Quantifying barrier effects of roads and seismic lines on movements of female woodland caribou in northeastern Alberta

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Abstract: Linear developments such as roads, seismic lines, and pipeline rights-of-way are common anthropogenic features in the boreal forest of Alberta. These features may act as barriers to the movement of threatened woodland caribou (*Rangifer tarandus caribou*). Thirty-six woodland caribou were captured and fitted with global positioning system collars. These collared caribou yielded 43 415 locations during the 12-month study period. We compared rates of crossing roads and seismic lines with rates at which caribou crossed simulated roads and seismic lines created using ArcInfo GIS. Seismic lines were not barriers to caribou movements, whereas roads with moderate vehicle traffic acted as semipermeable barriers to caribou movements. The greatest barrier effects were evident during late winter, when caribou crossed actual roads 6 times less frequently than simulated road networks. Semipermeable barrier effects may exacerbate functional habitat loss demonstrated through avoidance behaviour. This novel approach represents an important development in the burgeoning field of road ecology and has great potential for use in validating animal-movement models.

Résumé : Les structures linéaires, telles que les routes, les lignes sismiques et les passages de pipe-lines, sont des éléments anthropogènes communs dans la forêt boréale de l'Alberta. Ces structures peuvent créer des barrières aux déplacements du caribou des bois (*Rangifer tarandus caribou*), une sous-espèce menacée. Trente-six caribous des bois ont été capturés et munis d'un collier émetteur relié au système de positionnement global. Ces caribous ont fourni 43 415 données de repérage au cours des 12 mois qu'a duré l'étude. Nous avons comparé la fréquence des traversées de routes et de lignes sismiques chez ces caribous et la fréquence des traversées de routes et de lignes sismiques simulées créées au moyen du logiciel ArcInfo GIS. Les lignes sismiques n'entravent pas les déplacements des caribous, alors que les routes où l'achalandage de véhicules est modéré ont un effet de barrières semiperméables aux déplacements des caribous. Les effets inhibiteurs ont été manifestes surtout à la fin de l'hiver, alors que les caribous ont traversé 6 fois moins de routes réelles que de routes virtuelles. L'effet de barrière semiperméable peut exacerber la perte d'habitat fonctionnel, tel que le démontre le comportement d'évitement. Cette nouvelle approche représente un pas important dans le domaine nouveau de l'écologie des routes et sera très utile pour valider les modèles de déplacement des animaux.

[Traduit par la Rédaction]

Introduction

Linear developments such as roads, seismic lines, and pipeline rights-of-way are common anthropogenic features in the boreal forest of Alberta. In addition to direct mortality associated with human access to linear corridors (Johnson 1985), there is increasing concern that these features may act as barriers to the movement of woodland caribou (*Rangifer tarandus caribou*). Roads may present considerable barriers to movement for many species (Oxley et al. 1974; Mader 1984; Clarke et al. 1998). Fragmentation of populations in this way may reduce local population sizes and cause local extinctions (Fahrig and Merriam 1985, 1994; Lande 1988; Saunders et al. 1991). The influence of roads on biota is considered the great "sleeping giant" of ecology (Forman and Alexander 1998). If linear developments do act as barriers to caribou movements, they may exacerbate functional habitat degradation through avoidance behaviour (Dyer et al. 2001) and as a consequence, fragment threatened caribou populations in northeastern Alberta.

Studies addressing potential barriers to caribou movements focus on short-term responses of migratory barren-ground caribou, *Rangifer tarandus granti*, to human structures. Many anecdotal accounts and descriptive studies have attempted to assess the effects of human developments as barriers to caribou movements (Miller et al. 1971; Johnson and Todd 1977; Roby 1978; Klein 1980; Whitten and Cameron 1983; Bergerud et al. 1984). Roads and railways have been implicated in the abandonment of traditional migration routes by reindeer in Eurasia (Klein 1971, 1980), although Bergerud et al. (1984) challenged the assertion that these developments are barriers, arguing that range reductions caused by population de-

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clines due to overhunting are instead responsible for these observations. Controlled experiments that rigorously test hypotheses are less common and tend to be labour-intensive and limited to small areas (Curatolo and Murphy 1986; Eide et al. 1986).

