Assessing the Influence of in situ Industrial Development on Caribou (*Rangifer tarandus*) Movement in the Lower Athabasca Planning Region of Alberta

2012 Final Report

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by

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Executive Summary

In-situ oil sands extraction is rapidly expanding in northeast Alberta, and there is uncertainty whether features of in-situ developments (ISDs), e.g., above-ground pipelines, restrict caribou movements. Restricted movement has been shown to increase extinction probability of wide-ranging species and could have similar effects on caribou populations in northeast Alberta. Here we test for effects of simulated future (i.e., 50 years from now) ISDs on simulated caribou movements. We varied the spacing (no buffer, 800 m buffer and 2 km buffer between ISDs), protected areas (yes or no), and permeability (impermeable to completely permeable) of simulated future ISDs on caribou movement. We used t-tests and a generalized linear model (GLM) to test for the effects of these treatments on caribou step lengths (i.e., the distance between two successive locations) and annual home ranges (i.e., the space an animal occupies throughout its life), key metrics of small and large spatiotemporal scales of movement, respectively. Caribou movement simulations were parameterized with existing location data from GPS-collared individuals and using a step selection function. With few exceptions, permeability across ISDs was the main factor affecting caribou movement. However, minimal permeability (crossing rates of at least 25%, relative to an undisturbed site) was needed to maintain step length and home range sizes. Furthermore, the relationship was non-linear, suggesting that a minimum threshold of permeability is needed. Our simulations provide land use planners the ability to test and prioritize the most efficient means of mitigating the effects of ISDs on caribou movement.

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Introduction

Industrial development in northeast Alberta, such as road, forestry cutblock, pipeline and seismic line development called 'footprint', has been implicated as one of the ultimate causes of caribou decline in boreal Alberta (Sorensen et al. 2008). Increased footprint indirectly contributes to increased predator (i.e., wolf) populations and landscape permeability to predators that increases predation rates on caribou, the proximate cause of caribou decline (McLoughlin et al. 2003; DeCesare et al. 2010; Latham et al. 2011).

In-situ oil sands development is rapidly expanding in northeast Alberta. In-situ oil sands footprint consists of aboveground pipelines (AGPs), roads and processing facilities used to extract and transport subsurface bitumen. There is uncertainty whether these features restrict caribou movements in northeast Alberta and whether such restrictions would negatively affect caribou populations. Indeed, animal movement is a key link between individual behaviour and population dynamics (Turchin 1998; Nams 2006). Movement is critical for wide-ranging species, including caribou, to access resource patches for their survival (Johnson et al. 1992; Taylor et al. 1993; Nathan et al. 2008). Restricted movement (i.e., reduced landscape connectivity) has been shown to increase extinction probability of some wide-ranging species, for example, lynx (*Lynx lynx*; Revilla and Wiegand 2008). In-situ footprint development in northeast Alberta may limit caribou access to resources, particularly predator-free space, which may ultimately have implications for caribou survival and persistence.

Although previous research from Alberta has suggested that caribou movement patterns are highly variable with no obvious relationship to landscape features (Fuller and Keith 1981; Stuart-Smith et al. 1997), the effects of footprint on caribou movement have never explicitly been tested. Furthermore, maintaining unrestricted caribou movement within the boreal region of Alberta is an objective of the Governments of Canada and Alberta (Environment Canada 2012; D. Hervieux, Alberta Provincial Caribou Biologist, pers. comm.) with subsequent regulatory requirements that must be met by industry (i.e., providing crossing structures and pathways across footprint for caribou). Finally, current densities of in situ footprint are low in boreal Alberta, making it difficult to gather data to evaluate to what degree these footprints actually block caribou movements. Thus, it is unclear whether the future density and extent of in-situ footprint development will significantly influence caribou movements in northeast Alberta.

Here we test for effects of simulated future (i.e., 50 years from now) in-situ oil sands footprint development on simulated caribou movement in an area of northeast Alberta, Canada. We test for effects on caribou step lengths (i.e., the distance between two successive locations) and annual home ranges (i.e., the space an animal occupies over the course of a year), key metrics of small and large spatiotemporal scales of movement, respectively (Nathan et al. 2008). We vary the spacing (no buffer, 800 m buffer and 2 km buffer between developments) and permeability (impermeable to completely permeable) of simulated in-situ footprints across 30 different scenarios and test simulated caribou movement responses to these factors. We also test for the effects of establishing a large protected area in the study area on caribou movement. The expansion of in-situ footprint scenarios were spatially simulated and validated by industry partners on the Ecological Monitoring Committee for the Lower Athabasca (EMCLA). Caribou movements were parameterized with existing location data from Global Positioning System (GPS)-collared individuals in boreal Alberta using a step selection function (SSF; Fortin et al. 2005). Our simulations provide land use planners the ability to prioritize the most efficient means of mitigating the effects of in-situ development on caribou movement, by contrasting the benefits of permeability across in-situ footprint, spacing between separate developments, or the use of protected areas.

Methods

Study Area

Our study occurred in northeast Alberta, Canada (Fig. 1) in an area currently being developed to extract bitumen from in-situ oil sand deposits. The current technology used to extract bitumen involves steam assisted gravity drainage (SAGD), where steam is pumped via wells belowground to heat bitumen, rendering it less viscous and thus more easily pumped to the surface. This requires up to five 34 cm to 50 cm diameter pipelines bundled together on support racks to transport steam to each well from a central processing facility (CPF) and bitumen from the well to the CPF (Golder 2004; Dunne and Quinn 2009). These footprints are expected to remain on the landscape for at least 50 years.

The study area where caribou movement was simulated was 1,796,546 ha in size (i.e., the study area). In-situ developments were simulated within a 477,009 ha subset of this area (i.e., the development area), where development is expected to be at its most intensive. The study area is boreal forest dominated by black spruce (*Picea mariana*) in lowlands and aspen (*Populus tremuloides*) and mixed deciduous and coniferous forest in uplands, with an extensive network of bog, marsh and fen wetlands.

In-situ Footprint Simulation

We used the spatial distribution of actual planned footprint within four in-situ leases (i.e., single project development areas) in the study area as a basis for modelling and

