GIS-Generated, Expert-Based Models for Identifying Wildlife Habitat Linkages and Planning Mitigation Passages

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Abstract: *We developed three black bear (* Ursus americanus*) habitat models in the context of a geographic information system to identify linkage areas across a major transportation corridor. One model was based on empirical habitat data, and the other two (opinion- and literature-based) were based on expert information developed in a multicriteria decision-making process. We validated the performance of the models with an independent data set. Four classes of highway linkage zones were generated. Class 3 linkages were the most accurate for mapping cross-highway movement. Our tests showed that the model based on expert literature most closely approximated the empirical model, both in the results of statistical tests and the description of the class 3 linkages. In addition, the expert literature–based model was consistently more similar to the empirical model than either of two seasonal, expert opinion–based models. Among the expert models, the literature-based model had the strongest correlation with the empirical model. Expert-opinion models were less in agreement with the empirical model. The poor performance of the expert-opinion model may be explained by an overestimation of the importance of riparian habitat by experts compared with the literature. A small portion of the empirical data to test the models was from the pre-berry season and may have affected how well the model predicted linkage areas. Our empirical and expert models represent useful tools for resource and transportation planners charged with determining the location of mitigation passages for wildlife when baseline information is lacking and when time constraints do not allow for data collection before construction.*

Modelos Generados con GIS y Basados en Expertos para la Identificación de Conexiones del Hábitat para Vida Silvestre y la Planeación de Pasajes de Mitigación

Resumen: *Desarrollamos tres modelos para el hábitat del Oso Negro (* Ursus americanus*) en el contexto de un sistema de información geográfico para identificar las áreas de conexión a lo largo de un corredor de transporte grande. Un modelo estuvo basado en datos empíricos del hábitat y los otros dos (basados en opinión y en literatura) estuvieron basados en información de expertos desarrollada mediante un proceso de criterios múltiples y de toma de decisiones. Validamos el funcionamiento de los modelos con un juego de datos independiente. Se generaron cuatro clases de zonas de conexión en carreteras. Las conexiones clase 3 fueron las más precisas para el mapeo de movimientos de cruce de carreteras. Nuestras pruebas muestran que el modelo basado en literatura de expertos fue el que se aproximó más al modelo empírico, tanto en los resultados de las pruebas estadísticas, como en la descripción de las conexiones de clase 3. Aunado a esto, el modelo basado en la literatura de expertos fue consistentemente más similar al modelo empírico que cualquiera de los dos modelos estacionales basados en la opinión de los expertos. Entre los modelos de expertos, el modelo basado en la literatura tuvo la correlación más alta con el modelo empírico. Los modelos de opinión de expertos tuvieron menos concordancia con el modelo empírico. El bajo rendimiento de los modelos basados en*

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la opinión de los expertos puede ser explicado por una sobrestimación de los expertos de la importancia del hábitat ripario comparado con lo que se establece en la literatura. Una pequeña porción de los datos empíricos usados para probar los modelos correspondió a la estación previa a las bayas y pudo haber afectado la eficacia de los modelos para predecir las áreas de conexión. Nuestros modelos empíricos y de expertos representan herramientas útiles para los encargados del manejo de recursos y la planeación de la transportación y los que necesitan determinar la ubicación de pasajes de mitigación para la vida silvestre, cuando se carece de información base y cuando las limitantes de tiempo no permiten la recolección de datos antes de iniciar la construcción.

Introduction

During the last 30 years a substantial amount of time and energy has been spent designing and building mitigation passages across roadways. Surprisingly few studies have assessed the efficacy of these measures (Foster & Humphrey 1995; Pfister et al. 1997; Clevenger & Waltho 2000). More remarkable is that few methodological approaches to determine the placement of mitigation passages along road corridors have been explored. Most often, the location of wildlife passages is derived from information on the spatial distribution of wildlife-vehicle collisions, primarily where road-kill densities are highest (Reed et al. 1975; Singer & Doherty 1985; Evink 1996). Other methods for locating passages might utilize data obtained from radio-monitoring of animal movements or tracking surveys along roads (Evink 1996; Kobler & Adamic 1999; Scheick & Jones 1999). But not all transportation planners and land managers have the luxury of possessing preconstruction data on animal movements, their crossing locations, and road-kill locations or the time to initiate studies to acquire these data because infrastructure planning decisions are usually made over a short period of time.

Modeling habitat linkages with a geographic information system (GIS) is another means of determining optimal placement of wildlife crossing structures. With the increasing availability of digital data on habitat suitability, biophysical features, and land use, GIS tools and applications are becoming more popular among resource managers and transportation planners for amassing information and modeling the potential effects of roads (Dale et al. 1994; Reed et al. 1996; Treweek & Veitch 1996; Vos & Chardon 1998; Smith 1999). A biometrically based habitat-linkage model is preferred to qualitative or conceptual models based on limited data (Clark et al. 1993). In many cases, however, data necessary for empirically based models are not available. As a substitute for an empirically based model, expert information can be used to develop simple, predictive habitat-linkage models in a relatively short period of time (Marcot 1986; Giles 1998). Expert information may consist of models based on the opinion of experts or qualitative models based on the best information available from the literature (Servheen & Sandstrom 1993; Boone & Hunter 1996; Singleton & Lehmkuhl 1999).

