety of potential and actual risks to the natural systems they are embedded in. Factors such as road location and use, geomorphology, and ecosystem processes may influence the level of risk (Trombulak and Frissell 2000, USDA 2001). Forman (2000) summarizes many of the impacts road systems can have: (1) Road placement can affect surface water flows and stream channel morphology. (2) Runoff from roads may contain dust, salt, and various metals and hydrocarbons. (3) Roads fragment wildlife habitat and provide corridors for invading species. (4) Many human users of the landscape, for economic and recreational reasons, consider roads essential. (5) This valuation has contributed to development of the $>$ 6.2 million km of roads in the United States and the potential impact by roads to 20% of the US landscape. In the mountainous western United States., "roadless areas" are considered to be critical for the maintenance of landscape and habitat connectivity, protection of threatened natural values and biodiversity, which are especially valued at lower elevations due to their rarity.

Road effects on aquatic ecosystems have been measured primarily in terms of the deposition of metal, hydrocarbon, sediment, and salt contaminants from the traffic or road surface to waterways (Gjessing and others 1984, Hoffman 1981, Bell and Ashenden 1997, Ziegler and Giambelluca 1997) and alteration of aquatic community processes (Wilcox 1986, Maltby et al., 1995). Roadbeds and road-related infrastructure can also impinge upon the physical characteristics (e.g., channelization) and processes of stream systems and their ability to recover from land-use impacts (Meyers and Swanson 1995). High road densities have been correlated with loss of habitat for bull trout, which may be a product of fragmentation (due to crossings), erosion, or other factors (Dunham and Rieman 1999). Roads and bridges across streams have been accompanied by reduced riparian bird species richness and density (Rottenborn 1999) and overall species richness in wetlands (Findlay and Houlahan 1997).

Roads can also affect terrestrial biodiversity directly through loss of habitat and increased mortality, as well as indirectly by causing ecological changes in the "road-effect zone," hindering habitat connectivity and fragmenting habitat patches (Jonsen and Fahrig 1997, Chapin et al., 1998, Rosenberg et al., 1999, Baker and Knight 2000). Road system and associated land development can result in edge effects that vary in extent with landscape complexity and extent of human impacts and vary in impact on the natural process or wildlife in question (Yahner 1988, Theobald et al.,

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1997, Lidicker 1999). Fragmentation and disturbance impacts from roads may exacerbate threats of extinction from other factors through impacts on migration and habitat quality (Fahrig 2001). Not only do roads create artificial habitat edges, but they also pose a barrier to species dispersal and migration through aversion effects ("habitat alienation", e.g., Mac et al., 1996), direct mortality from traffic (Madsen 1996, Putman 1997, Rubin et al., 1998), and traffic noise-induced effects (Reijnen et al., 1997, Gill et al., 1996). The combination of edge and barrier can reduce the effective area for species that depend on intact habitat in the interior of patches. Mitigation efforts for fragmentation effects have been made in particular geographic locations by installing underpasses and overpasses intended for use by large mammals (e.g., Clevenger and Waltho, 2000) and by promoting postharvest logging road closures to protect mammals (Boone and Hunter 1996).

Partially in recognition of these various ecological impacts, the United States Forest Service (USFS) released a proposed rule on 3 March 2000 that would update the transportation management sections of the USFS regulations (36 CFR 212) and the Forest Service Manual (FSM 1920 and 7700). The USFS would rely on a "roads analysis process" (RAP) (USDA 1999) that incorporates consideration of ecological effects of roads, the economics of road management, the social and economic costs and benefits of roads (USDA 2001), and the contribution of roads to management objectives. The USFS intended for products of the RAP to be integrated into watershed analyses, landscape assessments, and other analyses supporting existing decision making processes (USDA 1999). The current process for roads analysis and decision-making is project by project and often does not include the full suite of experts needed to adequately assess environmental impacts (e.g., hydrologist, aquatic biologist, wildlife biologist, botanist, community ecologist, geomorphologist).

Working in conjunction with Tahoe National Forest (TNF) managers, we used the Ecosystem Management Decision Support system (EMDS) (Reynolds 1999) to analyze the environmental impact of each 30-m grid cell section of road in the TNF. We did not differentiate among possible sources of impacts from roads, rather we assumed that a variety of impacts could occur in association with each road type. We also assumed that using technical and scientific opinion to develop a holistic assessment for spatially explicit decision support was an improvement over a more fragmented (road-by-road) expert knowledge approach. In some respects our philosophy was similar to that of Lugo and Gucinski (2000), who propose viewing the road system as an ecosystem imposed upon the original ecosystem and therefore open to analysis in similar ways that we look at natural systems. The results of our analysis were compared with expert opinion of the road system impact (the usual analysis method), past management decisions, and road failure occurrences, as well as used to find a minimum network of roads needed to access points of interest in the forest. We assessed the structural fragmentation of the landscape by roads, regardless of road type. This new network describes the road network needed to access these points with minimum environmental cost. In addition we demonstrated the potential use of products of the road system assessment in watershed analysis.

Methods

Procedure

The overall goal of the project was to test the usefulness of a custom-made knowledge base in the Ecosystem Management Decision Support (EMDS) system for its usefulness in a roads analysis process for the Tahoe National Forest (TNF). This process involves identifying roads in a road system that are actually or potentially causing environmental harm, while also taking into account the use of the road for transportation and access. Working in conjunction with staff of the TNF, we created a knowledge base that dictates how spatial data is analyzed by EMDS for each 30-m grid cell in the forest. The results of this EMDS analysis were then averaged over each road segment and compared with the expert opinion of a TNF transportation engineer, compared with past management decisions regarding road removal, and compared with road failure occurrences. The potential environmental impacts of road segments (cost) were then used in conjunction with the ArcView Network Analyst extension (ESRI 1999) to weight roads and find a least-cost network to points of interest in the TNF.

Spatial Data

The TNF provided spatial road data (1:24,000 scale) that included attribute data for road surface type (i.e., paved vs unpaved). A 30-m grid coverage of road density for a 1.0-km radius around the grid cells was created. Throughout the analysis, a 30-m grid was used to match the scale of the digital elevation model (DEM) used in the analysis. TNF provided an ownership/administrative geographic information system (GIS) coverage that included boundaries for all privately owned parcels within the forest. From this we created a 30-m grid of administrative boundary density within 1.0 km

of grid cells as a surrogate for administrative complexity. The road coverage was built as a polygon coverage, and the adjacent roadless area patch sizes were calculated and attributed to the road segments. Cherry stem (dead-end) roads that did not bisect a patch were attributed with the size of the roadless patch it protruded into.

The stream coverage used (1:24,000 scale) was manually digitized by the TNF and was based on landscape crenulations from 7.5' topographic quadrangle maps. This coverage was used rather than the commonly available 1:100,000 scale streams coverage (National Hydrographic Database, NHD) because the TNF coverage contained 20,136 km of stream within the forest, while the NHD streams coverage for this same area contains only 4692 km of stream length. A 30-m grid of distance to nearest stream was created. A coverage of road-stream crossings was created by intersecting the road and stream coverages, then extracting all points of intersection between the two coverages. Density of crossings per road segment (road crossings per kilometer) was then calculated. The length of roads within 100 m of a stream per creek watershed was also calculated (watershed riparian road length). The creek watershed coverage was provided by TNF; the range of watershed sizes was 333–2032 ha and the mean size was 660 ha. The density of road-stream crossings per planning watershed (crossings per hectare), and length of roads per planning watershed were calculated.

The TNF provided a 30-m grid DEM, from which slope steepness was calculated. From this, a grid quantifying the effect of slope steepness on erosion based on the methods of Nearing (1997) was created. Road position on slope was calculated from the DEM using an ArcInfo markup language program created by National Forest Region 6 researchers as part of the Hydrologic Condition Assessment Tools—Module of Indicators for Roads Analysis project. Soil series GIS data (1:24,000 scale) was obtained from TNF, which included attributes for the soil erodibility factor (k in the universal soil loss equation). Average annual precipitation from the 1-km-grid PRISM model (Daly et al., 1994) was resampled to a 30-m grid using a cubic transformation in ARC/Info GRID.

TNF also provided all biological data used in the analysis, which were developed according to USFS standards, including (1) a perennial-streams coverage attributed with stream segments that were fish-bearing, (2) a polygon coverage denoting the extent of wetlands and meadows, (3) a point coverage showing locations of invasive weeds, and (4) polygon coverages showing areas that contained occurrences (e.g., nest areas) of wildlife populations of special interest from TNF, including peregrine falcon nesting areas, willow flycatcher habitat, bald eagle nest areas, spotted owl activity centers (home ranges), and goshawk management (nesting and home range) areas. Wildlife data were recently collected through intensive surveys by USFS biologists.

