Grosman, P. D., J. A. G. Jaeger, P. M. Biron, C. Dussault, and J.-P. Ouellet. 2009. Reducing moose–vehicle collisions through salt pool removal and displacement: an agent-based modeling approach. *Ecology and Society* **14**(2): 17. [online] URL: http://www.ecologyandsociety.org/vol14/iss2/art17/

Research, part of a Special Feature on Effects of Roads and Traffic on Wildlife Populations and Landscape Function

Reducing Moose–Vehicle Collisions through Salt Pool Removal and Displacement: an Agent-Based Modeling Approach

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ABSTRACT. Between 1990 and 2002, more than 200 moose–vehicle collisions occurred each year in Quebec, including about 50/yr in the Laurentides Wildlife Reserve. One cause is the presence of roadside salt pools that attract moose near roads in the spring and summer. Using the computer simulation technique of agent-based modeling, this study investigated whether salt pool removal and displacement, i.e., a compensatory salt pool set up 100 to 1500 m away from the road shoulder, would reduce the number of moose–vehicle collisions. Moose road crossings were used as a proxy measure. A GPS telemetry data set consisting of approximately 200,000 locations of 47 moose over 2 yr in the Laurentides Wildlife Reserve was used as an empirical basis for the model. Twelve moose were selected from this data set and programmed in the model to forage and travel in the study area. Five parameters with an additional application of stochasticity were used to determine moose movement between forest polygons. These included food quality; cover quality, i.e., protection from predators and thermal stress; proximity to salt pools; proximity to water; and slope. There was a significant reduction in road crossings when either all or two thirds of the roadside salt pools were removed, with and/or without salt pool displacement. With 100% salt pool removal, the reduction was greater (49%) without compensatory salt pools than with them (18%). When two thirds of the salt pools were removed, the reduction was the same with and without compensatory salt pools (16%). Although moose–vehicle collisions are not a significant mortality factor for the moose population in the Laurentides Wildlife Reserve, in areas with higher road densities, hunting pressure, and/or predator densities it could mean the difference between a stable and a declining population, and salt pool removal could be part of a good mitigation plan to halt population declines. This model can be used, with improvements such as spatial memory of salt pool locations and the addition of a road avoidance behavior, to assess the effectiveness of mitigation measures intended to reduce moose–vehicle collisions.

Key Words: *agent-based modeling, Alces alces, moose, Laurentides Wildlife Reserve, Quebec, roads, road mortality, salt pools, wildlife–vehicle collisions*

INTRODUCTION

Humans have been constructing road networks for many centuries, and the effects of roads on the distribution and abundance of wildlife have become an important issue (Canters et al. 1997, Jaeger 2002, Sherwood et al. 2002, Spellerberg 2002, Forman et al. 2003, National Research Council of the National Academies 2006). For many members of modern societies, wildlife–vehicle collisions are one of the rare occasions when they directly experience the prevailing conflicts between wildlife populations and expanding human societies. Roads and traffic fragment the habitats of many wildlife species, leading to a decrease in habitat amount and quality, increased mortality because of collisions with vehicles, reduced access to resources on the other side of the road, and the subdivision of animal populations into smaller and more vulnerable fractions (Jaeger et al. 2005). In the case of larger land mammals, wildlife–vehicle collisions also pose a risk to traffic safety (Forman et al. 2003). It is estimated that, globally, there are several million vehicle collisions with moose (*Alces alces*), elk (*Cervus canadensis*), caribou (*Rangifer tarandus*), and other members of the cervidae family each year (Groot Bruinderink and Hazebroek 1996, Romin and Bissonette 1996, Conover 1997).

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Fig. 1. Salt pools near roads. (A) A moose at a roadside salt pool, B) a roadside salt pool after it has been drained and filled with rocks. (Photographs courtesy of M. Leblond, Université du Québec à Rimouski).