With the advent of GIS there is now the opportunity for a more explicitly reasoned environmental decision-making process based on qualitative or expert-opinion data in multicriteria evaluations (Eastman et al. 1995). The multicriteria decision-making process is attractive in the context of transportation planning because the results are geographically coherent and meaningful in terms of the criteria specified. Further, it is a conservation tool that is easy for the nonexpert to use and understand (Stewart 1992), and it can provide robust results (Ralls & Starfield 1995).

We developed three different but spatially explicit habitat models to identify linkage areas across a major road corridor. One model is based on empirical data, and the other two are based on expert information developed in a multicriteria decision-making process. We used the empirical model as a yardstick with which to measure the accuracy of the expert-based models. We created decision rules for identifying linkage zones and validated the expert-based models with field data on crossing and mortality locations. Our purposes were to introduce these methods into the conservation biology literature and to encourage the use of structured decision-making methods in the spatial planning and mitigation of road networks.

Methods

Our study was carried out in Banff National Park (BNP), Alberta, Canada. Specifically, we focused on the Trans-Canada highway (TCH) transportation corridor between Castle Mountain junction and the provincial border between Alberta and British Columbia. This section of highway is 30 km long and has two lanes and an average summer daily traffic volume of 13,100 vehicles per day (Parks Canada Highway Services, unpublished data). Plans exist to upgrade this section to four lanes with fencing and wildlife crossing structures within the next 5–10 years.

The Trans-Canada highway in BNP runs along the floor of the Bow Valley, sharing the valley bottom with the Bow River, the township of Banff (population 9000), several high-volume two-lane highways, numerous secondary roads, and the Canadian Pacific Railway. The TCH is the major transportation corridor through the park (park length 76 km), carrying an estimated 5 million visitors to the park per year, with an additional 5 million users en route between Calgary and Vancouver (Parks Canada Highway Services, unpublished data).

The Bow River Valley in BNP is situated within the front and main ranges of the Canadian Rocky Mountains. Its topography is regarded as mountainous; elevations range from 1300 m to over 3400 m, and the width of the valley floor varies from 2 to 5 km. The climate is continental and characterized by relatively long winters and short summers (Holland & Coen 1983). Mean annual snowfall at the town of Banff is 249 cm. The transportation corridor traverses the montane and subalpine ecoregions. Vegetation consists of open forests dominated by Douglas fir (*Pseudotsuga menziesii*), white spruce (*Picea glauca*), lodgepole pine (*Pinus contorta*), aspen (*Populus tremuloides*), buffaloberry (*Shepherdia canadensis*), juniper (*Juniperus communis*), bearberry (*Arctostaphylos uva-ursi*), and natural grasslands.

We selected black bears (*Ursus americanus*) as the species with which to model habitat use and identify linkage areas across the TCH. Black bears were the only species in the park for which we had sufficient empirical location data to build a habitat model and sufficient field data from crossings and mortality locations to test the model. Although we were unable to prove that the unsuccessful crossing locations were different from successful ones, we assumed that mortality locations were crossing locations.

Empirical Model Development

HABITAT SELECTION

To develop the empirical habitat model, we first determined the habitat characteristics of black bears in the study area. We obtained data by monitoring the movements of nine radiocollared black bears between 1998 and 1999. Radiolocations were distributed throughout the 24-hour period and obtained on average every 2 days. We conducted radiotelemetry from the ground using standard techniques (Kenward 1987). The average telemetry error tested at the onset of the study (Zimmerman & Powell 1995) was 145 m ($\pm$33 m SE, 95% confidence limits). Locations were assigned a universal transverse mercator coordinate, referenced to $\pm$50 m on orthocorrected aerial photograph maps and later converted to GIS maps with Idrisi software (Eastman 1997). Digital maps were in a raster format with a pixel size of 30 $\times$ 30 m. More than 95% of all telemetry locations were $<$2 km from the TCH, so we delineated the study area (16,170 ha) by buffering the road at that distance. A total of 580 radiolocations were used in the analysis.

Nine biophysical variables were used in the analysis. Elevation, slope, and aspect were extracted from the 1:50,000 digital elevation model. Terrain ruggedness (TR) was calculated within a 250-m radius and a 500-m radius based on the following formula:

$$\mathrm{TR} = ([\mathrm{CD}r]^*[\mathrm{AV}r])/([\mathrm{CD}r] + [\mathrm{AV}r]), \qquad (1)$$

where CD is the density of contour lines within a given kernel, AV is the variability of eight cardinal aspects within a given kernel, and r is kernel size. A classified, validated habitat map did not exist for the study area, so we used a LANDSAT thematic mapper (TM) satellite image to develop a pseudohabitat map. The image was transformed into greenness and wetness bands by the tasselled-cap transformation of the six TM bands (1, 2, 3, 4, 5, and 7) designed to emphasize vegetation. Increasing values of greenness related to increasing amounts of deciduous, green vegetation (e.g., leaf-area index). Wetness was designed to emphasize vegetation moisture content. From the hydrology theme of the digital 1:50,000 national topographic database, we obtained values for distance to nearest drainage (running water of streams, creeks, rivers) and density of water bodies (running water, ponds, lakes, dammed water).