To assess access needs in TNF, we used the USGS Geographic Names and Information System database to create a digital map of places of interest within the national forest. From the GNIS database the following types of points were used in this analysis: infrastructure (e.g., airports, post offices, populated places, schools, radio towers, etc.), resource uses (e.g., dams, mines, etc.), and potential recreation places (e.g., campgrounds, etc.). In order to ensure access to private parcels in the national forest, we digitally added points on roads within privately owned parcels to this list. Only points within 1 km of a road were used in the analysis.

All GIS data processing was done using ArcView GIS 3.2 (ESRI 1999) and ArcInfo 7.2.1 (ESRI 1998). A 250-m buffer was drawn around the edge of the digital streams map (roughly the administrative boundary of the TNF) and the buffered area (streams map plus 250 m) used as the analysis area.

Developing the Decision Support System and Knowledge Base

EMDS links the GIS program ArcView 3.2 with the knowledge base development program Netweaver (Saunders et al., 1990). EMDS uses the knowledge base structure to combine the necessary spatial base data using fuzzy logic rules to determine degree of truth for an assertion (Reynolds et al., 1996, Reynolds 1999). The Netweaver user creates an object-oriented hierarchy of networks (e.g., a knowledge base), with nodes based on fuzzy logic relationships. Conventional, or Boolean, logic is a subset of fuzzy logic, which was introduced in order to accommodate "partial truths" (Zadeh 1965). Partial truth refers to truth values between "completely true" and "completely false." Truth values can also be called "strength of evidence" that an assertion about a process or phenomenon is true. It is literally a measure of set membership, with the possibility of intermediate values for membership. For example, when we think of slope steepness, what we call "steep" or "not steep" usually occurs on a continuum that would be best described by a statement of the relative truth that a slope is steep, as opposed to setting some threshold of degrees slope above which the slope is "steep". The user of this system decides what is "true" and "false" for an assertion, such as "the slope is steep," and intermediate values for the parameter (e.g., steepness) get intermediate truth values.

Truth values of subassertions in this linguistic modeling system can be combined using a variety of relationship types. In this case we combined assertions and data using "AND", and "OR" fuzzy logic relationships. The "AND" relationship combines the truth- values of two sub-assertions or base data using the formula:

$$\text{AND}(t) = \min(t) + [\text{average}(t) - \min(t)] *[\min(t) + 1]/2$$

Thus, any AND assertion is completely false if any of its subassertions is false; if one subassertion is completely true (1) and the other is undetermined (0), the assertion is given a truth value of 0.25. Thus, the AND relation is a conservative estimate of truth. The OR relationship gives the assertion the truth value of the most true subassertion. Thus, for the OR relationship even if only one subassertion is completely true(1) the entire assertion is true,even if all of the other subassertions are false(Reynolds 1999). AND relationships are used when the truth of an assertion is assumed to be based on the combination of subassertions, whereas OR relationships are used when the truth of the assertions could be based on any one of the subassertions.

In conjunction with an interdisciplinary (ID) team composed of staff from the TNF districts and supervisor's office, we created a fuzzy logic network testing the assertion that "the road segment has a high potential for causing environmental damage." This assertion has subassertions (dependency networks) that are nested within the overall network (see below for detailed descriptions). Eventually these subassertions connect to base data that address a single assertion, such as "the road is on a steep slope." The fuzzy logic capabilities of this model allow us to give intermediate truth values to base data assertions; an assertion can be given a truth value between −1.0 (completely false), 0 (undetermined), and +1.0 (completely true).

The TNF ID team consisted of USFS experts in the fields of aquatic biology, wildlife biology, plant biology, hydrology, soil science, watershed science, fuels and fire, silviculture, and transportation engineering. The ID team decided which data sets were to be used and how they would relate in the knowledge base model. Where possible the relationships among data sources and the set membership functions (in Netweaver) were defined based on the scientific and technical literature. Where this was not possible, linear relationships from minimum to maximum values for the particular input variable were used, or discrete sets with simple Boolean logic boundaries were established. We considered this approach adequate for assessing relative risk of roads within the TNF. An example of a linear relationship used was the impact of precipitation on the risk of soil erosion. Since we did not have a complete physical model for the effect of precipitation on soil erosion in TNF, we based the relationship on the knowledge that more precipitation can result in more soil erosion. An example of a discrete set is the boundary of a California spotted owl protected activity center (PAC, or nesting and foraging area). If the road was inside the PAC, it received an impact truth value of 1.0 (true); at the boundary of the PAC, the impact truth value became zero (undetermined). After explaining to the ID team the use of AND and OR relationships in the knowledge base, we allowed them to select the relationships with minimal guidance.

The "Roads Analysis" guidance document (USDA 1999) was used as a source of questions and direction. The vast majority of specific questions in the guidance document could be directly linked to components of the knowledge base. This was determined to be a critical step to take, in order to make explicit the process used to develop the knowledge base and to allow for the use of the custom-made decision support system in similar road analyses being conducted on other Forests. The original knowledge base developed by the team had twice as many components as the one eventually used, but was not used because of the lack of specific spatial data or knowledge about impact or causation. The difference between the original and final knowledge bases informed data and knowledge gap determination associated with the roads analysis process. The final knowledge base was used to calculate the truth value of the assertion that each 30-m grid cell of a road has a negative impact on the aquatic and the terrestrial environments (Figure 1) and is described in detail in the following sections.

Potential Environmental Impact of Roads

Aquatic impact. The truth value (TV) for the effect a road has on the aquatic environment is determined by an OR relationship among the assertions of: stream channel integrity, erosion risk, and biological condition (Figure 1). Thus, if any of these three subassertions have a high truth value, the potential aquatic impact value will have a high truth value.

Stream channel integrity can be impacted by roads running adjacent to or near streams or by roads crossing streams. The knowledge base asserts that a road affects the stream channel dependent upon its distance to the stream. The TV for a road affecting stream morphology linearly increased from TV = 0 to TV = 1 as it moves from > 100 m to 0 m from the channel. The effect of stream crossings on stream channel integrity is dependent on the density of crossings along a given