Figure 1A

Figure 1B

Fig. 2. The winter (1 October–30 April) and summer (1 May–30 September) home ranges of three moose. Note that each summer range is elongated to encompass the roadside salt pools. The home range boundaries were drawn based on GPS telemetry data, approximating the minimum concave polygon method.

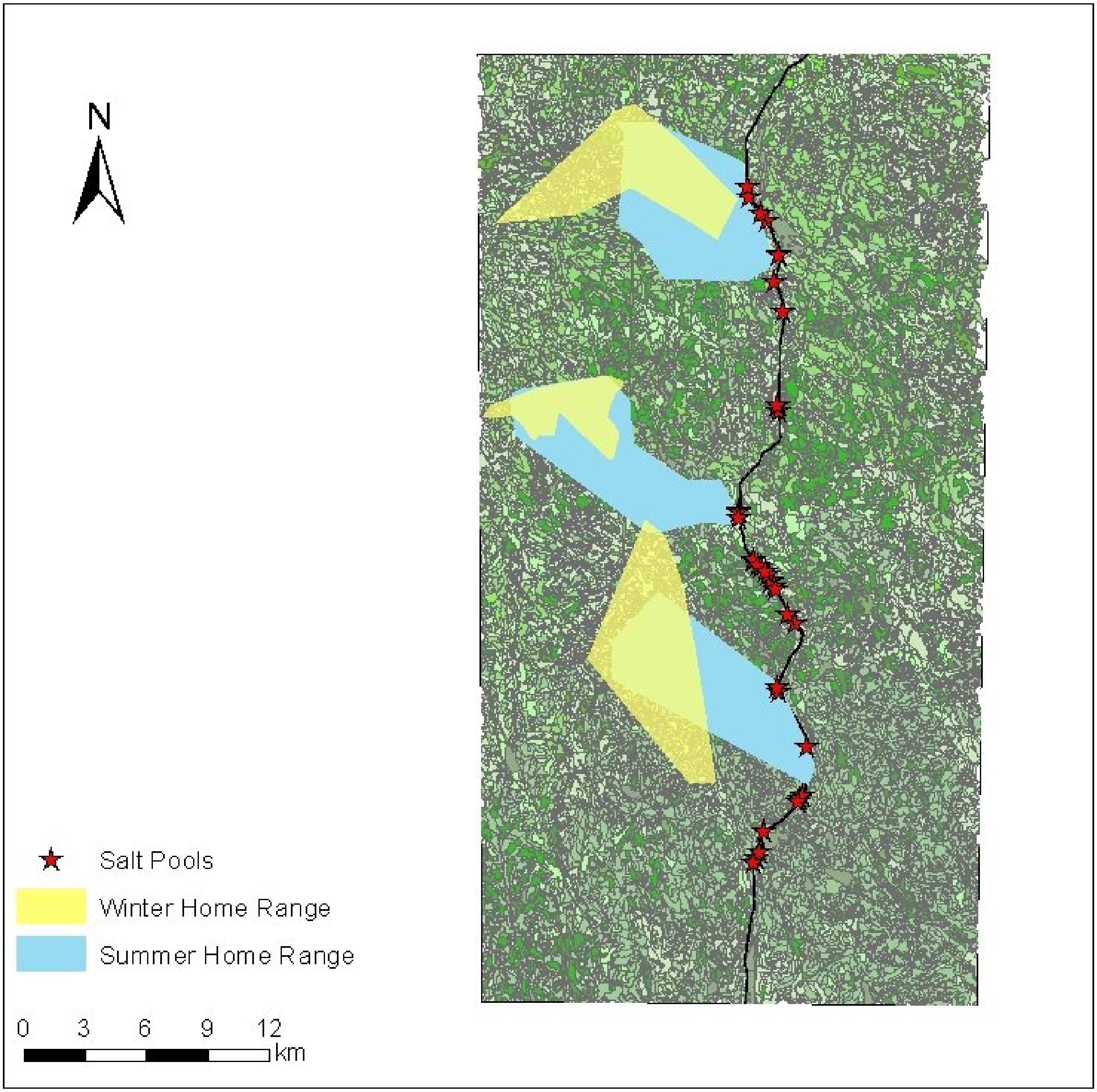


Fig. 3. The study area is the narrow black rectangle centered on the upper portion of Route 175 above the junction with Route 169. The boundary of the Laurentides Wildlife Reserve (LWR) is outlined in green. The LWR is situated between Quebec City and Chicoutimi in the Province of Quebec.