We analyzed the data with the programs Microsoft Excel and SPSS (SPSS 1998) for Windows. We used a probability function that tied the distribution of bear locations to the variables in the study area (Pereira & Itami 1991; Manly et al. 1993). To incorporate the landscape perception depth of black bear, we tied the dimensions of the kernels (500-m radius) that were used to calculate landscape indices and radiotelemetry density maps to the reported average daily movement rates of black bears (Alt et al. 1980; Garshelis et al. 1983). To account for telemetry error, each location was buffered 175 m (the maximum average error recorded in our tests) and assigned a probability of occurrence (PO) value. Where buffers overlapped we assigned a higher PO value, with a multiplying factor equal to the number of mutually overlapping buffers. The PO value was adjusted for the kernel and pixel size so that a single, isolated telemetry point and buffer would have, within a moving window of a given size, a value equal to 1. To facilitate statistical analysis, we stratified the density maps into PO classes. We removed all density values below 0.5 animals per kernel area (the null class) and calculated the twenty-fifth, fiftieth, and seventy-fifth percentile for each of the density distributions. These percentiles were used as the cut-out values in defining four PO categories: low ($<$25%), moderate (25–50%), high (50–75%), and very high ($>$75%). We generated a stratified random sample of points to extract and then compare the landscape and biophysical descriptors of the land within each of the PO categories.

One of the basic assumptions of radiotelemetry studies assessing habitat selection is that the sample of marked animals is representative of the population being investigated. To meet this criterion, optimally, a random sample of individual animals of a statistically sufficient size should be drawn from within the study area. For logistical reasons, this could not be accomplished in our study. Therefore, we decided against the frequently practiced univariate-selection-versus-avoidance approach to habitat modeling. Instead we identified explicitly directional trends in habitat selection across the full set of the PO categories supported by the statistical analysis of the observed patterns. In terms of how bears use the landscape, the consistency of the observed patterns of land use (e.g., a decrease in elevation synchronized with a decrease of the density of radiolocations) forms a more compelling argument than statistical significance between the used and avoided habitat categories. This approach did away with the null class, defined as areas where no animal locations were found and often wrongly labelled as avoided. Our approach—random sampling of the PO categories as an alternative to using actual radiotelemetry locations—also overcame problems associated with low sample sizes and potential spatial autocorrelation of the radiocollared animals, but it did not fully mitigate the effects of a nonrandom selection of the study animals. Another potential error within the model stems from the fact that the limited number of radiolocations allowed us to develop only a cumulative model of black-bear habitat that did not take into account potential differences in seasonal habitat use.

HABITAT MODEL

The univariate analysis does not reveal the relative importance of the biophysical variables to habitat selection. We therefore used a multivariate discriminant-function analysis (DFA) to address these questions. We used the Mahalanobis distances criterion in the stepwise method for entry and removal of variables. To improve power, we opted for binary models contrasting very high PO with the low PO. We judged the relative contribution of the variables with an analysis of the order in which the variables were entered and removed, combined with the analysis of the structure matrix and the magnitude of the standardized canonical-function coefficients. We estimated the overall power of the models by scrutinizing the eigen values, Wilk's lambdas, canonical correlation coefficients, and the percentage of correctly classified cases. Approximately 10% of the locations ($n = 68$) from the black bear telemetry database were excluded from the habitat-selection analysis and reserved to test the validity of the model. To develop spatially explicit empirical habitat models, we used the GIS environment to apply the DFA findings to calculate the Mahalanobis distances (to group centroids) for each pixel of the study area and to calculate the posterior probabilities of group membership (a probability of a given pixel belonging to the high probability of occurrence group) (Clark et al. 1993; Knick & Rotenberry 1998).

Development of Expert Models

Both expert habitat models were developed as weighted linear combinations of each model's layers (landscape and biophysical variables) obtained by (1) expert opinion or (2) review of the literature on black bear habitat requirements. With a weighted linear combination approach, we combined the variables by applying a weight to each, followed by a summation of the results to yield a suitability map. This procedure is not uncommon in GIS and has a form similar to a regression equation (Eastman et al. 1995). All GIS software systems provide the basic tools for evaluating such models, but the main issues relate to the standardization of criteria scores and the development of weights.