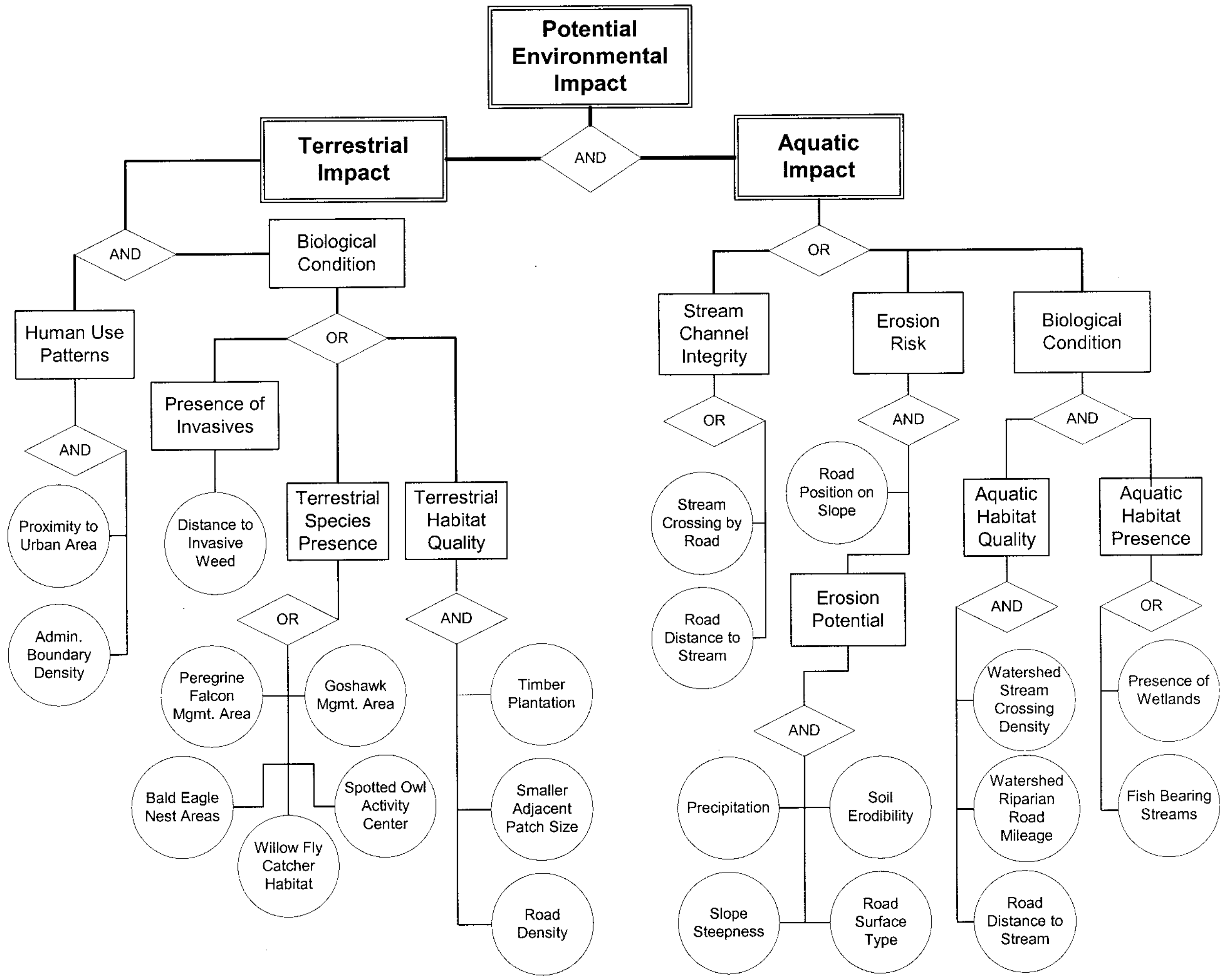

Figure 1. Knowledge base used for the EMDS road system analysis. The rectangular boxes indicate assertions (double rectangles) and subassertions (single rectangles), the circles indicate the spatial data used to evaluate the subassertions. The AND and OR linkages refer to the types of fuzzy logic relationships among the concepts or base data.

road segment (number of crossings per kilometer of road) and was given a truth value that linearly increases from 0.0 crossings/km (TV = 0) to > 5.00 crossings/km (TV = 1).

Erosion risk was based on the Revised Universal Soil Loss Equation (RUSLE) (Renard and Ferreira 1993), the fuzzy logic erosion prediction model created by Mitra et al., (1998), and the position of a road on the hillside. The erosion potential portion of our knowledge base uses the relationship AND to combine the effects of slope steepness on erosion, soil type erodibility (*k* value), mean annual precipitation, and road surface type. Values for the effective slope steepness of roads on erosion were calculated based on a formula from Nearing (1997). These values were assigned truth values in a linear fashion, from flat slope (TV = 0) to the maximum slope value 15.1 = 85.4° (TV = 1). The *k* value for soils was input linearly into the EMDS model from 0.10 (TV = 0) to 0.43 (TV = 1). Precipitation data were input into the model linearly from the minimum value of 31 cm/yr (TV = 0) to the maximum value of 234 cm/yr (TV = 1). Unpaved roads were given a TV of 1 for the potential for the road surface to contribute to sediment, while paved roads were given a TV of 0. In addition to these factors, road position on slope is an important consideration for evaluating risk of sediment delivery to streams (Leslie Reid personal communication). A truth value for erosion risk was then calculated by combining erosion potential with road position on slope. Mid-slope roads (TV = 1) have been found to contribute the most sediment to streams because they are prone to move large amounts of sediment in mass

wasting events when they fail, as well as contributing continual surface erosion. Ridge roads (TV = 0.5) contribute moderately, usually not through mass wasting events, but through continual road surface erosion. Stream-side roads (TV = 0) tend to contribute little to erosion, and can even act as a sink collecting sediment from upslope and preventing it from entering the stream channel, although they can affect aquatic integrity in other ways, such as stream channelization, and road-stream crossings.

The potential impact of roads to the biological condition of streams was considered to be due to both the presence of wetlands or fish-bearing streams, and the quality of the aquatic habitat (Figure 1). Roads within 100 m of either wetlands or fish-bearing streams were given a TV of 1 for impact on habitat presence. This concept was then combined using an AND statement with the biological condition of that grid cell. Biological condition was defined as combination of distance to stream, watershed riparian-road length (WRRL), and watershed stream crossing density (WSCD). These factors were combined using an AND statement because all of these three factors having a high truth value would have the highest impact on aquatic habitat quality. Truth values for road distance to stream linearly increased from 0 to 1.0 as the distance decreased from > 100 m to 0 m. Truth values for WRRL and WSCD linearly increased from 0 to 1.0 as the values increased from zero to the maximum value ($WRRL_{max}$ = 26.3 km; $WSCD_{max}$ = 6.9 crossings/ha).

Terrestrial impact. In our knowledge base, a road affects the terrestrial environment through an interaction between human use patterns and an impact on terrestrial biological condition (Figure 1). We asserted that human use is greatest on roads that are close to urban areas and that are in an area of high degree of ownership complexity. Truth values for roads near urban areas increased linearly from < 1.6 km (1.0 miles, TV = 1.0) to > 16.1 km (10 miles, TV = 0). Ownership complexity was measured by the density of ownership boundary lines in a 1.0-km radius around a given grid cell. As ownership density increased from 0 km/km^2 to the maximum value (4.81 km/km^2), the TV increased linearly from 0 to 1.0.

The knowledge base asserts that a road affects the terrestrial biological condition by being in contact with high quality habitat, species of importance, or exotic/invasive weeds (Figure 1). Quality of habitat was a combination of patch fragmentation, presence of timber plantations, and road density. We used the area of the smaller adjacent roadless patch as a measure of the effect a road segment has on fragmenting large roadless patches. A large "smaller adjacent roadless patch" means the road greatly fragments an even larger roadless patch. If the road were removed, the large "smaller adjacent patch" would be combined with the larger adjacent patch to create an even larger roadless patch. However, a road with a small "smaller adjacent patch" would only produce a slightly larger patch if the road were removed. As the smaller adjacent patch size increased from 0 to > 2023 ha (5000 acres), the TV increased from 0 to 1.0. A road present in a timber plantation was given a TV of 0, otherwise roads were given a TV of 1.0. As road density increased from 0 to 1.5 km/km^2, the TV increased from 0 to 1.0. A road within any area of designated habitat for peregrine falcon, bald eagle, willow flycatcher, spotted owl, or goshawk was given a TV of 1.0. A road was said to be a high risk for promotion of invasive weeds by getting a TV of 1.0 if it passed within 200 m of a mapped occurrence of an invasive weed.

Overall impact. We used the AND relationship to bring together the truth values for potential aquatic and terrestrial impacts into a single metric, the overall environmental impact. The reasoning for using the AND relationship was that both TNF planners and the roads analysis manual (USDA 1999) wanted an analysis of combined impacts from the road system expressed as a single value, necessitating the use of AND rather than OR.

Comparison of EMDS Result with Expert Opinion, Management Decisions, and Observed Road Failures

The TNF, like other forests, uses expert opinion about road condition in the majority of analyses for project preparation (e.g., logging sale). We drove with TNF transportation engineer Scott Hussman along roads in the Cavanah project area, and had him rank each road segment with risk values of low, medium, or high environmental risk before he had seen the results of the analysis. His risk assessment was based on consideration of potential impacts to surrounding natural resources (e.g., waterways, down-slope areas, and known critical wildlife habitat). The 30-m grid of EMDS truth values was averaged over the length of each road segment in the GIS line coverage and attributed to that road segment. The road segments were ranked according to mean EMDS truth value. Differences in mean percent ranked EMDS truth values between the transportation engineer's ranked categories for road segments were found using a one-way ANOVA with randomization (Manly 1997) using a script written in MATLAB 6.0. The data were percent ranked to minimize the effect of the model output not being normally distributed. The percent rank was found by ranking all

data points from one to the maximum number of data points, then dividing by the maximum number of data points to produce a rank from 0 to 1.0. To perform this test, first an *F* value was calculated for the original data set. Then the data were randomly shuffled 10,000 times, and an *F* value was calculated for each of these random permutations. A *P* value was then determined by finding the proportion of random *F* values greater than or equal to the original *F* value. A randomized test was used to avoid problems associated with the data potentially being spatially autocorrelated, not independent, and nonparametric. A separation of means was then performed using Tukey's HSD ($\alpha = 0.05$). This statistical method was also used to test the EMDS results against past management decisions for roads in the End of the World sale area and past road failures over the entire forest. The two management decision types analyzed were: road closure/removal (decommissioned) and road remains open. In addition, we obtained a map of road failures that occurred during early 1997 from the TNF and compared the aquatic risk EMDS results of road segments that failed with those that did not fail. Only the aquatic risk EMDS results were used in this analysis, because road failures are unlikely to have a significant effect on the terrestrial environment and thus would not be expected to correlate with either the terrestrial risk or environmental risk EMDS scores. In addition, the factors considered in the aquatic risk part of the analysis were conceptually related to the reasons that road-cuts and road-beds fail, that is, precipitation, slope steepness, soil type, and channel crossing.