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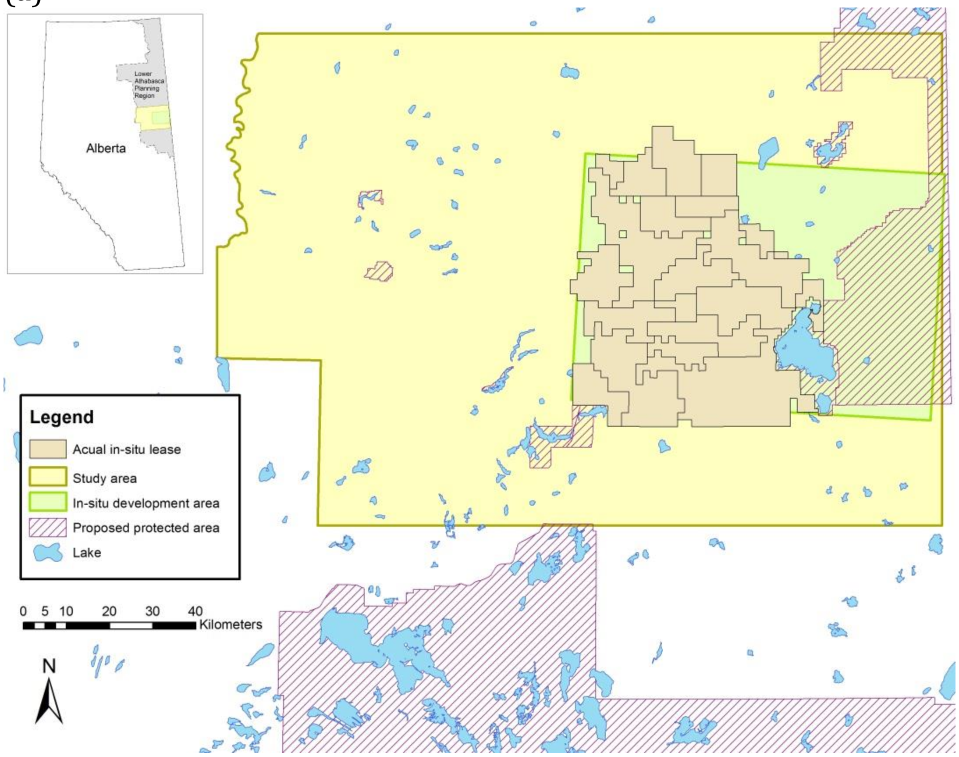
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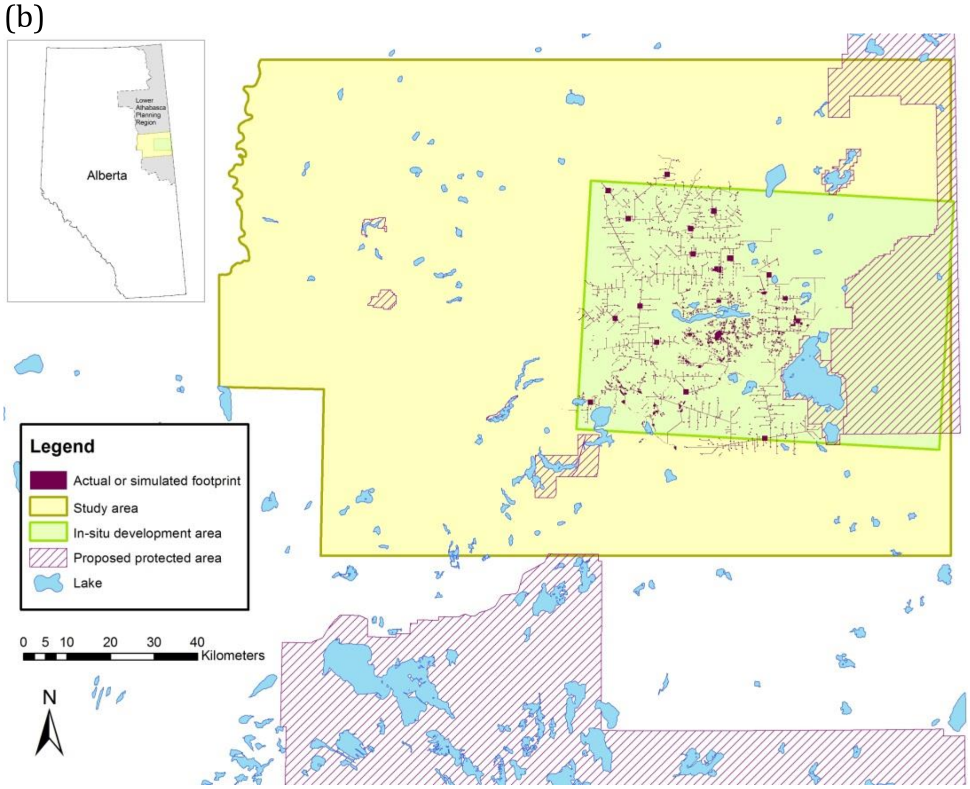
Lower Athabasca Planning Region
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Actual or simulated footprint
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Proposed protected area
Lake
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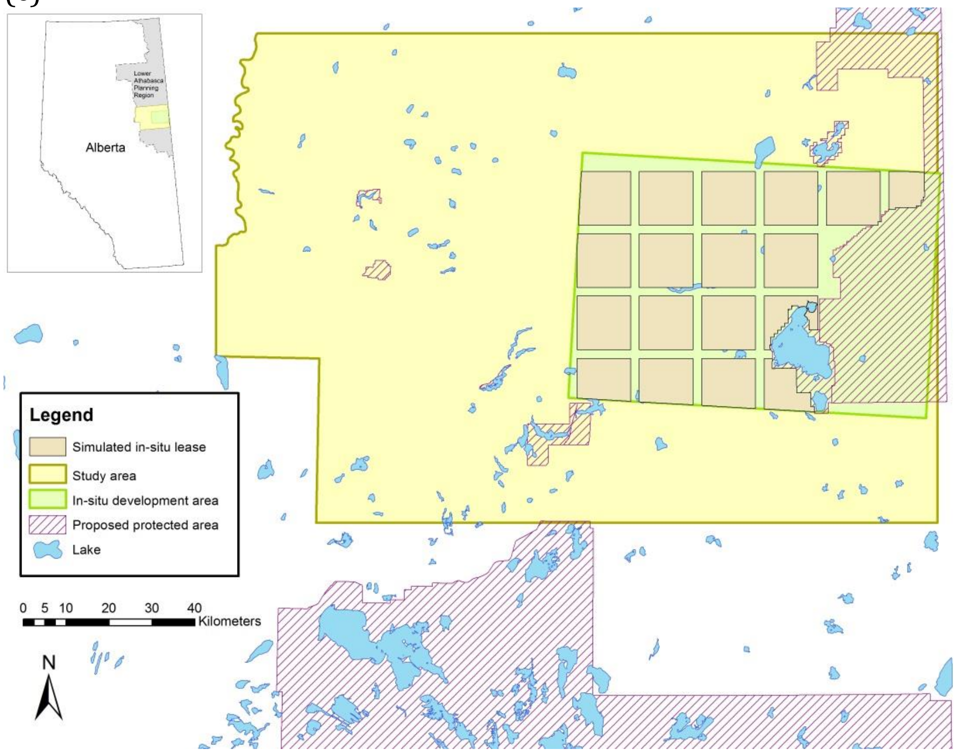

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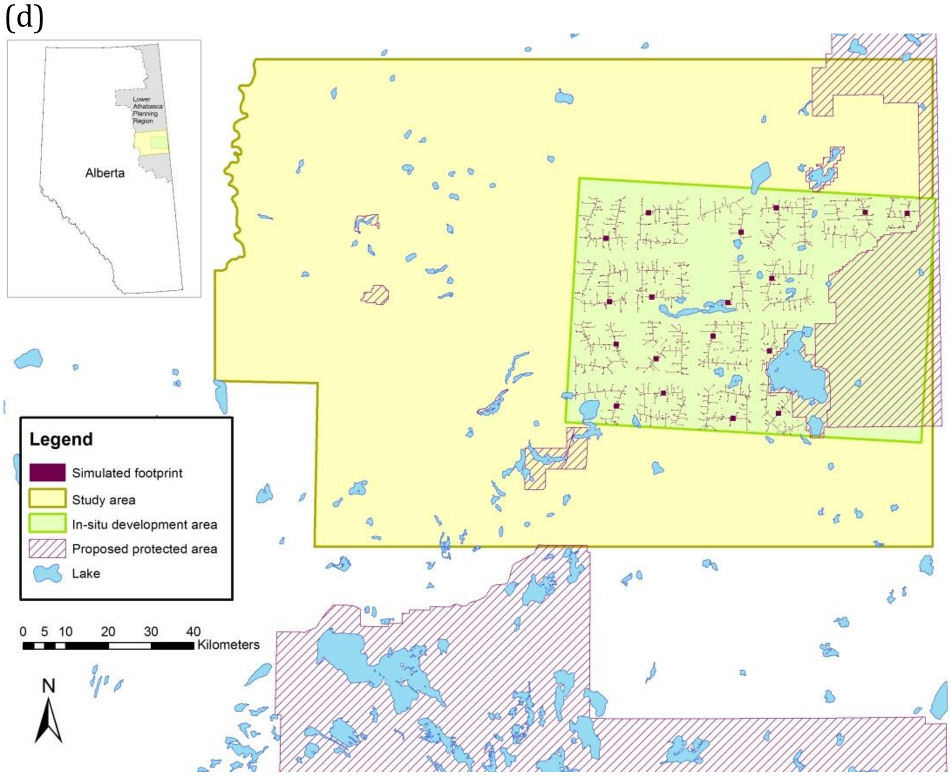


Figure 1. In-situ oil sands footprint development scenarios simulated to test footprint effects on caribou movement, including: (a) actual lease boundaries with, (b) a combination of actual proposed and simulated footprint, and (c) simulated lease boundaries with a 2 km buffer between them with, (d) simulated footprint with the 2km buffer between projects.

simulating future footprint in leases where planned footprint was unknown. Using the lease boundary shapefile and well pad locations, a point pattern object (NLppp) was created for analysis in the R (R Development Core Team 2012) package 'spatstat' (Baddeley et al. 2010). A spatial logistic regression model (slrm) that used a discretized pixel grid with 1 assigned to pixels with a well and 0 assigned to pixels with no well, was fitted to the NLppp. We then used the fitted model to simulate well distributions within lease boundaries where footprint was unknown. A 244 m x 191 m rectangle (i.e., the average well pad size within the known proposed footprints) was created around each simulated point centroid to represent the simulated well pad footprint.