Although there are an assortment of techniques for developing weights, one of the most promising appears to be that of pairwise comparisons developed by Saaty (1977) in the context of a decision-making process known as the analytical hierarchy process (Rao et al. 1991; Eastman et al. 1995). This technique is particularly appealing because it serves as an excellent vehicle for discussion of the criteria and objectives involved and their relative strengths (Starfield & Herr 1991; Llewellyn et al. 1996). The pairwise comparisons concern the relative importance of the two criteria involved in determining suitability for the stated objective—in our study, black bear habitat. In developing the weights, a group of individuals (minimum of two) compares every possible pairing and enters the Saaty ratings into a pairwise comparison matrix. Ratings are on a nine-point continuous scale: 9, extremely more important; 7, very strongly more important; 5, strongly more important; 3, moderately more important; 1, equally more important; 1/3, moderately less important; 1/5, strongly less important; 1/7, very strongly less important; and 1/9, extremely less important (Saaty 1977). In terms of black bear habitat, south-facing slopes were considered moderately more important than north-facing slopes (Table 1). In the procedure for multicriteria evaluation using a weighted linear combination, it is necessary that the weights sum to 1. Because the pairwise-comparison matrix has multiple paths by which the relative importance of criteria can be assessed, we determined the degree of consistency, or the consistency ratio, used in developing the ratings. The consistency ratio indicated the probability that the matrix ratings were randomly generated. If matrices had consistency ratios of >1.0, they were reevaluated by the group of individuals, as recommended by Saaty (1977).

OPINION-BASED MODEL

The expert opinion–based model required the collaboration of experts in assessing the importance of variables

Table 1. Example of a pairwise-comparison matrix for assessing the relative importance of within-variable features (aspect).

	North	*East*	*South*	*West*
North	1			
East	1/5	1		
South	3	1/3	1	
West	1/7	1/3	1/5	1

influencing black-bear habitat selection in the study area. We solicited the cooperation of five biologists with substantial experience studying black-bear habitat. Two experts committed themselves to developing the weights for the pairwise comparison matrix. The investigators had 47 years of experience combined (30 and 17 years) studying black bears and their habitat in the Bow River Valley. We provided the experts with a list of potential variables for the habitat model. We considered only variables with accompanying digital layers. Initially we solicited input from the experts in selecting variables for building the model and dividing them for the pairwise comparison matrix. Once their input was received, we arranged a time when the experts could meet with us to perform the weighting process and complete the pairwise-comparison matrix.

We met with the experts to carry out the multicriteria evaluation. The experts agreed on the variables selected and the within-variable categories to use in the model. They decided not to score year-round variables but preferred to divide them into two seasons relevant to the biological needs of bears: pre-berry season (den exit to 15 July) and berry season (15 July to den entry). Scoring of the matrix was done within and among variables. We used five habitat variables in the analysis: elevation, slope, aspect, greenness, and distance to nearest drainage. Pixel and kernel sizes were kept constant throughout the analysis. The time required to perform the pairwise comparisons (n = 12) for both seasons was 90 minutes.

LITERATURE-BASED MODEL

Expert models based on data obtained from the literature were developed in the same fashion as the expert-opinion models. Instead of experts providing weights for the variables, we used the available literature on black-bear habitat selection to assist us in weighting the variables and completing the pairwise-comparison matrices. Three of the authors (A.P.C., B.C., and K.G.) carried out this part of the study. The authors had no prior knowledge of the pattern of bear movements across the TCH and therefore believe that there was no bias in weighting the variables from the literature. After searching the literature, we selected three sources of information on black-bear habitat use for the model. Two of the studies were habitat-related and one was movement-related; all were based in the Bow Valley (Holroyd & VanTighem 1983; Beak Associates Consulting 1989; Serrouya 1999). We searched the literature to obtain as much information as possible on black-bear habitat needs. We used information from the study area, preferably from within the same ecoprovince if available. The same variables were scored in a pairwise-comparison procedure as for the expert opinion model. All pairwise comparisons were carried out with the "weight" procedure in the Idrisi geographic analysis software (Eastman 1997). The time required to conduct the 12 pairwise comparisons was 110 minutes. Once the comparisons were completed, we developed criteria maps by multiplying each factor map (i.e., each raster cell within each map) by its weight and then summing the results.

Linkage-Zone Identification

We based our linkage-analysis model on the assumption that the probability of a bear crossing a highway increases in areas where the highway directly bisects high-quality bear habitat, and that the highest probability of crossings occurs in areas where a set of topographic and landscape features are conducive to lateral, cross-valley movements.

To facilitate statistical comparisons between the empirical and expert-based models, the latter being a habitat-suitability-index (HSI) type of model (U.S. Fish and Wildlife Service 1980, 1981), we reclassified the continuous empirical habitat-quality surface into 20 habitat favorability (or probability) classes, indexed from low (0%) to high (100%). We then applied the same rule to the expert models. The reclassification process allowed us to express the best black bear habitat as a percentage of the maximum habitat-favorability value, regardless of the unit of measurement (a probability value for the empirical model and the highest HSI–type score for the expert models). We defined prime black bear habitat as areas with habitat favorability values of >70% for both model types.

We used the GIS environment to generate four classes of highway crossing/habitat linkage zones: class 1, sections of TCH crossing prime black bear habitat extending up to 100 m on both sides of the highway; class 2, sections of TCH crossing prime black bear habitat extending over 100 m on both sides of the highway; class 3, sections of TCH ≥250 m away from any permanent human development, nested within the class 2 linkages and within the areas conducive to cross-valley movement (interactively mapped with orthophotographs and a digital-elevation model of the area); and class 4, sections of TCH not directly crossing the prime black bear habitat but having such habitat within no more than 700 m on both sides of the highway.