Modifying the Road Network

Using the ArcView Network Analyst extension, we found the route that takes the least cost to connect all 1573 points of interest in TNF, including all private in-holdings and other places of interest from the USGS GNIS database. We call this the modified road network. We defined total cost as a combination of travel time and environmental risk. We calculated time of travel for each road segment by multiplying the length of the segment by the average speed for that road type; we assumed 89 kph (55 mph) for highways, 64 kph (40 mph) for major paved, 48 kph (30 mph) for minor paved, 32 kph (20 mph) for gravel, 24 kph (15 mph) for improved dirt, and 13 kph (8 mph) for unimproved dirtroads. We then multiplied the time of travel by an environmental cost factor. This factor was obtained by normalizing the EMDS results to a range of 1.00–2.00. We normalized the EMDS result by subtracting the minimum score (0.032) from all scores, then dividing by the range (0.968), and finally adding 1.0. Thus, the driving time cost of travel on a road segment could as much as double if the segment had the highest environmental risk. This environmental risk factor for this analysis was chosen to have a maximum of 2.00 (i.e., double), but any risk factor could be used depending on the desire of the user.

The modified road network was then analyzed for its effect on habitat fragmentation as compared to the current road network using the FRAGSTATS Arc/INFO extension (McGarigal and Marks 1995, Pacific Meridian Resources). We assumed equal impact of road types with this approach, which may not be true in considering traffic disturbance; however, we were only concerned with structural fragmentation, making FRAGSTATS an appropriate tool. In addition, we did not have any way to discriminate among roads or road types based on traffic volumes or other considerations, due to lack of these kinds of data. Patches were defined by buffering roads by 10 m. We placed these roadless patches into categories based on size on a logarithmic scale: < 1, 1–10, 10–100, 100–1000, 1000–10,000, and $> 10{,}000$ ha. Since these data were found to not be normally distributed and possibly spatially autocorrelated, we used an ANOVA with randomization to compare landscape indices between the original and modified network for patches in each of these patch size categories.

We calculated the length of "cherry stem" roads per patch by summing the length of all roads with the right polygon identification number equal to the left polygon identification number then attributing that summed length to that given polygon. We then calculated the density of cherry stem roads per patch by dividing the total cherry stem length by the patch area. A Mann-Whitney U test (SAS Institute 2000) was used to compare cherry stem density per patch between the original and modified networks.

Watershed Analysis

In designing projects, national forest planners often consider existing environmental impacts at the creek watershed scale. In order to understand the utility of risks associated with road segments to watershed processes, we summarized environmental risk of roads over creek watersheds. We summed the overall environmental impact EMDS truth values associated with the 30-m grid cells for each planning watershed using the *summarize by zones* command, then divided by the watershed area (in ArcView 3.2), creating a metric we call watershed area-weighted environmental risk (WAWER). We tested for spatial autocorrelation of WAWER values using Moran's *I* statistic with binary connectivity used as the algorithm to calculate the spatial weight matrix for

this analysis (Lee and Wong 2001). Both a normal distribution and randomized distribution were used to calculate *P* values, and both produced similar results.

Results

Spatial Data

The analysis area for this project spans 522,359 ha. Of this, Tahoe National Forest (TNF) manages 333,954 ha, other public institutions (e.g., Bureau of Land Management) manage 5251 ha, and the remaining 183,154 ha are privately owned. There are 8233 km of roads in our analysis area. Approximately two thirds of these roads are on national forest-owned land with the other third on other publicly owned land and private inholdings. Of the total road network, 3% of road length is classified as major highway, 4% is minor highway/major paved, 6% is minor paved, 5% is gravel, 19% is improved dirt, and 63% is unimproved dirt.

There are 20,136 km of digitized stream length within our analysis area, an average density of 4.1 km/km^2. Of these streams, 68% are ephemeral, 12% are seasonal, and 20% are perennial. There are 14,724 stream crossings by roads in the TNF, a crossing density of 1.92 crossings/km of road. Twenty-eight percent of stream length lies within 100 m of a road, while 59% of all road length lies within 100 m of a stream, and 17% lies within 25 m of a stream. Fifty-three percent of all roads lie on a $> 30°$ slope, with 40% of paved roads and 55% of nonpaved roads on such a slope.

Potential Environmental Impact of Roads

The average truth value (TV) of potential environmental impact for all 30-m road grid cells in the TNF was 0.617, with a range of 0.058–1.000. These TVs were a composite of potential impacts to aquatic and terrestrial conditions (Figure 2). The average EMDS truth value for aquatic impact was 0.757 (SD = 0.243). The average EMDS terrestrial risk truth value was 0.548 (SD = 0.216). The potential impact from individual road segments to terrestrial features and processes sometimes overlapped the potential impacts to the aquatic environment (Figure 2). An ANOVA with randomization showed unimproved dirt road segments had a significantly higher aquatic risk ($P < 0.001$), as compared to improved dirt and gravel road segments, although we found no significant difference ($P = 0.07$) for terrestrial risk. Paved roads were not analyzed due to the model's dependence on road surface type (paved vs nonpaved).

Comparison of EMDS Result with Expert Opinion, Management Decisions, and Observed Road Failures

The independent expert opinion of road segment environmental risk—determined by a TNF transportation engineer—was compared with the EMDS results using an ANOVA with randomization to find differences in means of percent ranked EMDS results between the three expert opinion environmental impact classes (low, medium, high). For combined environmental impact, the mean percent ranked truth value in the low class was 35.6%, in the medium class was 52.0%, and in the high class was 60.6%. For aquatic impact the mean percent ranked truth-value in the low class was 37.3%, in the medium class was 50.0%, and in the high class was 61.2%. For terrestrial impact, the mean percent ranked truth value in the low class was 36.9%, in the medium class was 51.9%, and in the high class was 58.9%. The ANOVA using randomization found significant differences among these classes with respect to mean percent ranked truth value for each of overall environmental impact, aquatic impact, and terrestrial impact ($P < 0.001$). Using Tukey's honestly significant difference ($\alpha = 0.05$), we found significant differences between the low and both medium and high, but not between medium and high for aquatic terrestrial and overall environmental impact results (Figure 3).

We compared the EMDS result with past road-management decisions made for a road subsystem in the TNF (End of the World project area, TNF). In contrast to the result above, using an ANOVA by randomization we found that the roads chosen for decommissioning (17 km) had a significantly lower ($P < 0.05$) mean percent-ranked truth value for overall environmental impact (mean percent-ranked TV = 38.8%) as compared to the roads that remained in commission (342 km; mean percent-ranked TV = 50.4%), in the project area. However, these two groups of roads showed no significant difference for either aquatic ($P = 0.11$) or terrestrial ($P = 0.07$) impact, separately.

During and immediately after intense storms in January 1997, there were 179 road-bed, road-surface, road-stream crossing, and road-cut failures in the TNF. Using an ANOVA with randomization, we compared the percent-ranked mean truth values for potential aquatic system impacts of road segments experiencing a failure with all other road segments in the TNF. The truth values for aquatic risk were significantly higher ($P < 0.001$) for the road segments with failure during the winter of 1997 (mean TV = 0.809; percent-ranked mean TV = 59.8%) than for road segments without

Figure 2. Subregion of the Tahoe National Forest used to show the range of potential impact scores. The "quantile" protocol in ArcView 3.2 was used to determine the range of EMDS truth-values for "low" (lowest third of values), "medium" (middle third), and "high" (top third) classes. (A) Relative potential for damage from roads to aquatic environment. (B) Relative potential for damage from roads to terrestrial environment. (C) Relative potential for damage from roads to aquatic AND terrestrial environments.

failures (mean TV = 0.729; percent-ranked mean TV = 49.1%).