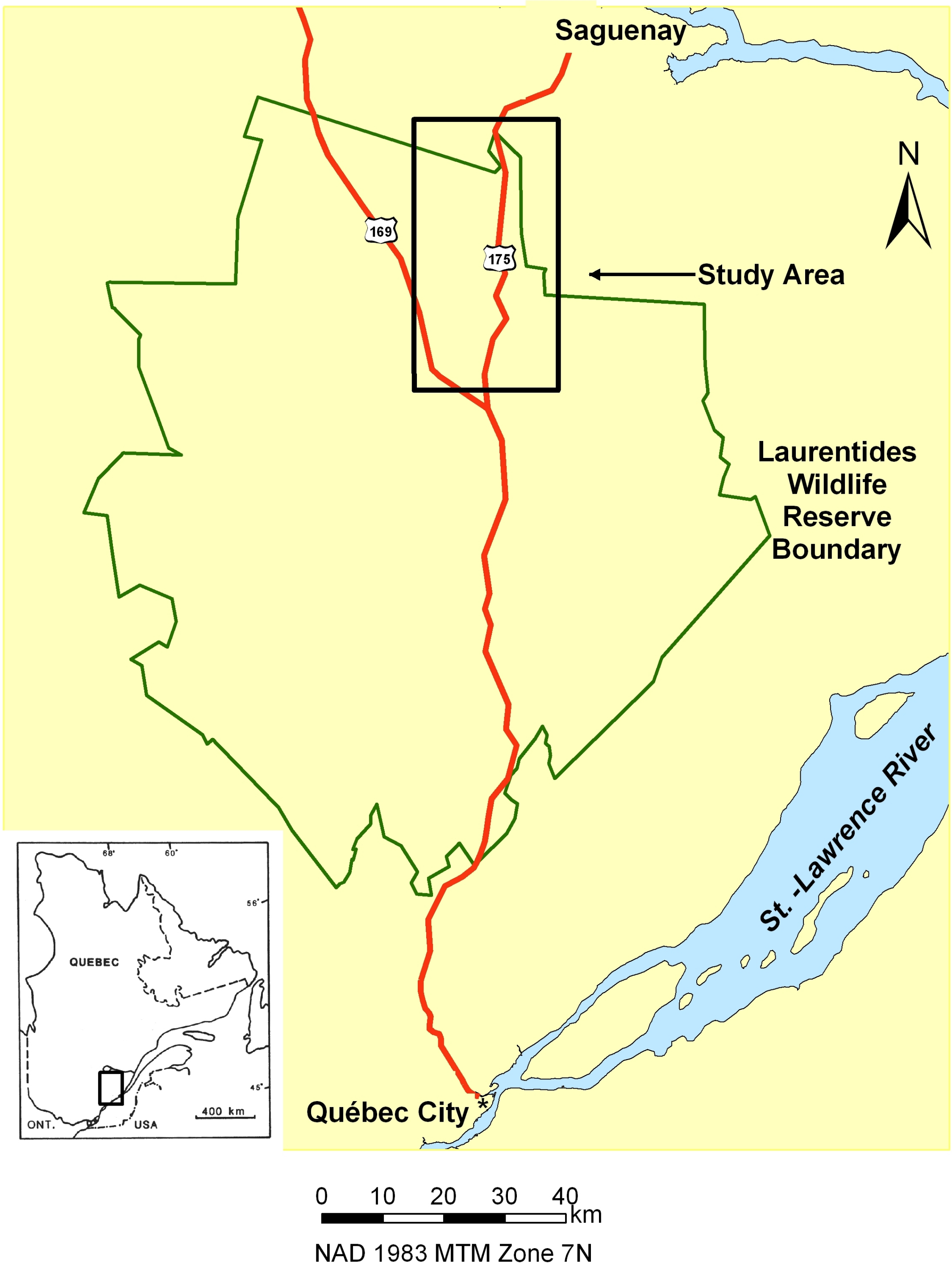


Table 1. Description of habitat types used to model moose behavior along highways in the Laurentides Wildlife Reserve, Quebec, Canada. Habitat types were based on the vegetation available in each forest polygon found on forest maps of the study area. Each habitat type was also assigned a value for its food and cover quality attributes as suggested by Dussault et al. (2006*b*).

Habitat type	Description	Food quality	Cover quality
Other	Lakes, islands, other	2	1
Fi50	Deciduous, intolerant hardwoods up to 50 yr old	4	2
Ft50	Deciduous, tolerant hardwoods up to 50 yr old	5	2
IMP	Buildings, urban area, fens, bogs, alder stands	2	1
Mi10	Mixed and intolerant hardwoods ≥ 10 yr old	5	1
Mi30	Mixed and intolerant hardwoods ≥ 30 yr old	4	3
Mi50	Mixed and intolerant hardwoods ≥ 50 yr old	3	3
Mt50	Mixed and tolerant hardwoods ≥ 50 yr old	5	3
R10	Conifers regenerating	3	1
RE30	Conifers with black spruce ≥ 30 yr old	1	4
RS30	Conifers with balsam fir or white spruce ≥ 30 yr old	2	4

Measures to mitigate wildlife–vehicle collisions are directed either at the human driver or at the wildlife and its environment. Measures targeting the wildlife and its environment consist of fencing, overpasses and underpasses, hazing, habitat alteration, and mirrors and reflectors (Forman et al. 2003). These measures are less used than those directed at the driver, even if they are considered more effective (Romin and Bissonette 1996). Fencing can help reduce highway crossings by up to 80% for ungulate species such as deer, moose, and elk (Clevenger et al. 2001, Leblond et al. 2007*a*). However, fences create an impermeable barrier that may result in population viability issues for endangered species (Jaeger and Fahrig 2004), although wildlife passages and fences used together improve habitat connectivity and population persistence.