A linear feature network connecting all simulated well pads within each simulated lease was generated in a series of steps. First, the well distribution was separated into three clusters using the 'partitioning –around-medoids' function in the R (R Development Core Team 2012) package 'cluster' (Maechler et al. 2012) and an ellipse enclosing one standard deviation was drawn around each cluster. We intersected the ellipse with its minimum bounding rectangle to derive end points that were connected with a line to generate a trunk line through each cluster. To connect trunk lines to simulated well pads, a Cost Distance/Cost Path was calculated with a fishnet cost raster in which cross hatched 'on-grid' lines were slightly less expensive than the enclosed 'off-grid' squares (ratio 10/12). A second Cost Distance/Cost Path operation connected the three cluster trunk lines. The line raster was converted to a polyline file and buffered by 62 m (the average width of linear features in the actual proposed footprint data). Central processing facilities (CPFs) were simulated by creating a 1.2 km square feature (i.e., the average size of CPFs in the known footprints) at the midpoint of the first trunk line.

Footprints were simulated on the landscape within actual and simulated in-situ lease boundaries under different scenarios (Appendix A). We simulated scenarios with different lease spacing including: (1) within actual existing leases (no spacing), (2) within 15,675 ha rectangle leases (i.e., the average actual lease size) spaced 800 m apart, and; (3) within 15,675 ha rectangle leases spaced 2 km apart (Fig. 1). These scenarios were simulated with and without the Lower Athabasca Regional Plan (LARP) protected areas proposed for the study area (Fig. 1), where no development was permitted within these protected areas (Government of Alberta 2012). We simulated full in-situ footprint development of all leases in the study area that is expected to occur within 50 years without any reclamation. Simulated footprints were converted to rasters with a 10 m spatial resolution and attributed a value on the logit scale to model relative permeability, including:

(1) moderate permeability = 0.10;

(2) low-moderate permeability = 0.01;

(3) low permeability = 0.0001,

(4) very low permeability = 0.00001, and;

(5) impermeable = 0.

All simulated in-situ footprint scenarios were mapped and then qualitatively validated for accuracy by nine in-situ oil sands companies (i.e., industry partners on the EMCLA) operating in the study area. In addition, we compared the number of wells simulated within actual leases to actual number of planned wells as a quantitative means of evaluating the footprint simulations.

Caribou Movement Simulation

Caribou location data

We obtained location data from 19 GPS-collared female caribou from the East Side of the Athabasca River (ESAR; six individuals) and Richardson (13 individuals) caribou populations in northeast Alberta, Canada. Data were collected by Alberta Environment Sustainable Resource Development (AESRD), Government of Alberta and screened to remove inaccurate locations by removing all locations with a 2-dimensional fix and a horizontal dilution of precision (DOP) > 12 (M. Russell, Government of Alberta, pers. comm.). Locations were collected year-round from 2008 to 2011 at two-hour intervals. We calculated turning angles and step length (distances) between locations using the movement.pathmetrics tool in Geospatial Modelling Environment (GME: Beyer 2012).

Step selection functions

We measured caribou habitat selection along movement steps by calculating step-selection functions (SSFs; Turchin 1998, Fortin et al. 2005) for each individual caribou. SSFs use conditional logistic regression and a case-control sampling design to compare habitat measured along observed caribou steps to habitat measured along a random sample of "available" steps from each location (Fortin et al. 2005). We generated ten available steps from each observed location by randomly drawing turning angles and step lengths from the observed distribution of each individual, calculated from the actual caribou GPS-location data (Fortin et al. 2005) using the movement.ssfsamples tool in GME (Beyer 2012). We then measured the proportion of vegetation cover types (i.e., water, disturbed, shrubs, wetland/conifer, deciduous forest and mixedwood forest) along each step using a vegetation cover map developed by the ABMI.

SSF analyses comparing actual to available steps were conducted for each individual caribou using conditional logistic regression in STATA 10. Standard errors of SSF parameters were obtained using a Huber-White sandwich estimate of the co-variance matrix (Pendergast et al. 1996), as successive steps were likely not independent from one another, which can bias the standard errors (Nielson et al. 2002; Fortin et al. 2005; Gillies et al. 2006). Prior to conditional logistic regression, covariates were screened for co-linearity using Spearman correlation. When covariates had $r > 0.7$ then the covariate least correlated with observed movement steps was removed from the analysis. Statistical significance of covariates included in the model was assessed using z-tests. We calculated a population-averaged caribou SSF model by calculating the standard-error weighted average of individual caribou beta coefficients (Murtaugh 2007), but with the highest and lowest beta coefficient values for each covariate removed to exclude unusual habitat selection behaviours from the population.

Simulated movements

We simulated movements of 25 caribou over a one year period (steps every two hours, n = 2,190) within the study area under the different in-situ footprint scenarios (Appendix A) using the movement.ssfsim1 tool in GME (Beyer 2012). We found that 25 individuals was an adequate sample because in an initial simulation of 100 individuals, an asymptote in standard deviation of home range size and step length was reached at 12 individuals (Appendix B). One random starting point per caribou was generated within the study area. Movement steps were simulated by drawing 100 random step lengths and turning angles from the distribution of actual caribou step lengths and turning angles obtained from GPS-location data. Then the SSF model was applied to calculate the relative probability of selecting each simulated step based on the underlying land cover type. In addition to the land cover covariates, we included a footprint covariate in the SSF model. Footprint covariate values were generated on the logit scale for each modelled permeability scenario (see above). Thus, in scenarios with less permeable footprint, those steps crossing footprints were less likely to be selected than those in scenarios with more permeable footprint. A step was generated at each location based on its probability of being selected, and this process was repeated iteratively for 2,190 steps per individual (Fortin et al. 2005).

To further test for the effects of lease spacing and protected areas on caribou movement, we included a scenario where simulated caribou were restricted to moving within the developed area only (i.e., the 477,009 ha subset; Fig. 1). Whereas simulating caribou movement in the study area allowed us to simulate more realistic caribou home range sizes and step lengths when compared to the actual telemetry data, we were concerned that if simulated caribou were allowed to move in a large area where development was absent, the undeveloped area acted as a *de facto* protected area, and any benefits of 2 km spacing would be diluted by the larger undeveloped area. We therefore included the 'developed area' scenario to adequately simulate caribou movements in response to protected areas and footprint spacing. Within the developed area scenario, in-situ lease spacing was varied between 2 km or 800 m and the in-situ footprint modelled permeability was varied from 0%, 0.001%, 0.01%, 1%, 10% and 100%.

We measured the number of times each individual simulated caribou crossed in-situ footprint for each scenario and calculated the average number of crossings per scenario as an indicator of actual footprint permeability. Thus we could explicitly test how changes to modelled permeability affected the actual caribou rate of crossing footprint.