Modifying the Road Network

The range of truth values for potential environmental impact (average per road segment) was linearly transformed to a range from 1.0 to 2.0. This resulted in these segments having a mean normalized score of 1.56 (SD = 0.18). This normalized score was then used as a multiplicative weight for adjusting the total cost of travel down a road segment. This total cost of travel was used in a least-cost path network analysis to 1573 points

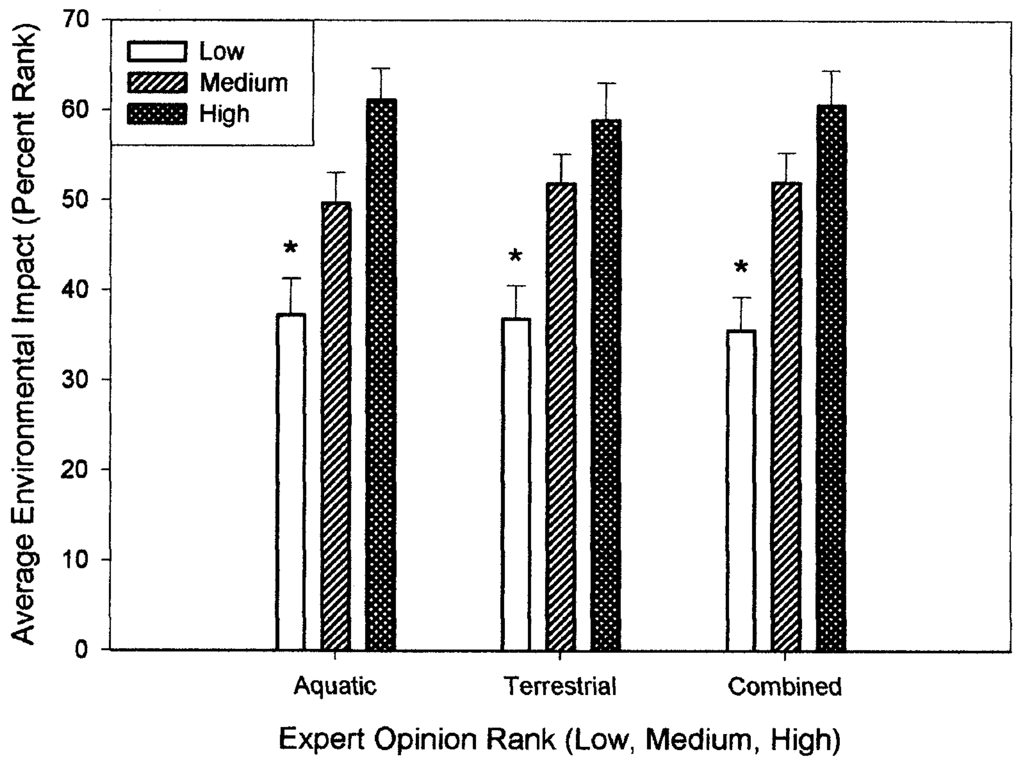

Figure 3. Relationship between EMDS truth values for risk from roads to aquatic, terrestrial, or total environment and risk as assessed by the TNF transportation engineer. Low, Medium, and High refer to the categories used by the engineer to denote relative risk in his expert opinion. Error bars show 95% confidence intervals around the mean truth value for the roads in each of the three categories. *Significant difference ($P < 0.05$, Tukey's HSD) between value (bar) and other values (bars) within group.

of interest within the TNF and within 1 km of a road. The network analysis showed that of 8233 km of road analyzed in TNF, 3483 km (42%) must be kept in the modified network to ensure access to all the identified points of interest (Figure 4). The modified network consisted of all highways and major paved roads, 71% of minor paved, 60% of gravel, 68% of improved dirt, and 30% of unimproved dirt roads from the original network. The total number of stream crossings in the modified network was 5627 (1.61 crossings/km), a 62% reduction in total crossings and a 16% reduction in crossing density as compared with the original network. However, the percentage of road network length on a > 30° slope and within 100m of a stream did not change in the modified network.

There are 2765 total patches defined by the original transportation network, with an average patch size of 182 ha, while there are 318 patches defined by the modified network, with an average patch size of 1646 ha. The largest patch increased in area from 40,757 ha in the original network to 45,295 ha in the modified network. The percent of total landscape area in roadless patches > 1000 ha increased from 69.8% in the original network to 93.0% in the modified network, and area in patches > 10,000 ha increased from 37.7% to 57.8% (Table 1). Proportions of patches in all size classes changed from the original to the modified network, with fewer patches in the smaller size classes (100 to 10,000 ha) and more in the large size classes (> 10,000 ha) for the modified network (Table 1).

Using the Arc/INFO extension FRAGSTATS (Pacific Meridian Resources 2000), we found that the area-weighted shape index decreased from 6.15 with the original network to 4.51 with the modified network, showing an improvement in overall landscape patch shape. In addition, a Mann-Whitney U test (JMP 4.0, SAS Institute 2000) showed the average shape index of patches in the three highest size classes (> 100 ha) was significantly lower ($P < 0.01$) in the modified network as compared to the original network and significantly higher in the three lowest size classes (< 100 ha) (Table 1).

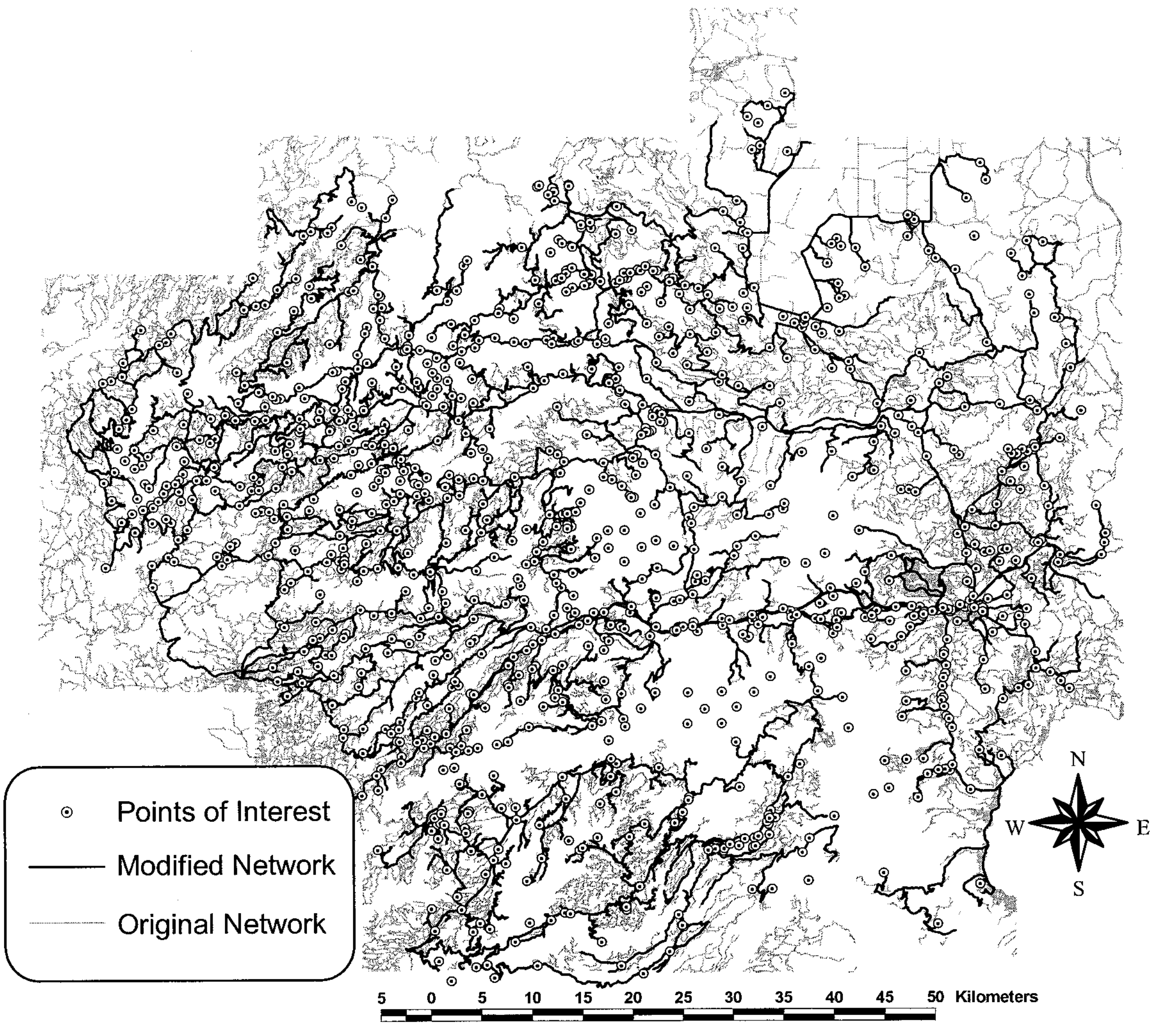

Figure 4. Original (light gray) and modified (black) road network within the administrative boundary of the TNF. The black dots show places of interest (derived from the USGS named places database (GNIS) and private property in-holdings within the TNF) used to develop the modified road network.