Data Analysis

We used a set of empirical black bear crossing and mortality points to test each of the linkage models. Crossing locations were defined as the point on the TCH connecting a straight line between consecutive radiolocations on opposite sides of the road and obtained within 24 hours. Mortality locations were obtained from the BNP wildlife mortality database (Banff National Park, unpublished data). We tested whether black bear empirical crossing and mortality points were randomly distributed with respect to the distance to the linkage zones. To do this we generated a random set of highway crossings, equal in size to the empirical set, and calculated the distances from both sets of points to the class 3 and 4 linkage zones. We repeated these calculations for each of the habitat models and used the kappa index of agreement to measure the similarity between models and linkage areas (Campbell 1996). The kappa index is a measure of association for two map layers with exactly the same number of categories. Indices range from 0.0 (no agreement) to 1.0 (spatially identical). Between map layers, values of >0.75 indicate excellent agreement beyond chance; values between 0.4 and 0.75 demonstrate fair to good agreement; and values of <0.4 indicate poor agreement (SPSS 1998). We used the SPSS (version 8.0) statistical package for all analyses (SPSS 1998) and the software Idrisi to measure the kappa index of agreement (Eastman 1997).

Results

Empirical Model

HABITAT SELECTION

Black bears selected relatively gentle terrain at lower elevations in the areas of high concentrations of and close proximity to water and in the areas of reduced wetness index (Table 2). The latter often corresponds with valley-bottom coniferous stands with semi-open vegetation types. There was no selection for greenness. Bears preferred flat areas (0–3°) with southerly aspects (χ^2 = 3072.8, df = 32, $p < 0.0001$; Fig. 1).

Table 2. Analysis-of-variance parameter estimates of black bear habitat selection in the Bow River Valley, Banff National Park, Alberta, Canada.

Dependent variable	*Parameter*	*Mean*	*SE*	p
Elevation	low	1656.9	3.17	0.000
	moderate	1582.6	3.23	0.000
	high	1537.9	3.11	0.000
	very high	1516.6	3.06	0.000
Greenness	low	21.4	0.133	0.558
	moderate	21.8	0.135	0.067
	high	21.1	0.130	0.000
	very high	21.0	0.128	0.790
Slope (degrees)	low	9.66	0.178	0.000
	moderate	8.38	0.182	0.000
	high	6.62	0.175	0.000
	very high	4.75	0.172	0.000
Wetness	low	−13.3	0.106	0.000
	moderate	−13.4	0.107	0.000
	high	−14.3	0.103	0.000
	very high	−14.7	0.102	0.007
Terrain ruggedness (<250 m)	low	0.119	0.002	0.000
	moderate	0.109	0.002	0.000
	high	0.089	0.001	0.000
	very high	0.076	0.001	0.000
Terrain ruggedness (<500 m)	low	0.128	0.001	0.000
	moderate	0.118	0.001	0.000
	high	0.098	0.001	0.000
	very high	0.076	0.001	0.000
Distance to nearest drainage	low	421.5	7.29	0.000
	moderate	365.0	7.43	0.000
	high	358.6	7.14	0.000
	very high	288.9	7.03	0.000
Density of water bodies	low	0.026	0.000	0.000
	moderate	0.030	0.000	0.000
	high	0.030	0.000	0.000
	very high	0.033	0.000	0.000

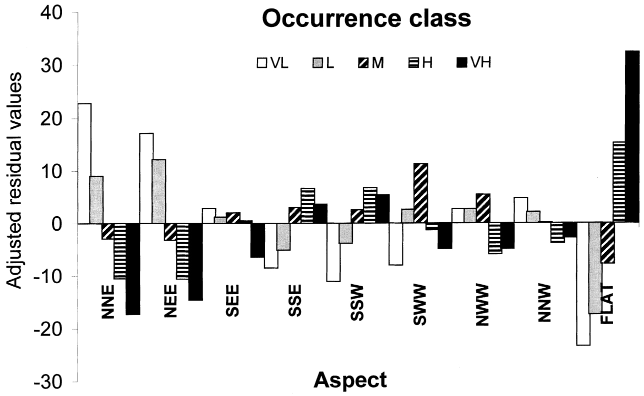

Figure 1. Adjusted residuals based on cross tabulation of selection of aspect by black bears with the probability of occurrence classes (VL, very low; L, low; M, moderate; H, high; VH, very high).

HABITAT MODEL

We generated the most parsimonious model with the following eight variables (in order of importance): elevation, flat aspect, south-southeast aspect, south-southwest aspect, density of water bodies, distance to drainages, slope, and terrain ruggedness. The order of importance is that of a multivariate type and was based on the analysis of the standardized-function coefficients. The structure matrix is its univariate equivalent because it shows the bivariate correlations of the variables with the DFA (Table 3). Here, slope, distance to drainages, and terrain ruggedness showed a much greater contribution to the model, superseding south-southwest and south-southeast aspects. The relatively small, standardized coefficients of slope, terrain ruggedness, and distance to drainages are a result of their intercorrelations as confirmed by the covariance matrices. Overall, the DFA produced a sound statistical model. The high canonical correlation coefficient (0.755) indicated that the DFA was strong and discriminated well between the groups. Also, the Wilk's lambda was low (0.43), denoting a relatively high discriminating power of the DFA. The overall cross-validated classification accuracy was 86.5%. The model correctly classified 78.6% of the set-aside radiolocations into prime black-bear habitat.