Testing the Relative Effects of In-situ Footprint Permeability, Protected Areas and Lease Spacing on Caribou Movement

We calculated t-tests in STATA 10.1 to determine whether simulated caribou home range sizes and step lengths were significantly different between scenarios. Specifically, we tested whether home range size and step length were different between treatments with different modelled permeability under the same protected area and spacing scenario, different protected area treatments under the same modelled permeability and spacing scenario, and different spacing treatments under the same modelled permeability and protected area scenario.

Finally, we calculated generalized linear models (GLMs) of home range and step length as a function of in-situ footprint permeability (number of crossings), in-situ lease spacing, and protected areas to test for and compare relative effects of each on caribou movement. We calculated GLMs with all combinations of covariates, including models with and without a squared term for number of crossings to test for a non-linear relationship. We compared model fit using corrected Akaike's Information Criteria (AIC_c), where the model with the lowest AIC_c value and models with a difference in AIC_c value less than two from the lowest AIC_c model were considered the most parsimonious for predicting caribou home range and step length (Burnham and Anderson 2002). We calculated GLM's with a Huber-White sandwich estimator clustered for scenario to account for correlation between the 25 individual simulated caribou within each scenario (Nielson et al. 2002; Fortin et al.

2005; Gillies et al. 2006). GLM analyses were conducted in Stata 10.1 using the GLM package.

Results

In-situ Footprint Simulation

Our in-situ footprint model accurately simulated the actual number of wells within in-situ project boundaries. The average number of wells simulated within a lease over 100 iterations (mean = 75, mode = 90-95) was similar to the number of actual wells (94) within leases (Fig. 2). Furthermore, the EMCLA considered our simulated footprint scenarios as reasonable representations of future footprint on the landscape.

Caribou Movement Simulation

Step selection functions

Results of the SSF analysis indicated that on average caribou avoided water, shrub, disturbed and mixedwood forest land cover types and selected for deciduous forest and conifer forest/wetland cover types relative to open (i.e., grassland and bare) cover types (Table 1). Some selection coefficients (i.e., shrubs and deciduous forest) had high standard errors, indicating a high degree of variability in selection for those features across individual animals.

Effect of In-situ Footprint Permeability on Caribou Movement

In-situ footprint permeability appeared to have an effect on both caribou home range size and step length (Fig. 3). In general, home range sizes and step lengths were significantly smaller and shorter in size and length, respectively, when footprint was impermeable or had very low permeability (0.001%) compared to when it was low

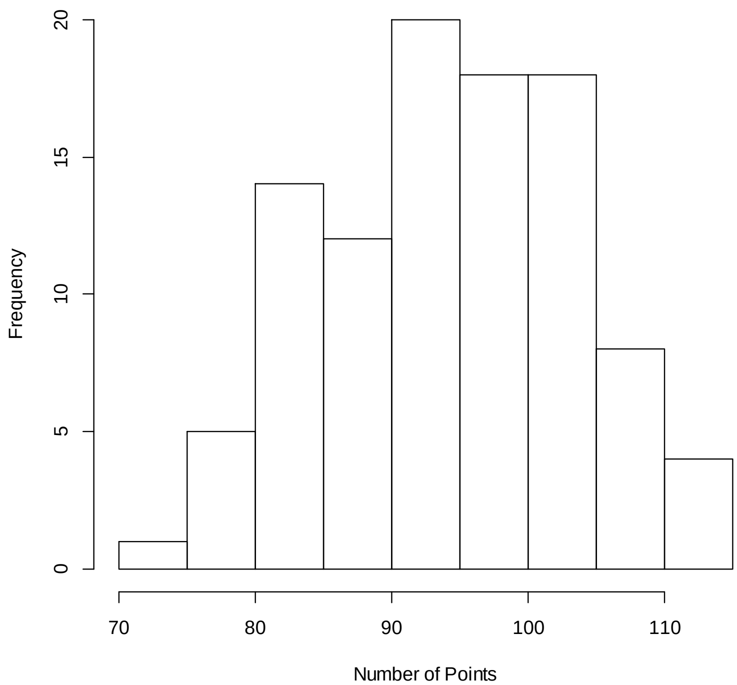


Figure 2. Number of simulated points (well pads) per simulation generated by 100 simulations within actual in-situ oil sands leases. The average number of actual well pads within leases was 94.

Table 1. Habitat selection coefficients (β) and standard errors calculated from a step selection function (SSF) of 19 female caribou in northeast Alberta.

Habitat Covariate	**β**	**Standard Error**
Proportion of step that is water	-0.04	0.74
Proportion of step that is shrubs	-0.17	2620.24
Proportion of step that is disturbance (anthropogenic + barren ground)	-0.13	1.10
Proportion of step that is deciduous forest	0.08	5.85
Proportion of step that is mixedwood forest	-0.03	0.43
Proportion of step that is conifer forest/wetland	0.04	0.82

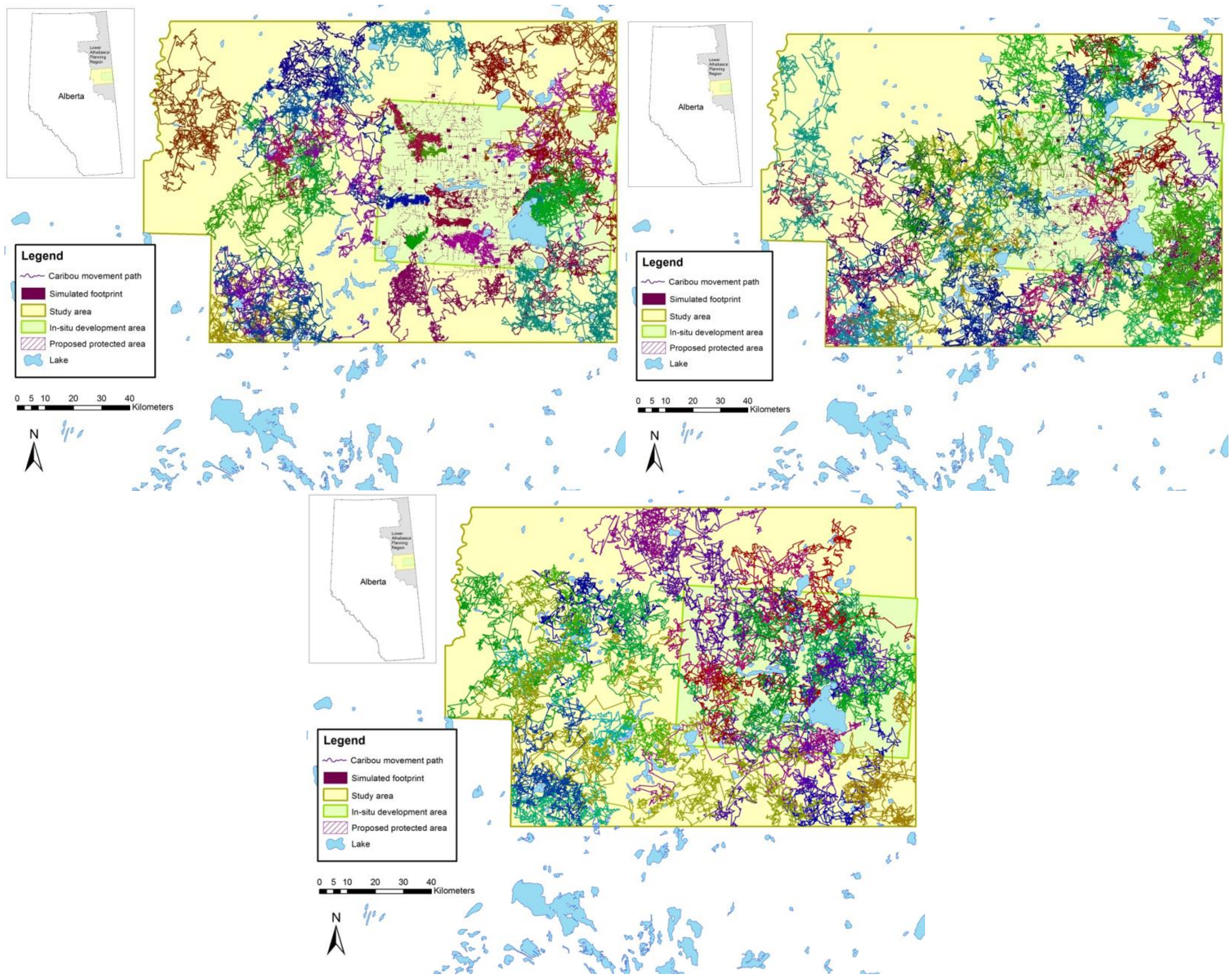


Figure 3. Simulated movements of 25 caribou over a one year period relative to in-situ oil sands footprint that is modelled as completely impermeable (0%; top left), low-medium permeability (1%; top right), and completely permeable (no in-situ footprint; bottom).