We calculated the length of cherry stem road per area (i.e., cherry stem density) for patches and found that patches in the original network have 18.58 km/km^2 of cherry stems while the modified network has 5.58 km/km^2. A Mann-Whitney U test (JMP 4.0, SAS Institute 2000) was used to determine differences in cherry stem density between patches in the original and modified road systems for patches delineated by roads > 10 ha. The modified network was found to delineate patches with significantly (P, 0.001) lower cherry stem road density than patches delineated by the original network. The results were also significant analyzing separately size classes of patches 10–100 ha ($P < 0.05$), patches 100–1000 ha ($P < 0.0001$), patches 1000–10,000 ha ($P < 0.0001$), and patches > 10,000 ha ($P < 0.001$).

Watershed Analysis

We calculated a watershed area-weighted environmental risk metric (WAWER) for each USFS-defined creek watershed (660 ha average size, Figure 5), producing an average value of 328.9 and a standard deviation of 219.4. The utility of this approach for forest planners and resource specialists is for prioritization of funds for "watershed protection" and to identify watersheds that might need special management attention. Since the spatial relationship of watersheds and the environmental impact of the road system are potentially complex, we also analyzed the spatial autocorrelation of WAWER values among neighboring planning watersheds. Moran's I was used to test for spatial autocorrelation of EMDS truth values using binary connec-

Table 1. Characteristics of patch size classes with the original and modified road networks[a]

	Number of patches		Area (ha)		% of landscape		Average shape index		Cherry stem length (m)	
	Original	Modified	Original	Modified	Original	Modified	Original	Modified	Original	Modfied
< 1 ha	619	61	232	13	0.0%	0.0%	1.73	2.13	< 0.1	< 0.1
1 to 10	900	65	3,355	291	0.6%	0.1%	1.59	1.72	7	< 0.1
10 to 100	801	68	26,007	2,611	5.0%	0.5%	1.78	2.26	189	76
100 to 1000	370	61	108,236	25,070	20.7%	4.8%	2.48	1.88	4,462	845
1000 to 10,000	67	51	168,022	184,404	32.1%	35.2%	4.66	2.67	46,523	17,734
> 10,000	8	12	197,310	302,469	37.7%	57.8%	8.95	5.31	345,769	187,740
Road Buffer	N/A	N/A	20,064	8,534	3.8%	1.6%	N/A	N/A	N/A	N/A

[a]Patches are the area of the landscape delineated by roads and were defined by the road lines plus a 10 m buffer. Shape index is a measure of the degree of edge convolution relative to interior area. "Cherry stems" are roads that extend into patches without forming a loop or exiting the patch.

tions between watersheds as the correlation distance (Lee and Wong 2001). Average EMDS truth values per planning watershed for aquatic impact, terrestrial impact, and combined environmental impact are significantly ($P < 0.001$) positively spatially autocorrelated.

Discussion

We used a knowledge base decision support model to determine potential environmental risk for all road segments in the Tahoe National Forest. This gives a relative value of risk to all road segments that can be used to support management decisions about the current road network. We then created a scenario where we used a least-cost analysis, taking into account potential environmental impacts and efficiency of travel to find an optimized transportation network, or modified network, to link 1573 points of interest (e.g., campgrounds, dams, etc.). Only 42% of the road system was needed to access these points, resulting in a network with less potential for environmental impact. The implications of this finding are that road systems in national forests are potentially more extensive than needed and that to correct this imbalance the US Forest Service is challenged with the daunting task of rationalizing the removal and then actually funding the removal of excess roads. The approaches demonstrated here are useful for any national forest conducting a roads analysis and for identification of roads for removal, subwatersheds facing relatively greater risk from road impacts, and impact of the road network on landscape patch characteristics. The TNF is continuing to use this approach for their roads analysis process. This method is relatively cheap and fast to implement, and it can serve as a continuing decision-support tool for road system management.

Data and Knowledge Gaps

A critical result of this process was organization and display of information available for road system analysis and the subsequent identification of data and knowledge gaps for understanding the potential impacts of the system. In response to the questions raised by the USFS guidance document (USDA 1999), the original knowledge base developed by the interdisciplinary (ID) team had twice as many components as the one used, but it was not used because of the lack of spatial data or knowledge about impact or causation. The ID team identified major data gaps as being distribution of wildlife, traffic disturbance, natural disturbance, spread of exotic species, and physical attributes of aquatic habitat. Major knowledge gaps included the actual impacts of the road system on geomorphological and hydrological processes and the actual interactions between the road system and wildlife and vegetation communities. One value of developing this knowledge base was to identify the data and knowledge gaps, which will inform future data collection and development by the US Forest Service. In road analyses completed by individual National Forests, these gaps should be clearly laid out, plans made to fill them, and gap filling implemented before the analysis is considered complete. One qualifier for this approach is that the products will be only as good as the expert opinion that went into developing the knowledge base and choosing appropriate data sources for the concepts addressed. In the worst case, we can say that application of this approach in the TNF to making analysis and decision-making objective and spatially explicit has been an improvement over the visual estimate of risk that was previously used in the forest. Because we did include findings from the literature (many of which are cited here) and the RAP manual (USDA 1999) in developing the system, the