We tested each of the linkage models with a set of 37 empirical black bear crossing and mortality points. With respect to the distances to the class 4 linkages, the analysis showed no statistical difference between the empirical crossings and random locations ($p > 0.05$). We interpreted this as an indication that class 4 linkages were a poor predictive tool for mapping cross-highway movement. The differences between the distance from the empirical points and random locations to the class 3 linkages were significant. There was strong statistical evidence that the empirical bear crossing and mortality locations were much closer to class 3 linkages than expected by chance for the empirical model ($p = 0.018$), the expert opinion-based berry-season model ($p = 0.027$), and the expert literature-based model ($p = 0.005$) (Fig. 2). Distances from the empirical points to the class 3 linkages for the expert opinion-based pre-berry-season model were not significantly different from the random locations ($p = 0.10$).

Descriptive statistics of the class 3 linkage zones showed both that seasonal expert opinion-based models had more linkage zones and that they were on average smaller in length than the empirical and expert literature-based model linkage zones (Table 4). There was a relatively strong correlation between the empirical model and the expert literature-based model (kappa index = 0.662). The expert opinion-based pre-berry-season and berry-season models were only fair (0.416) to moderate (0.569) in agreement with the empirical model.

The expert literature-based model most closely approximated the empirical model, both in the results of the statistical tests and the description of the class 3 linkages. To further our understanding of the similarities and differences among the three models, we compared them in terms of the level of juxtaposition of both the prime bear-habitat maps and the class 2, 3, and 4 linkage zones (Table 5). Class 1 linkages were excluded from the analysis because they were nested within class 2 linkages. The expert literature-based model was consistently more similar to the empirical model than either of the two expert opinion-based models. Class 3 linkages for all three expert models had the greatest similarity with the empirical model. Class 4 associations were the weakest of all. Among the expert models, the literature-based model had the strongest correlation with the empirical model. Expert opinion-based models ranged in kappa index measures from 0.02 to 0.44, whereas expert literature-based models varied from 0.25 to 0.55.

Discussion

Geographic information system-based models have been used elsewhere to examine dispersal and connectivity in complex landscapes and to identify large-scale wildlife corridors. Grid- and vector-oriented least-cost path models have been used to simulate the movements of individual animals from diverse taxa with varying dispersal potential and habitat needs (Schippers et al. 1996; Bakker et al. 1997; Singleton & Lehmkuhl 1999). An individual-based diffusion model was used to simulate grizzly bear (*U. arctos*) response to land-management practices and habitat fragmentation in the Rocky Mountains of the United States (Boone & Hunter 1996). Yet GIS models specifically addressing the effects of human activities, including road networks designed to identify habitat linkages, are relatively recent in origin (Servheen & Sandstrom 1993; Boone & Hunter 1996; Apps 1997; Singleton & Lehmkuhl 1999). How ro-

Table 3. Standardized discriminant-function coefficients and structure matrix of discriminant-function analysis of black bear habitat model in Banff National Park, Alberta, Canada.[a]

Standardized discriminant-function coefficient		*Structure matrix[b]*	
variables	*function 1*	*variables*	*function 1*
Slope (degrees)	0.069	elevation (m)	−0.747
Terrain ruggedness (<500 m)	0.060	density of water bodies	0.587
Distance to nearest drainage	−0.090	flat	0.507
Density of water bodies	0.290	slope (degrees)	−0.505
Flat	0.559	distance to nearest drainage	−0.454
South-southeast	0.406	terrain ruggedness (<500 m)	−0.411
South-southwest	0.338	south-southwest	0.151
Elevation (m)	−0.627	south-southeast	0.112

[a]Variables are ordered by absolute size of correlation within function.
[b]Pooled within-groups correlations between discriminating variables and standardized canonical discriminant functions.

bust these models are at actually predicting corridors for dispersal and habitat linkages remains uncertain because no validation tests were conducted.

Our GIS-based models differ from those developed previously because they are spatially explicit and local in scale and not regional or large-scale models. Nonetheless, the model function of identifying critical linkages between habitats and across potential barriers caused by roads is the same. Model building is a deductive-inductive process, with model formulation and validation occur-