(0.01%) or higher permeability (Figs. 4 and 5). Specifically, we found a significant decrease in simulated caribou home range size between completely permeable (100%) and very low permeability (0.001%) scenarios with actual lease spacing and protected areas ($t = -3.297$, $p < 0.001$), 2 km lease spacing with no protected areas ($t = -2.536$, $p = 0.008$), 800 m lease spacing with protected areas ($t = -1.922$, $p = 0.030$), and 800 m lease spacing with no protected areas ($t = -2.257$, $p = 0.014$). Similarly, we found a significant decrease in simulated caribou step length between completely permeable and very low permeability scenarios with actual lease spacing and protected areas ($t = -3.052$, $p = 0.002$), 2 km spacing with protected areas ($t = -2.617$, $p = 0.006$), 2 km lease spacing with no protected areas ($t = -3.092$, $p = 0.002$), 800 m lease spacing with protected areas ($t = -2.637$, $p = 0.006$), and 800 m lease spacing with no protected areas ($t = -4.418$, $p < 0.001$). However, we found no difference in home range size regardless of in-situ footprint permeability in the 2 km lease spacing and protected area scenario.

The average number of crossings across in-situ footprint was typically significantly fewer in very low permeability (0.001%) compared to completely permeable (100%) in-situ footprint scenarios, but not significantly different between low permeability (0.01%) and completely permeable in-situ footprint scenarios. Specifically, the average number of simulated caribou crossings of very low permeability compared to completely permeable footprint decreased in scenarios with actual lease spacing and protected areas ($t = -3.380$, $p < 0.001$), 2 km lease spacing with protected areas ($t = - 3.689$, $p < 0.001$), 2 km lease spacing with no protected areas ($t = - 3.391$, $p < 0.001$), 800 m lease spacing with protected areas ($t = -3.276$, $p = 0.001$), and 800 m lease spacing with no protected areas ($t = - 3.681$, $p< 0.001$) scenarios. There was no significant decrease in average number of simulated

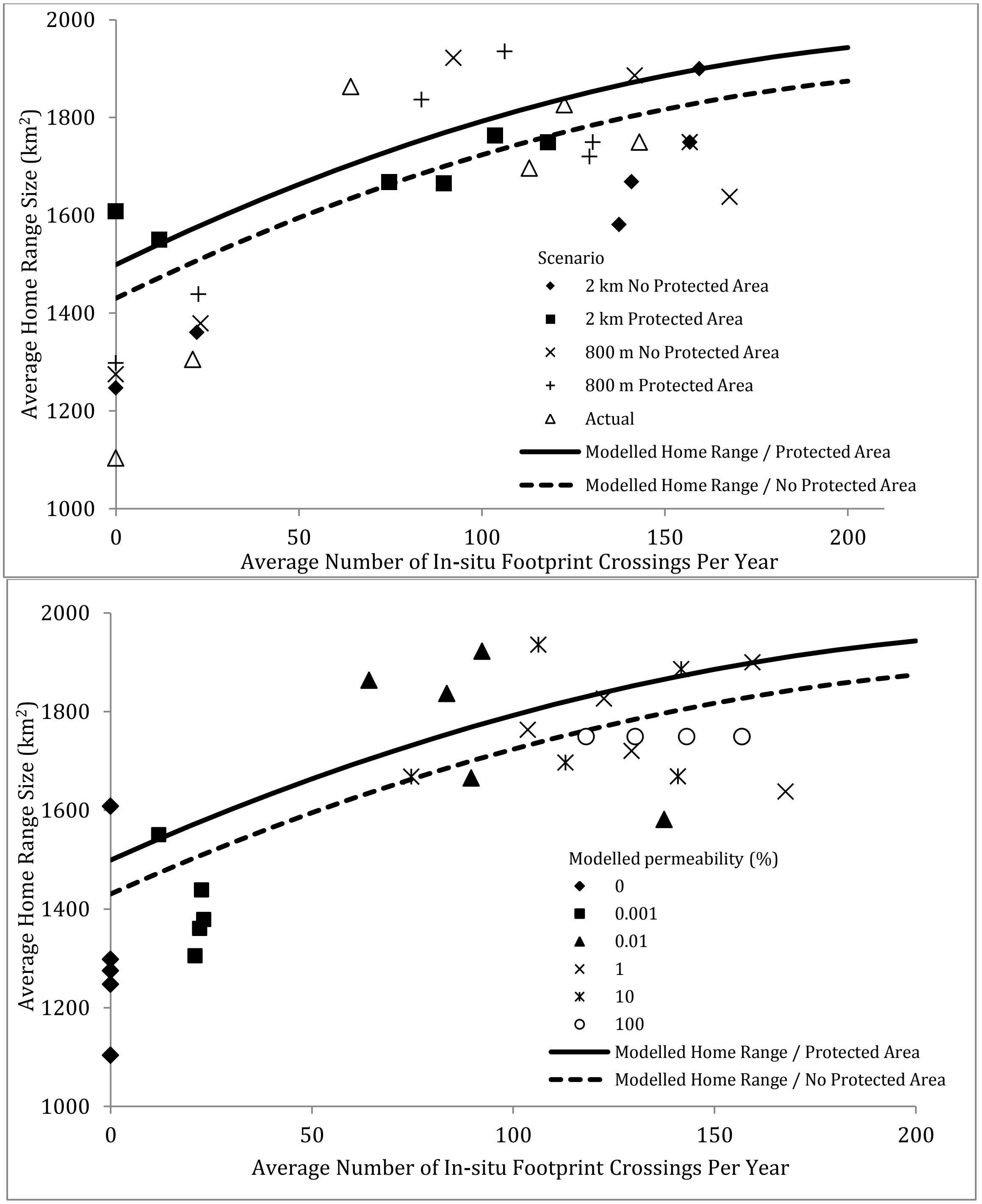
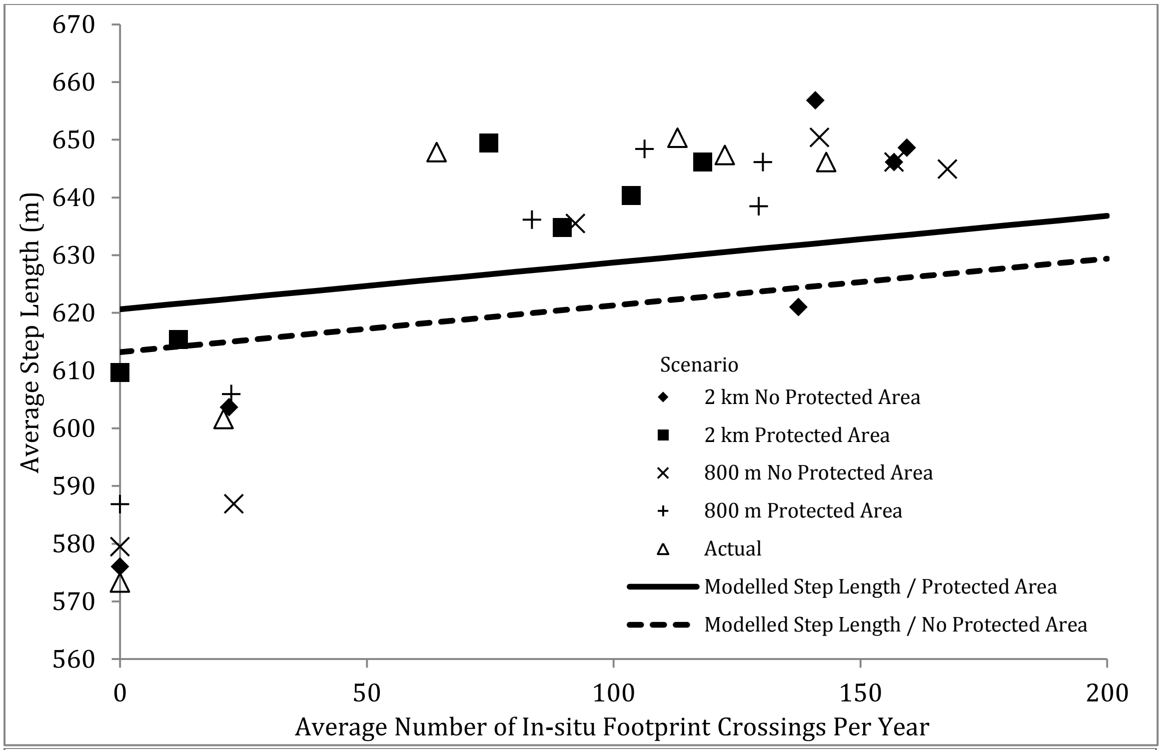