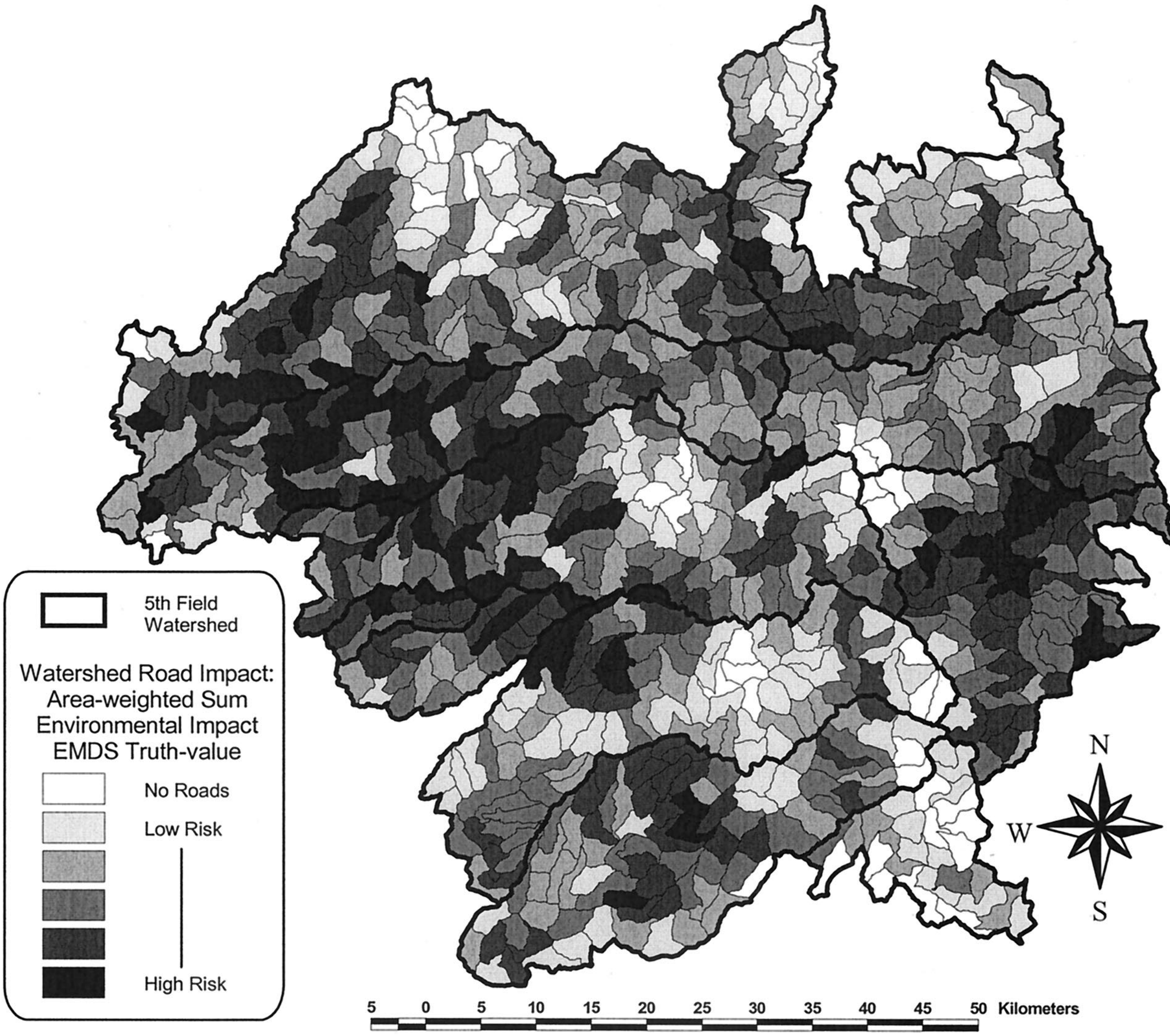

Figure 5. Subwatershed scale summed potential for damage from roads within the TNF network. The 5th field watershed boundaries (black lines) enclose major river forks, the subwatersheds (gray lines) enclose small creeks and stream forks. Truth values for roads within each sub-watershed were summed and the sum divided by the area of the sub-watershed. Note the clumping (similar shading) of watersheds within the west side of the TNF.

quality is improved over relying primarily on best guesses. An important question is whether or not inclusion of multidisciplinary expert opinion in knowledge base development is an improvement over other possible approaches for road system impact analysis.

Truth Values as Index of Impact

This analysis provides an index (truth values) for relative risk of environmental impact from the road system within the TNF. The truth values provide a numeric index of the degree of impact from a specific road segment on a particular resource of value (e.g., stream channel), which allows a high degree of resolution for monitoring or restoration activities by the TNF. Since the truth values are relative indices of impact and are not normally distributed, the data are best expressed in rankings or percent ranks, allowing for nonparametric statistical analyses to be performed. This also allows for better comparisons among assertions (e.g., aquatic and terrestrial) that may have different distributions of truth values from each other.

Modifying the Road Network

Road systems are a critical part of human interaction with natural landscapes as they facilitate the movement of goods from the landscape to human consumption

centers (Lugo and Gucinski 2000). The maintenance of an efficient and well-placed system is the main way to reduce the environmental and economic costs of a road-network-based rural economy. The network analysis we used to connect 1573 points of interest along the existing road network shows that less than half of the roads are needed to access these points. We showed that removal of roads not needed to access these points could have large habitat benefits by improving habitat patch size and shape and by reducing fragmentation. However, removing even the roads not needed for access to these points is a difficult task, because these roads can have many uses that were not captured by these points, such as recreation, fire suppression, range management, and silviculture. In addition, points of interest identified by the USGS may have no actual interested audience, or access to them may have unacceptable environmental cost, which may change the distribution of the points needing access. We ran this network analysis as a demonstration of how a modified road network could be derived from an existing road network, and different scenarios can be run to assist with management decisions. A more thorough analysis of road use in Tahoe National Forest would better show which roads could be removed.

One of our main findings was that modifying road systems to suit actual access needs and reducing superfluous routes of travel could reduce landscape fragmentation. The potential fragmentation effects of roads on the landscape and specific plant community types has been proposed as a quantifiable ecological impact that could be included in legally mandated environmental impact assessments (Treweek and Veitch 1996). Fragmentation of terrestrial habitat due to roads and other infrastructure can be measured through change in patch sizes, changes in patch edge to patch core ratios (i.e., shape index), and by results in disturbance from traffic and other road-related disturbance and facilitation of land-use resulting in changes in patch habitat values (Baker 2000). With the modified road system, we found improvements in patch sizes and shape, which could translate into benefits to wildlife negatively impacted by road system-induced fragmentation. These results agree with a national forest study in the Rocky Mountains that found that the establishment of logging roads resulted in an increase in "mean shape index," an increase in "high contrast edge density," a decrease in vegetation patch size, and a decrease in patch core area size (McGarigal et al., 2001). A next step is to analyze the effect of roads on fragmentation in terms of vegetation habitat patches (see Saunders et al., 2002). By analyzing roads and vegetation together, we will get a better idea of how fragmentation caused by roads affects natural vegetation patch dynamics. Future research could include how plant community patches are defined by natural processes (e.g., succession after fire) and management/extraction activities (e.g., thinning or clear-cutting). These processes may have edge effects and landscape-scale patterns that have effects on certain wildlife and plant communities and species. Intersection of actual land cover data with digitized roads would provide a more detailed assessment of the cooccurrence of habitat edges and roads and show the relative contribution of roads to both habitat and landscape fragmentation (Tischendorf 2001). This use of actual land cover and land-use history would also enrich any road analysis by relating human-caused "disturbance" with road networks. These data have been developed by the Tahoe National Forest but are not available to the public. Finally, fragmentation analysis could include road use as a factor, or at least road type as an indicator of use, which would allow traffic-related disturbance to be incorporated.

Watershed Analysis

The distribution of potential impact of the road system across planning watersheds revealed zones of similar degrees of impact (Figure 5). This observation of zonality was confirmed by the results of positive spatial autocorrelation among neighboring planning watersheds. The area with the highest EMDS truth values is on the west side of slope of the Sierra Nevada. These areas have been logged and mined more extensively than the Sierra Nevada crest, an area that has fewer roads and relatively lower risk scores. The potential impact from roads at different watershed and regional scales is critical for restoration and management decision making by USFS personnel.

Utility and Feasibility of EMDS for Roads Analysis

An important finding of this study was that a typical interdisciplinary team from a land-management agency could develop a decision-support geographic information system founded on a knowledge-base describing the natural and human landscape. Although difficult to quantify, the abilities of the team to understand the system, develop the knowledge base, and suggest data inputs were sufficient to develop the base road analysis described here.

Decision-support systems have been intentionally developed for assessment and planning associated with landscape-scale resource planning (Kangas et al., 2000, Zhu and Dale 2000). These tools and others like them are intended to support decision-making in policy arenas where multiple uses and management objectives are involved. In the case of the US Forest Service, an

EMDS-based roads analysis would show the assumptions made during the analysis, provide products immediately useful for prioritizing areas and roads for management action, and aid the agency and the public in discussing and potentially changing how the analysis was conducted. Past decisions and current decision-making processes and products could also be compared to the results of the knowledge-base approach, allowing for refinement of both approaches.

Finding significant similarity of model predictions with expert opinion and actual road failures shows the usefulness of this method for assessing environmental impacts of forest roads on one national forest. However, this tool is not a mathematical model in terms of providing quantified relationships between features of a road system and probability of road failure and should be used cautiously in this application. Rather, this method gives a relative degree of truth for environmental impact based on the assumptions laid out in the knowledge-base. This method should be repeated in other national forests and the results compared to the findings in the TNF to see if the method works under different environmental and geographic conditions. This type of approach and tool could have important benefits to a user agency involved in resource decision-making due to the transparency of the process and analysis developed.

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References

Baker, W. L. 2000. Measuring and analyzing forest fragmentation in the Rocky Mountains and Western United States. Pages 55–94 *in* R. L. Knight, F. W. Smith, S. W. Bruskirk, W. H. Romme, and W. L. Baker. Eds, Forest fragmentation in the southern Rocky Mountains. University of Colorado Press, Boulder, Colorado, USA.

Baker, W. L., and R. L. Knight. 2000. Roads and forest fragmentation in the Southern Rocky Mountains. Pages 97–122 *in* R. L. Knight, F. W. Smith, S. W. Bruskirk, W. H. Romme, and W.I. Baker. Eds, forest fragmentation in the Southern Rocky Mountains. University of Colorado Press, Boulder, Colorado.

Bell, S., and T. W. Ashenden. 1997. Spatial and temporal variation in nitrogen dioxide pollution adjacent to rural roads. *Water Air and Soil Pollution* 95(1–4):87–98.

Boone, R. B., and M. L. Hunter. 1996. Using diffusing models to simulate the effects of land use on grizzly bear dispersal in the Rocky Mountains. *Landscape Ecology* 11(1):51–64.

Chapin, T. G., D. J. Harrison, and D. D. Katnik. 1998. Influence of landscape pattern on habitat use by American marten in an industrial forest. *Conservation Biology* 12(6):1327–1337.

Clevenger, A.P., and N. Waltho. 2000. Factors influencing the effectiveness of wildlife underpasses in Banff National Park, Alberta, Canada. *Conservation Biology* 14(1):47–56.