In northern countries in which large quantities of salt are used on roads, e.g., 100 metric tons of road salt per kilometer per year in the Laurentides Wildlife Reserve (LWR), Quebec (Jolicoeur and Crête 1994), in the spring snow melt the runoff takes the road salt to the ditches and depressions beside the road (Fig. 1A). Although this may seem to be a lot of road salt, it is estimated that 5 million metric tons are used in Canada every year, about 1.5 million of them in Quebec (Environment Canada and Health Canada 2001).

Mitigation measures for moose–vehicle collisions (MVC) include the removal of salt pools. In the LWR, the Quebec transport department has drained roadside salt pools and filled them with rocks (Fig. 1B) to dissuade moose from visiting them; it has also created compensatory salt pools further from the road (Leblond et al. 2007*b*). More than 200 MVC occurred in Quebec every year between 1990 and 2002, including an average of 50 MVC in the LWR. Most MVC occur between May and October, mainly between dusk and dawn even though traffic volumes are lower at night (Dussault et al. 2006*a*). Sodium is an essential nutrient in the moose’s diet (Jolicoeur and Crête 1994). Moose obtain it by either browsing on aquatic plants or making a quick trip to the roadside, which may involve crossing the road to get to the salt pools on the other side. The concentration of sodium is two or three times higher

Table 2. Slope classes obtained from forest maps used to model moose behavior along highways in the Laurentides Wildlife Reserve. Slope class for each forest polygon was obtained from forest maps of the study area. Water bodies, islands, and some other land types had no code, so we changed these to A. Slope classes were then converted to integer values in which 5 represents the flattest slope and 0 the steepest.