Figure 4. Average simulated caribou (n=25) home range size as a function of the number of caribou crossings of in-situ footprint under different buffer distance and protected area (top) and modelled in-situ footprint permeability (bottom) scenarios. Scenarios are indicated by different markers. The predicted relationship between home range size and number of crossings, as determined using a generalized linear model, is also indicated for scenarios with (solid line) and without (dashed line) protected areas.



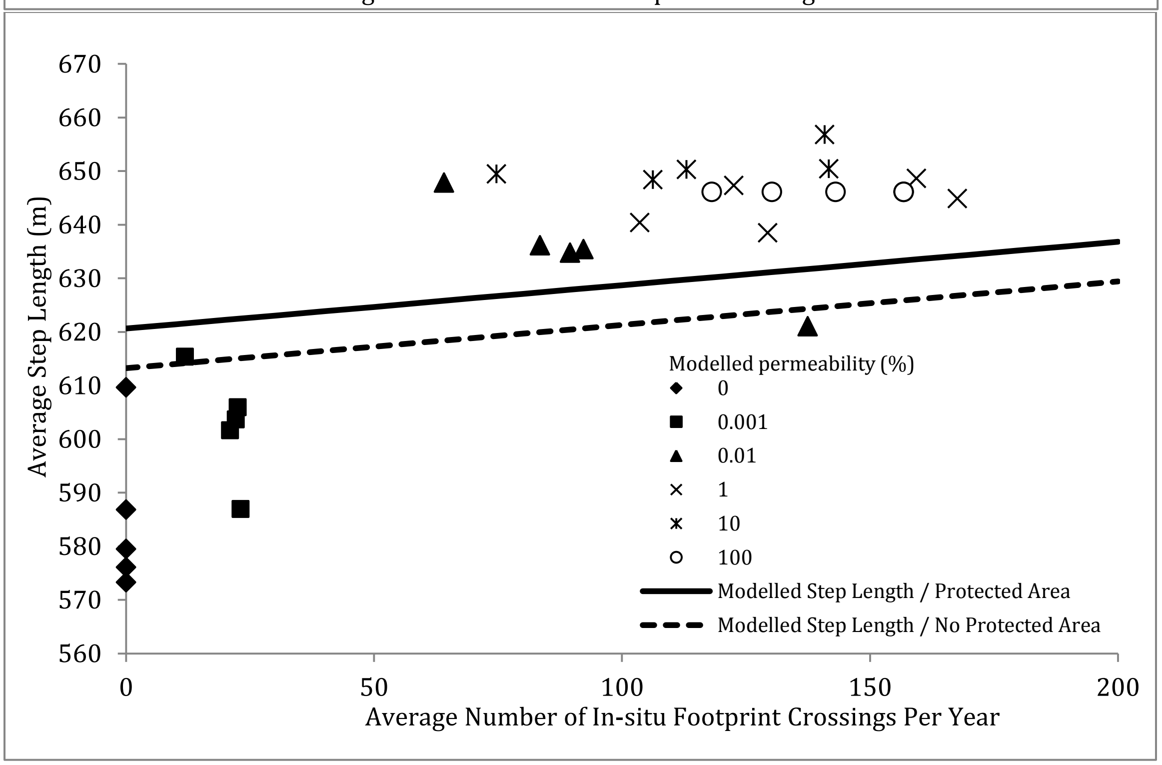


Figure 5. Average simulated caribou (n=25) step length as a function of the number of caribou crossings of in-situ footprint under different buffer distance and protected area (top) and modelled in-situ footprint permeability (bottom) scenarios. Scenarios are indicated by different markers. The relationship between step length and number of crossings, as determined using a generalized linear model, is also indicated for scenarios with (solid line) and without (dashed line) protected areas.

caribou crossings between low permeability and completely permeable footprint scenarios, except in the actual lease spacing and protected area scenario ($t = -1.949$ $p = 0.029$). In that scenario there was no significant difference in average number of simulated caribou crossings between low-moderate permeability and completely permeable footprint scenarios.

The average number of simulated crossings of in-situ footprint was significantly higher in very low (0.001%) and low (0.01%) permeability compared to impermeable (0%) in-situ footprint scenarios. Specifically, the average number of simulated caribou crossings between impermeable and very low permeability footprint increased in scenarios with actual lease spacing and protected areas ($t = 2.831$, $p = 0.003$), 2 km lease spacing with protected areas ($t = 2.973$, $p = 0.002$), 2 km lease spacing with no protected areas ($t = 4.452$, $p < 0.001$), 800 m lease spacing with protected areas ($t = 3.889$, $p < 0.001$), and 800 m lease spacing with no protected areas ($t = 4.218$, $p < 0.001$) scenarios. In addition, the average number of simulated caribou crossings between very low and low permeability footprint increased in actual lease densities ($t = 2.040$, $p < 0.023$), 2 km spacing with protected areas ($t = 3.438$, $p < 0.001$), 2 km spacing with no protected areas ($t = 4.992$, $p < 0.001$), 800 m spacing with protected areas ($t = 3.181$, $p = 0.001$), and 800 m spacing with no protected areas ($t = -3.343$, $p < 0.001$) scenarios. Finally, there was no significant difference between the average number of simulated crossings across in-situ footprint between low and low-moderate (1%) permeability in-situ footprint scenarios.

Effect of In-situ Footprint Spacing on Caribou Movement

In the study area simulations, we typically found no statistically significant difference between caribou home range size, step length and the number of in-situ footprint crossings between the different spacing scenarios (Figs. 4 and 5). One exception was a significantly smaller home range in the actual lease spacing scenario compared to the 2 km lease spacing scenario with protected areas and impermeable in-situ footprint ($t = -2.059$, $p = 0.023$). Furthermore, in the developed area simulations, we only found significantly smaller home ranges ($t = -3.207$, $p = 0.002$) in the 800 m lease spacing scenario compared to the 2 km lease spacing scenario with no protected areas and impermeable in-situ footprint. Thus, spacing did not influence home range size or step length when permeability was greater than zero.