Methodologies that exist to examine crossing success of small animals are well defined and generally involve capture and recapture of organisms on opposite sides of local obstacles (Oxley et al. 1974; Mader 1984). Studies with larger mammals have examined the importance of culverts and other non-wildlife passages (Yanes et al. 1995; Rodriguez et al. 1996) and specialized crossing structures (Reed 1981; Singer and Doherty 1985) to animal crossing success, but no technique presently exists to rigorously quantify crossing success over larger areas. In this study we used geographic information system (GIS) technology to examine whether linear developments are barriers to woodland caribou movements.

Description of study area

The study area is approximately 6000 km^2 of boreal mixed-wood and peatland vegetation (Strong and Leggat 1992) in northeastern Alberta, Canada (centre at 56°N, 113°W), located at the southwest corner of the Athabasca oil-sands deposits (Crandall and Prime 1998). There is minimal topographic variation within the study site, with elevation varying between 500 and 700 m above sea level. Lowland vegetation includes black spruce (*Picea mariana*) and black spruce – tamarack (*Larix laricina*) bogs and fens. Upland areas are dominated by trembling aspen (*Populus tremuloides*), white spruce (*Picea glauca*), jack pine (*Pinus banksiana*), and black spruce. In 1998 the study area contained 236 km of improved gravel roads accessible by two-wheel-drive vehicles and 7111 km of seismic lines (lines cut for geophysical exploration, generally with a width of 5–9 m).

Materials and methods

Twenty-two adult female and 1 adult male woodland caribou were captured and collared on 17–19 February 1998. Animals were captured using a Hughes 500C helicopter and net gun. Each caribou was fitted with a global positioning system (GPS) collar (Lotek Engineering Systems, Newmarket, Ont.). Caribou were recaptured in January 1999 and refitted with collars with new batteries. Thirteen additional caribou (all adult females) were captured using the same methods and fitted with GPS collars in January 1999. Caribou locations were collected at both 2- and 6-h intervals throughout the study. All animal-treatment procedures were approved by the Canadian Council on Animal Care Animal Welfare Protocol, University of Alberta Biosciences Animal Care Committee (No. 230901).

GPSHost software (Lotek Engineering Systems, Newmarket, Ont.) was used to download caribou locations from GPS collars. Owing to the selective availability policy of the U.S. Department of Defense, these uncorrected locations are accurate to 40–65.5 m (Moen et al. 1997). Caribou locations were corrected using N3Win Version 2.40, a differential correction program that reduces the locational error created by selective availability to 4–5 m (Rempel and Rodgers 1997). The N3Win program uses a base station as a reference point for satellite signals (Alberta–Pacific Mill site, latitude 54°55′17.60387′′N, longitude 112°51′44.99926′′W, elevation 654.837 m). Corrected GPS locations were entered into a GIS (ArcInfo version 7.1.1, Environmental Systems Research Institute Inc., Redlands, Calif.).

Digital geographic data for the study area were obtained from Alberta–Pacific Forest Industries, Lorrnel Consultants, Veritas DGC Inc., Focus Corporation Ltd., and individual oil companies active in the study area (projection: UTM, Zone 12; datum: NAD 27). Data on vehicle traffic on roads in the study area were collected using Unicorn Traffic Classifiers (Diamond Traffic Products, Oakridge, Oreg.). These consisted of two electromagnetic loops placed under the road surface and attached to a monitoring device that recorded the length and velocity of passing vehicles and the date and time of each record. Three traffic classifiers were placed throughout the study-area road network to obtain an index of vehicle-traffic levels in the study area. These data were augmented with two human-observation traffic surveys at three locations during February 1998 (late winter) and August 1998 (summer). No attempt was made to monitor the level of activity on seismic lines.