Original coding	Designation	Inclination (%)	New coding
A	None	0–3	5
B	Weak	4–8	5
C	mild	9–15	4
D	Moderate	16–30	4
E	Strong	31–40	1
F	Abrupt	≥ 41	0
S	Summit	Summit zone ≥ 41	0

in salt pools compared to aquatic plants (Leblond et al. 2007*b*). Miller and Litvaitis (1992) observed that moose in northern New Hampshire, USA, elongated their summer home ranges to encompass roadside salt pools. This is also the case for the LWR moose; GPS telemetry data for at least three LWR moose reveal a clear difference between the winter and summer home ranges (Fig. 2).

Dussault et al. (2006*a*) estimated that the probability of an MVC increases by 80% in the proximity of roadside salt pools. With the modification of Route 175 in the LWR from a two-lane highway to a four-lane divided highway, the Quebec ministry of transport planned to eliminate roadside salt pools as a mitigation measure. They also planned to experiment with the placement of compensatory salt pools located further from the road shoulder, i.e., approximately 100 to 1500 m with a mean of 475 m, in the vicinity of the eliminated roadside salt pools (Leblanc et al. 2005). Although MVCs are not a significant mortality factor for moose in the LWR, they can, in areas with higher road densities and hunting pressure and with relatively high predator densities, affect population growth.

Agent-based modeling (ABM) can be used to predict the impacts of roads and traffic and of various mitigation measures on individual behavior. Such a model could be used to aid in the placement of mitigation measures to reduce MVC and restore habitat connectivity. An agent is an actor on a landscape that uses its limited knowledge of its surroundings to achieve its goals (Flake 1998). This computer-based modeling technique, also known as individual-based modeling or bottom-up modeling, takes into consideration the variability, life history, resource use, and other behavior of the individual units of a population (Railsback and Harvey 2002, Bennett and Tang 2006, Brown et al. 2008). ABM builds models of the individuals that, when aggregated, illustrate the population's “emergent” properties, such as the cyclical population curves in a predator–prey system (Grimm and Railsback 2005). This approach attempts to replicate the observed population patterns to explore the underlying processes that could be producing the patterns.

ABM can trace its beginnings back to Thomas Schelling, an American economist and the 2005 Nobel Prize co-winner in Economics. Schelling (1969) devised a very simple model that demonstrated the bottom-up effects of individuals' decisions on the city's composition. It showed that the decisions of individuals to move to a new neighborhood once they had exceeded their own fairly high tolerance or happiness threshold with

Table 3. Ranking values used to evaluate the attractiveness of each forest polygon in relation to the distance to the closest salt pool in modeling moose behavior along highways in the Laurentides Wildlife Reserve. Forest polygons that contained a salt pool were assigned a value of 5. Other values were assigned based on their proximity to the nearest salt pools as shown below.

Value	Distance to nearest salt pool (m)
5	Contains the salt pool
4	100
3	250
2	500
1	1000
0	> 1000

their immediate neighbours could lead to total segregation citywide. This simple model containing just one individual-based rule led to surprising properties at the next level of aggregation (Schelling 1969).

ABM has not yet been applied to the problem of MVC. The objective of this research was to use ABM to explore whether salt pool removal and displacement could reduce moose road crossings using this variable as a proxy measure for MVC. The total distance traveled by the moose was also examined to see if they would travel shorter or longer distances because of salt pool removal and displacement.