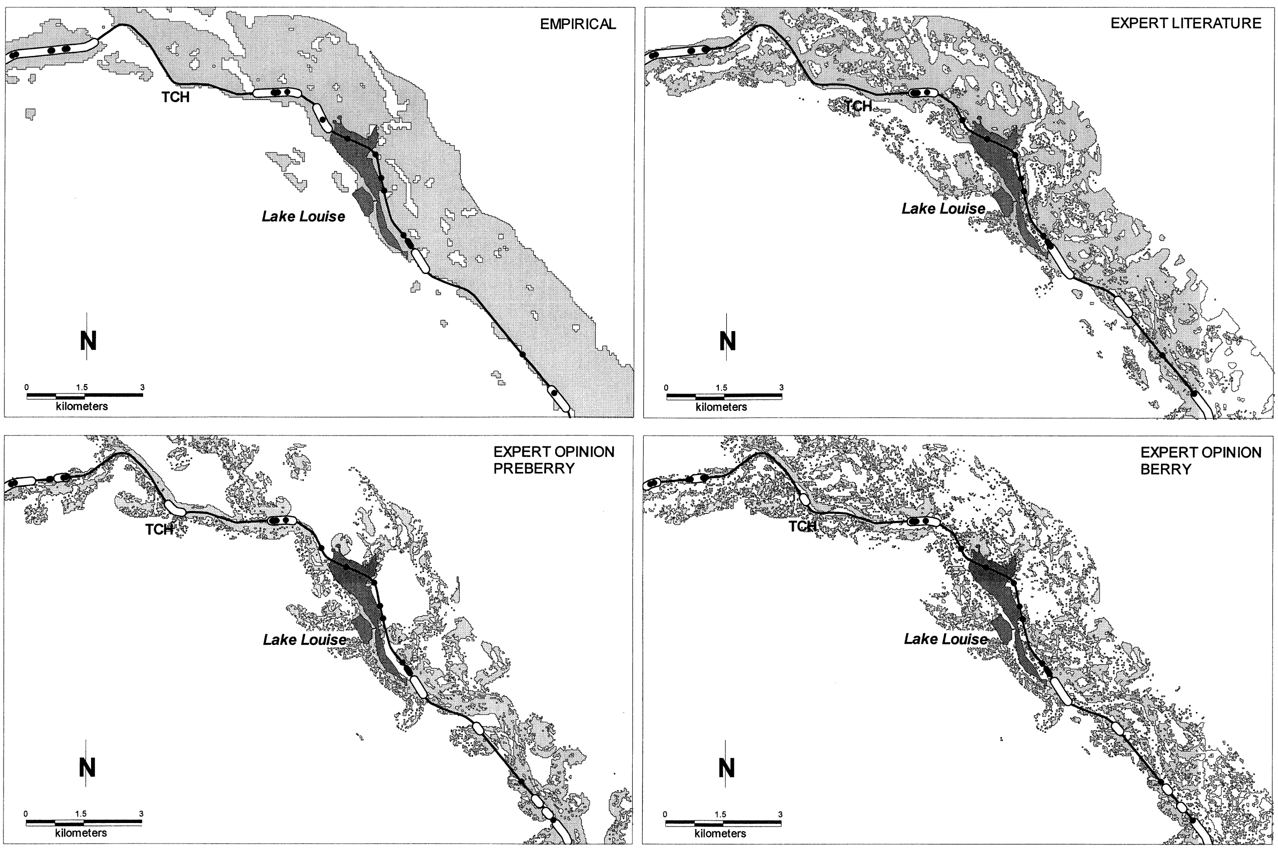

Figure 2. Location of empirical black bear crossings and mortality locations (black dots) with respect to class 3 linkage zones (white blocks) on the Lake Louise (dark shading) portion of the Trans-Canada highway (TCH, thin line) in Banff National Park, Alberta, Canada. Linkage zones were generated from models based on empirical habitat data, expert literature, expert opinion relative to the pre-berry season, and expert opinion relative to the berry season. Light shading around the TCH corresponds to prime black bear habitat.

Table 4. Physical characteristics of class 3 linkages* of empirical and expert linkage-zone models.

Linkage model	n	*Total length (km)*	*Mean length (km)*	*Minimum length (km)*	*Maximum length (km)*
Empirical	11	8.6	0.78	0.20	2.70
Expert opinion, pre-berry season	17	5.7	0.33	0.13	0.93
Expert opinion, berry season	18	4.7	0.26	0.08	0.72
Expert literature	9	6.3	0.70	0.30	1.90

**Identified as sections of Trans-Canada highway (TCH) ≥250 m away from permanent human development and nested within the class 2 linkages and within the areas conducive to cross-valley movement. Class 2 linkages were sections of TCH that crossed prime black bear habitat and extended over 100 m on both sides of the highway.*

ring iteratively (Stormer & Johnson 1986). Assumptions of our model were that linkages between high-quality bear habitat across road corridors were where black bears were most likely to travel and become vulnerable to collisions with motor vehicles. Contrary to other models, we tested the validity of the biometrically based or empirical model in terms of its ability to predict habitat-linkage areas across a major transportation corridor. Linkage areas identified from the expert literature–based model showed a relatively strong correlation with those identified by the empirical model, whereas the other expert models conformed less. Further, we devised a set of decision rules for delineating linkage zones across roads, which to our knowledge has not been done before.

The most noteworthy result from the exercise was not the lower performance of the expert opinion–based model but the approximation of the expert literature–based model to the empirical model. Our findings confirmed that the expert literature–based model was consistently more similar and conformed to the empirical model better than any of the expert opinion–based models. These results were based on the test of distribution of the empirical points from actual crossing and mortality locations in relation to the linkages, the descriptive characteristics of the class 3 linkages, the measure of agreement between models, and the measure of agreement between model linkage zones.