GIS analysis

The crossing analysis was performed for five distinct time periods: late winter (22 February 1998 – 30 April 1998), calving (1 May 1998 – 30 June 1998), summer (1 July 1998 – 15 September 1998), rut (16 September 1998 – 15 November 1998), and early winter (16 November 1998 – 21 February 1999). These time periods closely approximate different behaviour periods for woodland caribou (Bergerud 1975). The distinction between early and late winter is arbitrary and is related to the initial caribou capture dates. Spatial analysis was performed using the Arc Macro Language programming functionality of ArcInfo version 7.1.1 GIS. We generated minimum convex polygon home ranges (Mohr 1947) for each caribou for each time period and calculated the total length and density of roads and seismic lines in each home range. Any caribou home range that was completely included in the study area and contained at least 2 km of either linear feature was included in the analysis. Consecutive caribou locations were linked in a join-the-dot trajectory and each time this trajectory crossed either linear feature was recorded. To generate a control linear category we used the following strategy. One hundred pairs of random points were generated within a defined box that encompassed each home range. Each pair of randomly generated points was used to generate a line. This procedure resulted in 100 random lines of various lengths within the defined area. Portions of lines that fell outside home range were removed, so the remaining lines were completely contained within the home range. Lines were randomly selected one by one until a density of linear features ±10% of the actual density of roads or seismic lines in each home range was achieved. These lines became a simulated road or seismic-line network (Fig. 1). No attempt was made to model differences in habitat type in individual caribou home ranges.

The same caribou trajectory was laid over this control linear-feature network and the number of "crossings" recorded. Random line generation was repeated 200 times for each caribou for

Fig. 1. Woodland caribou (*Rangifer tarandus caribou*) home ranges with an actual road network (*a*) and random control road networks created at the same density as the actual road network (*b*–*d*). Two hundred control networks were created per caribou per time period, and the mean number of crossings was used to generate the control crossing frequency for each caribou.

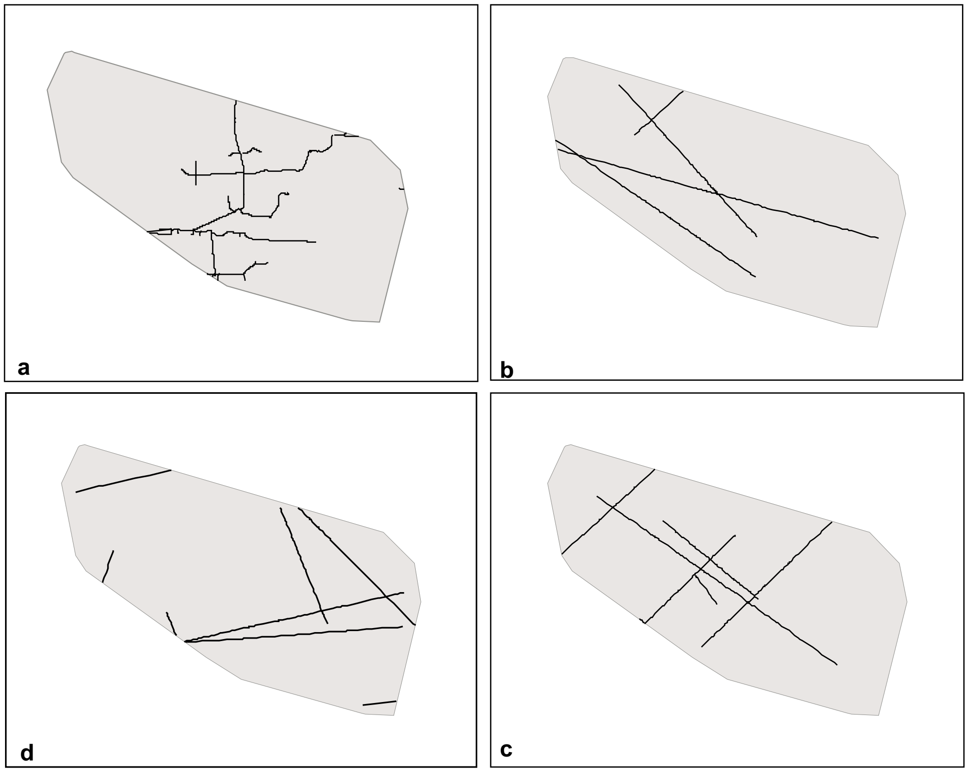


Table 1. Woodland caribou (*Rangifer tarandus caribou*) home-range size, density of roads within home ranges, and number of actual and control road crossings recorded during four time periods.