Daly, C., R. P. Neilson, and R. P. Phillips. 1994. A statistical–topographic-model for mapping climatological precipitation over mountanious terrain. *Journal of Applied Meteorology* 33:140–158.

Dunham, J. B., and B. E. Rieman. 1999. Metapopulation structure of bull trout: influences of physical, biotic, and geometrical landscape characteristics. *Ecological Applications* 9(2):642–655.

ESRI (Environmental Systems Research Institute) 1998. ArcInfo 7.2. ESRI, Redlands, California.

ESRI (Environmental Systems Research Institute) 1999. ArcView 3.2. ESRI, Redlands, California.

Fahrig, L. 2001. How much habitat is enough?. *Biological Conservation* 100:65–74.

Findlay, C. S., and J. Houlahan. 1997. Anthropogenic correlates of species richness in southeastern Ontario wetlands. *Conservation Biology* 11(4):1000–1009.

Forman, R. T. T. 2000. Estimate of the area affected ecologically by the road system in the United States. *Conservation Biology* 14(1):31–35.

Gill, J. A., W. J. Sutherland, and A. R. Watkinson. 1996. A method to quantify the effects of human disturbance on animal populations. *Journal of Applied Ecology* 33(4):786–792.

Gjessing, E., E. Lygren, L. Berglind, T. Gulbrandsen, and R. Skanne. 1984. Effect of highway runoff on lake water quality. *Science of the Total Environment* 33:247–257.

Hoffman, R. W., C. R. Goldman, S. Paulson, and G. R. Winters. 1981. Aquatic impacts of deicing salts in the central Sierra Nevada Mountains, California. *Water Resources Bulletin* 17:280–285.

Jonsen, I. D., and L. Fahrig. 1997. Response of generalist and specialist insect herbivores to landscape spatial structure. *Landscape Ecology* 12:185–197.

Kangas, J., R. Store, P. Leskinen, and L. Mehtatalo. 2000. Improving the quality of landscape ecological forest planning by utilizing advanced decision-support tools. *Forest Ecology and Management* 132:157–171.

Lidicker Jr, W. Z. 1999. Responses of mammals to habitat edges: an overview. *Landscape Ecology* 14:333–343.

Lee, J., and D. W. S. Wong. 2001. Statistical analysis with ArcView GIS®. John Wiley & Sons, New York.

Lugo, A. E., and Gucinski. 2000. Function, effects, and management of forest roads. *Forest Ecology and Management* 133(3):249–262.

Mac, R. D., J. S. Waller, T. L. Manley, L. J. Lyon, and H. Zuuring. 1996. Relationships among grizzly bears, roads and habitat in the Swan Mountains, Montana. *Journal of Applied Ecology* 33(6):1395–1404.

Madsen, A. B. 1996. Otter *Lutra lutra* mortality in relation to traffic, and experience with newly established fauna passages at existing road bridges. *Lutra* 39(2):76–88.

Maltby, L., A. B. A. Boxall, D. M. Farrow, P. Calow, and C. I. Betton. 1995. The effects of motorway runoff on freshwater ecosystems. 2. Identifying major toxicants. *Environmental Toxicology and Chemistry* 14:1093–1101.

Manly, B. J. F. 1997. Randomization, bootstrap, and Monte Carlo methods in biology. Chapman and Hall, London.

McGarigal, K., and B. J. Marks. 1995. FRAGSTATS: spatial pattern analysis program for quantifying landscape structure. General Technical Report PNW-GTR-351. USDA Forest Service, Pacific Northwest Research Station, Portland, Oregon.

McGarigal, K., W. H. Romme, M. Crist, and E. Roworth. 2001. Cumulative effects of roads and logging on landscape structure in the San Juan Mountains, Colorado (USA). *Landscape Ecology* 16:327–349.

Meyers, T. J., and S. Swanson. 1995. Impact of deferred rotation grazing on stream characteristics in central Nevada: a case study. *North American Journal of Fisheries Management* 15(2):428–439.

Mitra, B., H. D. Scott, J. C. Dixon, and J. M. McKimmey. 1998. Applications of fuzzy logic to the prediction of soil erosion in a large watershed. *Geoderma* 86:183–209.

Nearing, M. A. 1997. A single, continuous function for slope steepness influence on soil loss. *Soil Science Society of America Journal* 61:917–919.

Putman, R. J. 1997. Deer and road traffic accidents: options for management. *Journal of Environmental Management* 51(1):43–57.

Reijnen, R., R. Foppen, and G. Veenbaas. 1997. Disturbance by traffic of breeding birds: evaluation of the effect and considerations in planning and managing road corridors. *Biodiversity and Conservation* 6(4):567–581.

Renard, K. G., and V. A. Ferreira. 1993. RUSLE model description and database sensitivity. *Journal of Environmental Quality* 22(3):458–466.

Reynolds, K. 1999. Netweaver for EMDS user guide (version 1.1); a knowledge base development system. General technical Report PNW-GTR-471. USDA Forest Service, Pacific Northwest Research Station, Portland, OR.

Reynolds, K., C. Cunningham, L. Bednar, M. Saunders, M. Foster, R. Olson, D. Schmoldt, D. Latham, B. Miller, and J. Steffenson. 1996. A knowledge-based information management system for watershed analysis in the Pacific Northwest US. *AI Applications* 10:9–22.

Rosenberg, K. V., J. D. Lowe, and A. A. Dhondt. 1999. Effects of forest fragmentation on breeding tanagers: a continental perspective. *Conservation Biology* 13(3):568–583.

Rottenborn, S. C. 1999. Predicting the impacts of urbanization on riparian bird communities. *Biological Conservation* 88(3):289–299.

Rubin, E. S., W. M. Boyce, M. C. Jorgensen, S. G. Torres, C. L. Hayes, C. S. O'Brien, and D. A. Jessup. 1998. Distribution and abundance of bighorn sheep in the Peninsular Ranges, California. *Wildlife Society Bulletin* 26(3):539–551.

SAS Institute 2000. JMP 4.0. SAS Institute, & Inc, Cary, North Carolina.

Saunders, M. C., R. N. Coulson, and J. Folse. 1990. Applications of artificial intelligence in agriculture and natural resource management. Pages 1–14 *in* A. Kent, and J. Williams. Eds, Encyclopedia of computer science and technology. Vol 25, suppl. 10. Marcel Dekker, New York.

Saunders, S. C., M. R. Mislivets, J. Chen, and D. T. Cleland. 2002. Effects of roads on landscape structure within nested ecological units of the northern Great Lakes region, USA. *Biological Conservation* 103(2):209–225.

Theobald, D. M., J. R. Miller, and N. T. Hobbs. 1997. Estimating the cumulative effects of development on wildlife habitat. *Landscape and Urban Planning* 39(1):25–36.

Tischendorf, L. 2001. Can landscape indices predict ecological processes consistently?. *Landscape Ecology* 16:235–254.

Treweek, J., and N. Veitch. 1996. The potential application of GIS and remotely sensed data to the ecological assessment of proposed new road schemes. *Global Ecology and Biogeography Letters* 5:249–257.

Trombulak, S. C., and C. A. Frissell. 2000. Review of ecological effects of roads on terrestrial and aquatic communities. *Conservation Biology* 14(1):18–30.

USDA 1999. Roads analysis: informing decisions about managing the national forest transportation system. Misc. Rep. FS-643. USD Agriculture Forest Service, Washington DC, 222 pp.

USDA 2001. Forest roads: a synthesis of scientific information. Page 120 *in* H. Gucinski, M. J. Furniss, R. R. Ziemer, and M. H. Brookes. Eds, General Technical Report PNW-GTR-509. USD Agriculture Forest Service, Washington, DC.

Wilcox, D. A. 1986. The effects of deicing salts on vegetation in Pinhook Bog, Indiana. *Canadian Journal of Botany* 64:865–874.

Yahner, R. H. 1988. Changes in wildlife communities near edges. *Conservation Biology* 2(4):333–339.

Zadeh, L. 1965. Fuzzy Sets. *Information and Control* 8:338–353.

Zhu, X., and A. P. Dale. 2000. Identifying opportunities for decision support systems in support of regional resource use planning: an approach through soft systems methodology. *Environmental Management* 26(4):371–384.

Ziegler, A. D., and T. W. Giambelluca. 1997. Importance of rural roads as source areas of runoff in mountainous areas of northern Thailand. *Journal of Hydrology* 196(1-4):204–229.