Effect of Protected Areas on Caribou Movement

In the study area simulations, we typically found no statistically significant difference between caribou home range size, step length and the number of in-situ footprint crossings between the protected areas versus no protected areas scenarios. Two exceptions were a significantly smaller step length when leases were spaced 2 km and in-situ footprint was impermeable ($t = -1.695$, $p = 0.048$) and when leases were spaced 2 km and in-situ footprint had low permeability ($t = -1.678$, $p = 0.050$). Furthermore, in the developed area simulations, we found significantly smaller home ranges ($t = 1.831p = 0.040$) and shorter step lengths ($t = 2.485$, $p = 0.011$) in the no protected area scenario compared to the protected area scenario when in-situ footprint spacing was 800 m and impermeable.

Effect Size of In-situ Footprint Permeability, Protected Areas and Lease Spacing on Caribou Movement

In-situ footprint permeability, measured as number of successful in-situ footprint crossings, and protected areas were covariates included in the most parsimonious model for predicting caribou home range size and step length (Table 2). A squared term for number of crossings was also included in the most parsimonious model for predicting caribou home range size. Lease spacing was not included in either parsimonious model.

The number of in-situ footprint crossings and the squared number of in-situ footprint crossings were significant covariates in the model predicting caribou home range size, indicating a non-linear relationship between home range size and in-situ footprint permeability (Table 3; Fig. 4). Indeed, home range size levelled off as the number of in-situ footprint crossings increased (Fig. 4). Home range size decrease by 128 km^2 (7%) as the number of crossings decreased from 100 (a completely permeable scenario) to 50 and 293 km^2 (16%) as the number of crossings decreased from 100 to 0 (Fig. 4). Thus, as in-situ footprint permeability decreased the effect of permeability on caribou home range size increased. Protected areas were included in the most parsimonious model of caribou home range size (Table 2), but the covariate was not significant (Table 3) suggesting the type of effect (positive or negative) was not clear. Nevertheless, the presence of protected areas typically increased caribou home range size by 69 km^2 (4%).

The number of crossings was a significant covariate in the model predicting caribou step length, indicating a linear relationship between step length and in-situ footprint permeability (Table 3; Fig. 4). Step length decreased by 4 m (0.6%) as the number of crossings decreased from 100 (a completely permeable scenario) to 50 and 8 m (1.2%) as the number of crossings decreased from 100 to 0 (Fig. 4). Protected areas were included in the most parsimonious model of caribou step length (Table 2), but the covariate was not significant (Table 3) suggesting the type of effect (positive or negative) was not clear.

Table 2. Corrected Akaike Information Criteria (AIC_c) scores, differences and weights comparing models of caribou home range size and step length as a function of number of in-situ footprint crossings (permeability), protected areas and in-situ project lease spacing.

	Home Range			Step Length		
Model	AIC_c	ΔAIC_c	AIC_c weight	AIC_c	ΔAIC_c	AIC_c weight
Crossings + Crossings^2 + Protected Area	9965.4	0.0	0.688	6807.0	2.9	0.135
Crossings + Crossings^2 + Protected Area + Spacing	9968.3	2.9	0.159	6808.9	4.8	0.051
Crossings + Crossings^2 + Spacing	9968.5	3.1	0.146	6809.7	5.6	0.035
Crossings + Protected Area	9975.6	10.2	0.004	6804.1	0.0	0.565
Crossings + Protected Area + Spacing	9978.0	12.6	0.001	6807.1	3.0	0.127
Crossings + Spacing	9978.2	12.8	0.001	6807.8	3.7	0.088
Protected Area	9997.5	32.1	0.000	6819.1	15.0	0.000
Spacing	9998.9	33.5	0.000	6821.8	17.7	0.000
Protected Area + Spacing	9999.9	34.5	0.000	6822.2	18.1	0.000
Crossings + Crossings^2	10351.0	385.6	0.000	7060.4	256.3	0.000
Crossings	10361.8	396.4	0.000	7058.5	254.4	0.000

Table 3. Covariate beta coefficients, standard errors, z-values and p-values in the most parsimonious models of caribou home range size and step length.

	Home Range				Step Length			
Covariate	β	SE	z-value	p-value	β	SE	z-value	p-value
Crossings	3.646	0.683	5.340	<0.001	0.081	0.024	3.390	0.001
Crossings^2	-0.007	0.002	-3.950	<0.001	-	-	-	-
Protected Area	68.578	72.353	0.950	0.343	7.414	9.856	0.750	0.452
Constant	1430.564	60.513	23.640	<0.001	613.206	9.075	67.570	<0.001

Nevertheless, the presence of protected areas typically increased caribou step length by 8 m.

Discussion

We examined how three factors relating to in situ development could potentially affect caribou movement: permeability across in-situ footprint, spacing between in-situ development leases, and the inclusion of protected areas in regional planning. With few exceptions, permeability across footprint was the main factor affecting caribou home range size and step length. Permeability had a two to five times larger effect on caribou home range size than protected areas, and lease spacing had little to no effect. Protected areas increased caribou step length by 4% and impermeable in-situ footprint decreased caribou step length by 1.2%. Furthermore, the effect of permeability on caribou home range size became stronger at low levels, suggesting that a minimum threshold of permeability is needed to minimize effects on caribou home range size. This non-linear relationship is important because it means that only minor improvement in permeability are needed to provide a higher than proportional benefit.

The patterns we observed are intuitive when considered in our simulated landscape context. Regardless of whether 800 m or 2 km lease spacing is implemented, in-situ footprint will dominate the landscape in 50 years (Figs. 1 and 3). Therefore, permeability across footprint will be the greatest factor dictating caribou space use. Protected areas will also have an effect on caribou movement, albeit to a lesser degree than permeability, because they provide large undeveloped areas that caribou can move through freely.

In practical terms, if caribou movement across the landscape is restricted by in-situ footprint to <50% of unrestricted movements (Fig. 4), caribou may be incapable of maintaining their home range size. Caribou avoid predators by selecting low predator density areas at large scales (Rettie and Messier 2000; Rettie and Messier 2001). Thus, the implications of restricting caribou home ranges are reduced availability of resources, such as food, and more importantly for caribou in the study region, predator-free space. Restricting long distance movements by caribou may also have implications for caribou escaping predators at finer scales.

There were limitations to our modelling approach, most notably that we did not model whether the effects of in-situ footprint on caribou movement would ultimately affect caribou fitness or survival. Rather, we infer that restricting caribou movement will have negative consequences for caribou fitness and survival, as animal movement is linked to population dynamics (Turchin 1998; Nams 2006) via access to resources, including predator-free space. Furthermore, our scenarios assume permeability is the same across an entire in-situ project footprint. In practice this is likely not the case, as permeability likely varies within a projects footprint, for example, between well sites, above-ground pipelines and roads. Caribou step length and home range size may therefore be over-estimated in our high-permeability scenarios if some footprints are impermeable and under-estimated in low-permeability scenarios if some footprints are permeable, depending on their density within projects. If this limitation is of concern to the EMCLA, further work may be necessary to test whether different permeability footprint features within projects has a significant influence on caribou movement.

Recommendations

We found that simulated in-situ footprint densities in 50 years have the potential to significantly limit caribou movements if they have very low permeability. However, predation rate, not movement, appears to be the most important factor limiting caribou populations in boreal Alberta. Increased footprint likely indirectly contributes to increased predator populations and landscape permeability that increases predation rates on caribou (McLoughlin et al. 2003; Wittmer et al. 2007). At current footprint densities and estimated caribou population sizes, caribou populations are projected to decline to less than 10 individuals in the ESAR herd within the next 25 years (Schneider et al 2010). Restricting caribou movement may contribute to this decline by limiting predator-free space and caribou's ability to escape from predators. However, we caution that rising predator populations may cause caribou populations to decline or become extirpated prior to 50 years from now when effects of footprint on movements would be strongest.