	Late winter (n = 8)	Calving (n = 6)	Summer (n = 6)	Rut (n = 5)
Home-range size (km^2)	289.4 (200.5)	198.2 (181.2)	269.5 (244.2)	242.1 (114.8)
Density of roads in home range (km/km^2)	0.1 (0.1)	0.2 (0.2)	0.2 (0.1)	0.3 (0.2)
Number of actual crossings	4.1 (4.8)	6.8 (7.1)	15.8 (17.1)	14.4 (6.5)
Number of control crossings	21.6 (16.2)	19.2 (20.7)	45.7 (43.4)	46.1 (30.8)

Note: Values are given as the mean with the standard deviation in parentheses.

each time period for each linear disturbance to provide a mean number of "control crossings" to compare to actual crossing rates.

Crossing times were approximated by calculating the time exactly half way between two caribou locations that intersected a linear feature. The total numbers of crossings was summarized for each 2-h period.

Statistical analyses were performed using the SPSS statistical program (version 6.1, SPSS Inc., Chicago). Owing to a combination of collar failure, caribou mortality, and caribou distribution, too few caribou (3) had roads within their home ranges in early winter for this time period to be included in the analysis. Normality of data was tested using Kolmogorov–Smirnov tests (Zar 1984). Log and arcsine transformations were used where appropriate (Narusis 1994). The actual number of crossings per time period was compared with the mean number of control crossings using paired-sample t tests (Zar 1984). In all cases, p values <0.05 were considered to be statistically significant.

Results

The GPS collars yielded 43 415 locations during the 12-month study period. Caribou crossed both actual and control roads (Table 1) and seismic lines (Table 2) during all time periods. Sample sizes were greater for the seismic-line analysis because not all caribou home ranges contained improved roads. Caribou crossed roads significantly less than controls during late winter (t = 3.876, df = 7, p = 0.006), summer (t = 2.710, df = 5, p = 0.042), and rut (t = 3.982, df = 4, p = 0.016). Caribou crossed roads less frequently than controls during calving, although this difference was not statistically significant (t = 2.143, df = 5, p = 0.085) (Fig. 2). The greatest barrier effects were evident during late winter, when caribou crossed actual roads almost 6 times less frequently than control roads (Fig. 2).

Caribou crossed seismic lines at a similar frequency to controls during all five time periods (late winter: t = 0.012, df = 22, p = 0.912; calving: t = 0.472, df = 15, p = 0.644;

Fig. 2. Number of road crossings per time period presented as a percentage of control crossings.