The poor predictive power of the pre-berry expert opinion–based model may be explained by an overestimation (on the part of experts) of the importance of riparian habitat to the pre-berry habitat model compared with the opinions expressed in the literature. Another possible explanation for the difference between the two expert models is that the expert-literature model is based on an analytical process (data have been collected, statistically analyzed, and summarized), whereas the expert-opinion model is based on how experts perceive attributes from memory and experience. Furthermore, the fact that only 35% of the empirical black bear crossing and mortality locations were those of the pre-berry season may also have influenced how well it predicted linkage areas.

Table 5. Comparison of kappa index of agreement[a] of the empirical black bear habitat model with expert opinion–based models and expert literature–based model.

	Empirical model[b]		
Expert models	*class 2*	*class 3*	*class 4*
Expert opinion, berry season	0.3679	0.3792	0.3618
Expert opinion, pre-berry season	0.3243	0.4411	0.0274
Expert literature	0.4271	0.5568	0.2529

[a]The kappa index is a measure of association for two map layers with exactly the same number of categories. Indices range from 0.0 (no agreement) to 1.0 (spatially identical).
[b]See Table 4 for explanation of linkage classes.

There are several advantages to the expert-based techniques presented here. An assortment of GIS tools designed for model-building purposes are readily available today. Geographic information system applications such as Idrisi (Clark University, Worcester, Massachusetts), MapInfo Professional Software (MapInfo Corporation, Troy, New York), and ArcView GIS (Environmental Systems Research Institute, Redlands, California) are relatively inexpensive and easy to use. Idrisi has decision-support procedures as a program module built into the geographic analysis system. Remotely sensed data, digital land-cover data, and habitat-suitability maps are increasingly accessible, frequently updated, and refined for individual users or government agencies. Further, empirical data from field studies of most wildlife species, particularly game species, are obtainable in most developed countries where road-mitigation practices are presently implemented. The use of the Saaty's pairwise-comparison matrix requires little training and ensures consistency in developing relative weights for the expert-based models. This procedure is readily available in the Idrisi software package.

We recognize the shortcomings this work. Our empirical model predicted annual habitat selection by black bears and did not take seasonality into account. As mentioned earlier, this was not possible given the amount of field data available. Given the cumulative nature of the empirical model, however, the validation test was based on location data from both pre-berry and berry seasons and still demonstrated that the model was robust at predicting habitat use. We did not use vegetation cover as a variable in the models because the TM satellite imagery was not classified and validated in time for the study. Previous work showed that high greenness was highly selected by bears (Mace et al. 1999), so we used greenness as a surrogate for vegetation cover. We were unable to prove that the unsuccessful crossing locations (mortality locations) were different from successful ones (crossing locations). When the empirical points were plotted over the digital-elevation model, however, we found that crossing locations were associated with major drainages and that a high proportion of the mortality locations were <200 m from the nearest drainage.

Transportation planning for roads and highways has generally considered a one-dimensional, linear zone along the highway. Thus, engineering and design dimensions have been the primary concern for planners. But the ecological effects of roads are many times wider than the road itself and can be immense and pervasive (Forman & Alexander 1998; Trombulak & Frissell 2000). Because of the broad landscape context of road systems, it is essential to incorporate landscape patterns and processes into the planning and construction process (Forman 1987). When used in a GIS environment, regional- or landscape-level connectivity models can facilitate the identification and delineation of barriers and corridors for animal movement (van Bohemen et al. 1994; Bekker et al. 1995). This provides for the development of a more integrated land-use strategy by taking into account different land-management practices and prioritization of habitat-conservation concerns. With this approach, the site-specific, one-dimension (linear), sectional road-planning schemes traditionally used by transportation agencies will be relinquished, thereby promoting a more integrated, larger-scale methodological procedure that contemplates landscape patterns and processes in the planning of transportation corridors (Bennett 1999).

Our results should not be interpreted as a devaluation of the use of experts in developing resource-management strategies (Lein 1997; O'Connor 2000). Identifying linkage areas across road corridors with both expert model types (opinion- and literature-based) we have presented can provide a useful tool for resource and transportation planners charged with determining the location of mitigation passages for wildlife when baseline information is lacking and when time constraints do not allow for collection of preconstruction data. Regarding the latter, we spent approximately 2 months developing the four models. More than half of that time was dedicated to developing the more complex empirical black bear habitat model. We do not advocate modeling linkage zones based exclusively on expert information if empirical data are available, but we do encourage others with empirical data for model building and testing to develop expert models concurrently so that their findings may be contrasted with ours.

Roads will continue to be of major ecological significance, functioning as conduit, habitat, source, and sink (Bennett 1991; Forman 1995), yet there is increasing interest worldwide in sustainable transport systems. Road networks, wildlife corridors, and mitigation passages will undoubtedly play an increasingly critical role in ensuring that landscape patterns and processes are maintained, restored, and, if necessary, enhanced (Forman 1998). Mitigation planning will provide an excellent opportunity to integrate ecological processes and flows into the broader fabric of human land use.

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