If mitigating the effects of in-situ footprint development on caribou movement remains a priority for the EMCLA, then we recommend the EMCLA test how permeable aboveground pipelines (AGPs), which are considered the least permeable footprint type, are to caribou movement. Currently, in-situ oil sands companies in caribou range are required to monitor caribou crossing of above-ground pipelines (AGPs) using camera traps and winter tracking deployed at crossing structures and along AGPs, respectively. Here we propose an approach to use this existing camera trap and winter tracking data in combination with the results and caribou movement models described above to estimate current caribou crossing rate across AGPs.

Camera traps and track count studies are viable methods to measure animal use of crossing structures (Grilo et al. 2008; Ford et al. 2009). However, these data are limited in that they do not explicitly quantify the effectiveness of crossing structures (i.e., to what extent they mitigate barrier effects; van der Ree 2007). Thus, the value of this data has been limited to date because caribou interaction rate, i.e., crossing attempts, of AGPs was unknown. However, we can use the caribou movement simulation model we developed to estimate the number of caribou interactions with existing AGP footprint and compare that with the number of photographs and tracks of caribou crossing AGPs to estimate the rate that caribou cross AGPs. Finally, we can compare existing crossing rates with our previously simulated crossing rates (Fig. 4) needed to maintain caribou home ranges and step lengths to evaluate mitigation effectiveness. If the percentage of successful crossings is >50%, then we can reasonably conclude that current AGP crossing structure mitigation will indeed maintain caribou movement in the future. If successful crossing rates are lower, additional mitigation may be warranted. In 2013, we will compile data on the locations of AGPs and camera and winter tracking data from those AGPs to test whether caribou are crossing AGPs at a >50% rate.

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Appendix A. Footprint Simulation Scenarios

Table A1. Footprint simulation scenarios used to measure the influence of in-situ footprint permeability and spacing, and protected areas on caribou home range size and step lengths.

Scenario		
Permeability (%)	**Lease Spacing (m)**	**Protected Areas**
100	N/A	N/A
0	800	No
0.001	800	No
0.01	800	No
1	800	No
10	800	No
0	800	Yes
0.001	800	Yes
0.01	800	Yes
1	800	Yes
10	800	Yes
0	2,000	No
0.001	2,000	No
0.01	2,000	No
1	2,000	No
10	2,000	No
0	2,000	Yes
0.001	2,000	Yes
0.01	2,000	Yes
1	2,000	Yes
10	2,000	Yes

Appendix B. Number of Simulated Caribou Necessary to Achieve a Stable Measurement of Home Range Size and Step Length

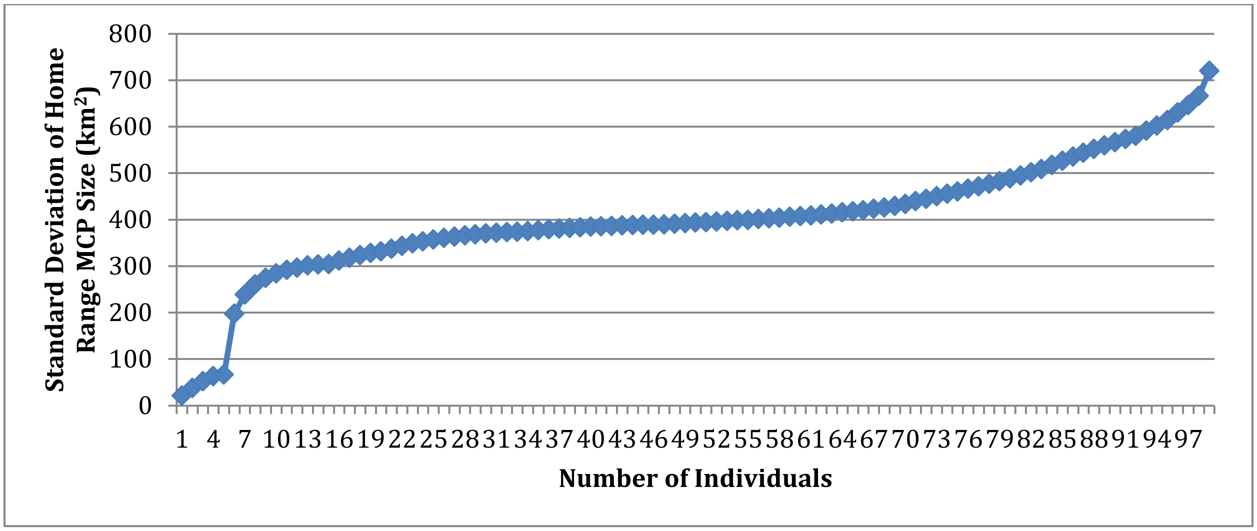

Figure B1. Number of individual caribou simulated over a one year period in a scenario with dense, impermeable in-situ oil sands footprint on the landscape and standard deviation of home range size, measured using a Minimum Convex Polygon (MCP). MCP size stabilizes at ~10 individual caribou simulated.

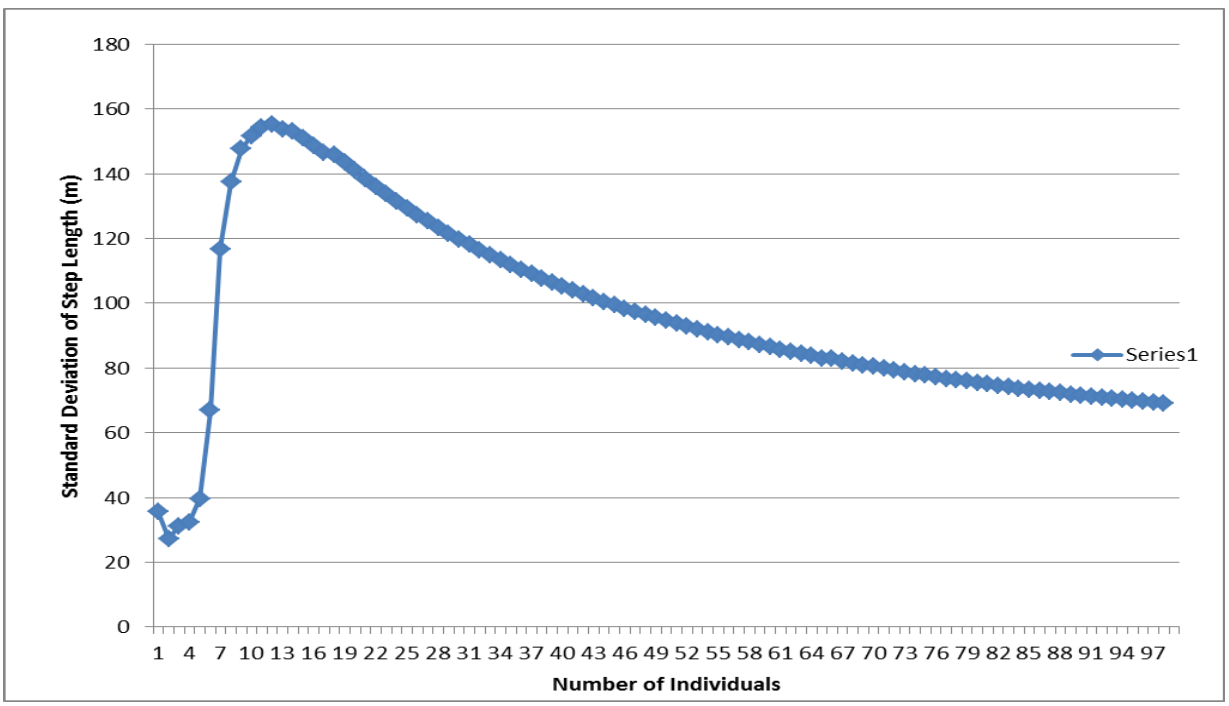

Figure B1. Number of individual caribou simulated over a one year period in a scenario with dense, impermeable in-situ oil sands footprint on the landscape and standard deviation of step length. Step length size stabilizes at ~15 individual caribou simulated.