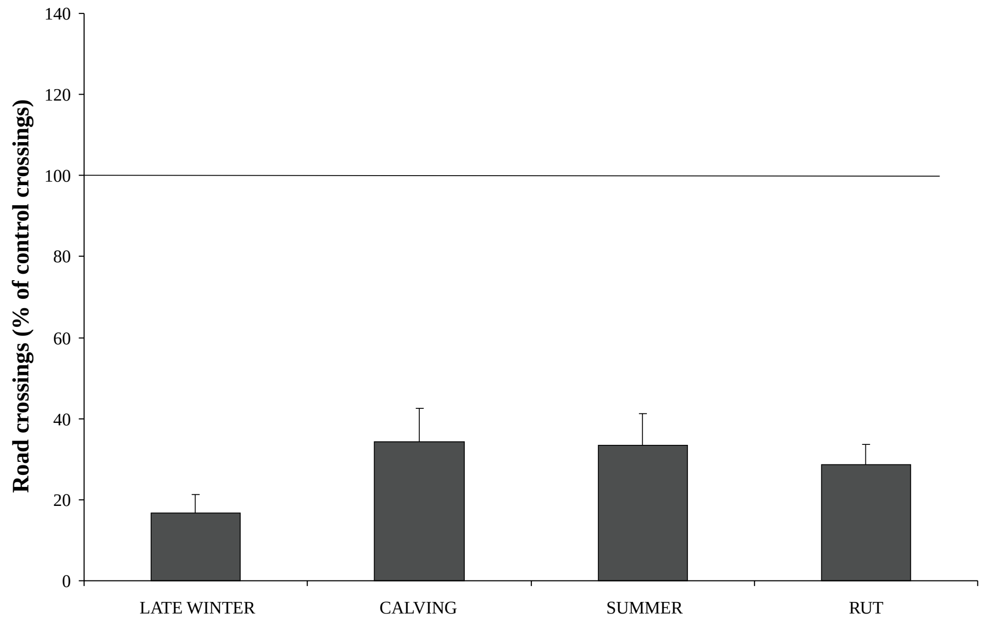


Table 2. Caribou home-range size, density of seismic lines within home ranges, and number of actual and control seismic-line crossings recorded for each time period.

	Late winter (n = 23)	Calving (n = 16)	Summer (n = 11)	Rut (n = 9)	Early winter (n = 17)
Home-range size (km^2)	222.7 (165.6)	99.6 (132.9)	108.5 (102.5)	203.5 (104.9)	192.5 (87.5)
Density of seismic lines in home range (km/km^2)	1.2 (0.3)	1.3 (0.4)	1.1 (0.4)	1.2 (0.3)	1.0 (0.6)
Number of actual crossings	153.1 (74.9)	114.8 (71.3)	134.0 (76.4)	195.6 (78.5)	119.5 (92.3)
Number of control crossings	154.2 (61.3)	110.1 (56.9)	140.1 (60.1)	175.4 (47.5)	111.6 (75.2)

Note: Values are given as the mean with the standard deviation in parentheses.

summer: t = 0.249, df = 10, p = 0.809; rut: t = –0.709, df = 7, p = 0.501; early winter: t = –1.071, df = 16, p = 0.300) (Fig. 3).

Caribou crossed roads throughout the day and night (Fig. 4). Crossings peaked between 8 a.m. and 10 a.m. and approximately 75% of crossings occurred between 6 a.m. and 6 p.m.

Daily records from the traffic classifiers ranged from 20.29 ± 9.38 (mean ± SD) vehicles per day during summer to 780.00 ± 73.87 vehicles per day during late winter. Human traffic monitors recorded higher traffic levels in late winter (91.46 ± 50.58) than in summer (61.67 ± 31.9). No road-traffic data were collected during other time periods.

Discussion

Even with a dense network of traffic classifiers, it is difficult to obtain detailed information about traffic levels on all roads in the study area at all times. Problems with severed recording loops and classifier battery failure meant that results from the traffic-classifier sites were not continuous. Nevertheless, a combination of the fragmentary classifier data and human sampling indicated a number of trends in vehicle traffic on roads in the study area. Roads were traveled by more traffic during winter than summer. This is not surprising because winter is the busiest season in the oilfield. It is expected that during calving and rut, traffic levels would be intermediate between these two extremes.

Caribou crossed roads significantly less frequently than expected during all time periods except calving. Maximum barrier effects occurred during late winter, when caribou crossed actual roads almost 6 times less frequently than control road networks. Caribou crossed seismic lines as often as expected during all time periods. Therefore, seismic lines were not barriers to caribou movements.

Dyer et al. (2001) demonstrated that there is a slight increase in the proportion of upland habitat close to roads in this study area. Although this effect was not statistically significant, it is acknowledged that habitat effects may result in a slight reduction in crossings compared with control roads. However, it is unlikely that the slight differences could have been responsible for the almost 6-fold reduction in crossings compared with control roads that was observed.

Caribou may cross roads less frequently than expected for a number of reasons, including an aversion to the physical barrier presented by a road and associated forest opening, vehicle traffic, or predation by humans. No studies have specifically tested the effects of different levels of vehicle traffic on caribou crossing success to see if thresholds to levels of vehicle traffic do exist. Barrier effects were more severe during late winter; this may have been due to higher traffic levels at

Fig. 3. Number of seismic-line crossings per time period presented as a percentage of control crossings.

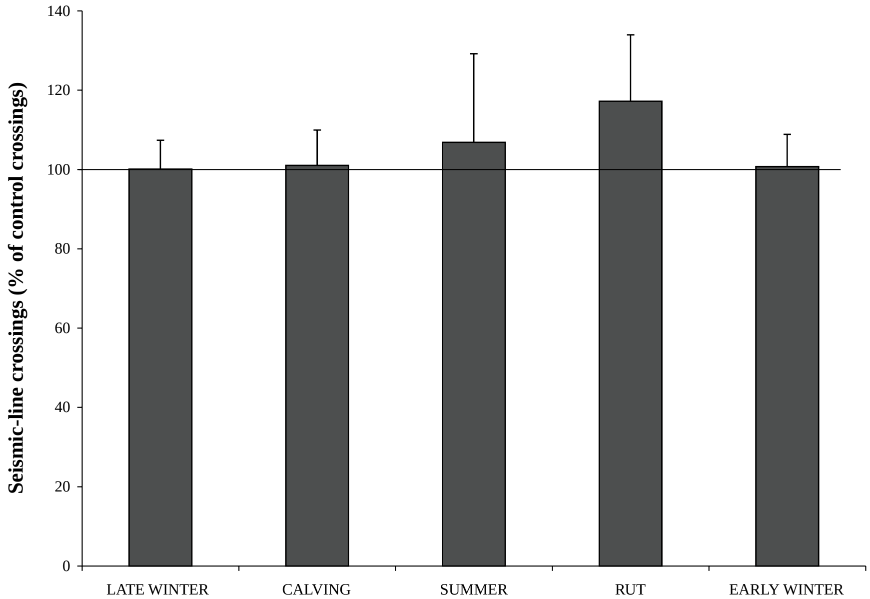
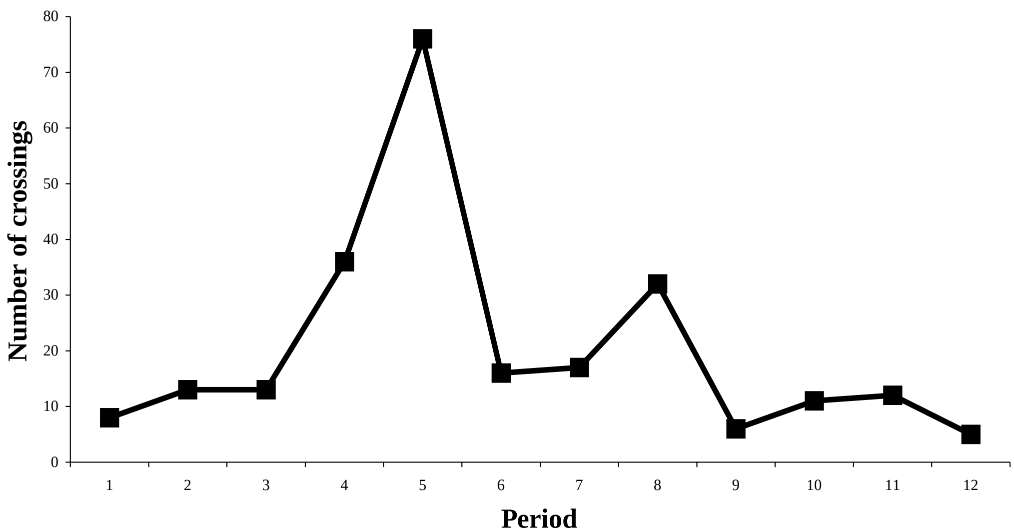


Fig. 4. Total number of road crossings per 2-h period. Period 1, 24:00–02:00; period 2, 02:00–04:00; period 3, 04:00–06:00, etc.



these times. Traffic levels were very low during summer, but significant barrier effects were also detected at this time. However, it should be noted that 75% of crossings took place between 6 a.m. and 6 p.m., when traffic levels in the study area should be highest. These peaks in crossing frequency likely correspond to periods of greater movement distances calculated by examining high-resolution location data for the same study area (Alastair Franke, personal communication).

Dyer et al. (2001) demonstrated that these caribou use areas close to roads and seismic lines less frequently than expected. Avoidance effects (areas of reduced use) were demonstrated up to 500 m away from developments. Semipermeable barrier effects associated with human developments could exacerbate the reduction in availability of habitat caused by avoidance effects. Klein (1980) states that caribou resident in areas of human developments should more readily habituate to human-associated disturbances than migratory caribou, which may encounter such disturbances only seasonally. Alternatively, the barriers presented by developments may have more severe consequences for woodland caribou habitat because sedentary animals may be less strongly motivated to cross developments (Klein 1980). Woodland caribou in northeastern Alberta are relatively sedentary, displaying no seasonal migrations (Stuart-Smith et al. 1997). Woodland caribou may therefore be less inclined to cross disturbance corridors than migratory barren-ground or mountain caribou, and barrier effects of these developments may be more pronounced.

Curatolo and Murphy (1986) reported that caribou in Alaska crossed roads and pipelines as frequently as controls. The presence of the Trans-Alaska Pipeline did not appear to affect the traditional migration of the Nelchina caribou herd (Carruthers and Jakimchuk 1987). However, where a pipeline paralleled a road with traffic, crossing frequencies were significantly lower than expected (Curatolo and Murphy 1986). The authors postulated that roads and pipelines act in a synergistic fashion. A small proportion of roads in our study area were associated with low (<50 cm from the ground) pipelines.

Woodland caribou in northeastern Alberta tend to be restricted to local populations within peatland complexes (Bradshaw et al. 1995; Stuart-Smith et al. 1997). These populations contain relatively few individuals (Boreal Caribou Research Program, unpublished data), thus the probability of local extinction is high (Richter-Dyn and Goel 1972). Metapopulation theory (Levins 1970) defines dispersal as a key process in the survival of local populations connected by interpatch dispersal. Metapopulations are defined as "systems of such local populations connected by dispersing individuals" (Hanski and Gilpin 1991). Movement between peatland complexes by caribou has been reported in northeastern Alberta (Stuart-Smith et al. 1997). Any process that affects the connectivity of a landscape will affect dispersal (Fahrig and Merriam 1985; Apeldoorn et al. 1992).

The effects of habitat fragmentation through habitat loss, avoidance, and the semipermeable barrier effects of roads should be considered in developing strategies to maintain woodland caribou populations in Alberta. Roads that act as semipermeable barriers to caribou movements may make the presence of caribou more predictable in space and time, and hence compromise the "spacing out" strategy that caribou adopt to reduce predation (Bergerud and Page 1987; Bergerud 1992; James 1999). Barrier effects associated with roads could be more severe at the edges of these peatland complexes, where a combination of inhospitable habitat and man-made barriers could potentially arrest dispersal. It is important to note, however, that our study primarily addressed females' movements. The study also covered only 1 year, and the sample size was restricted, so more studies are warranted to confirm the barrier effects of human developments on caribou under different conditions. Continued research is necessary to quantify the frequency of movements of both male and female caribou between peatland complexes, and to demonstrate the ultimate demographic consequences of roads acting as semipermeable barriers to caribou movements.

Animal-movement models have become popular with the advent of GIS. Schippers et al. (1996) distinguish three main approaches to modeling animal movements in response to landscape characteristics: distance-based models, diffusion models, and random-walk models. All three approaches suffer from limitations. Distance-based models and random-walk models (for a review see Johnson et al. 1992) ignore underlying differences in the landscape, whereas diffusion models fail to properly represent the complex decisions made by individuals (Schippers et al. 1996). Although these modeling approaches can provide many insights into the movement of animals through a landscape, many assumptions are made about animals' decisions. Schippers et al. (1996) argue that more effort should be put into quantifying these parameters. The approach we have outlined in this paper is a useful method to quantify the effects of human developments acting as semipermeable barriers to animal movements and should be considered in the development of animal-movement models.

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