METHODS

Study area

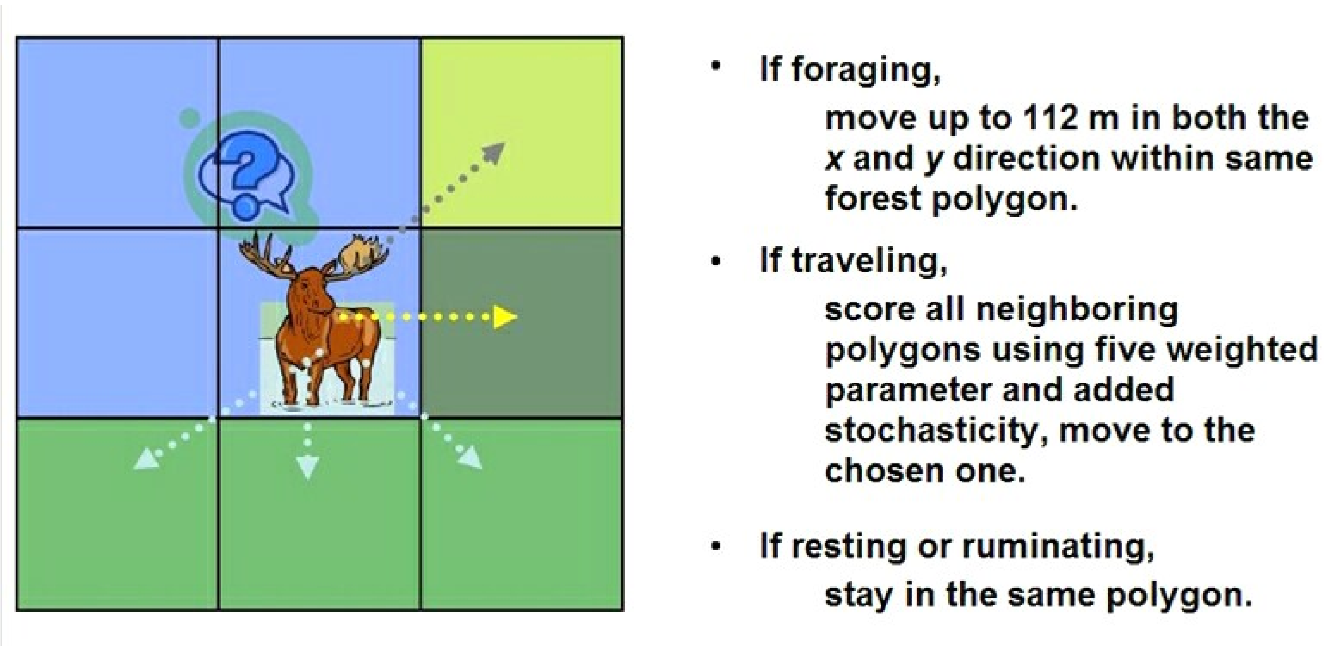
The study area is the northern portion of the LWR situated between Quebec City and Ville Saguenay (Fig. 3). The LWR is a forested area of 7861 km² (Dussault et al. 2006*a*) crossed by two provincial roads, Routes 175 and 169. Jacques-Cartier national park is located in the southern portion. Hunting is prohibited in this park but is permitted on a controlled basis in the LWR. In 2002, the average daily traffic volume on Route 175 north of the junction with Route 169 was 2800 vehicles, with the highest volumes in August and a peak on Friday nights (Dussault et al. 2006*a*).

A 24 x 46 km area centered on Route 175 above the junction with Route 169 was selected for this study. Twelve moose whose home ranges were almost wholly within 12 km of Route 175 were selected as agents for the model.

GPS telemetry data and moose behavior studies

The following GIS data were available for the study zone: moose movement locations in the LWR's northern section and Jacques-Cartier national park, forest vegetation (~10,000 polygons), roads, water bodies and streams, topography, and salt pool locations. Moose movement locations in the LWR's northern section were obtained from a GPS telemetry program performed by a joint research team from Quebec's Ministère des Transports, the province's Ministère des Ressources naturelles et de la faune, and the Université du Québec à Rimouski. The data set consisted of GPS telemetry locations for 47 moose, recorded every two hours for two years (~200,000 points). These 47 moose represented approximately 65% of the moose within 2 km of Routes 175 and 169 north of the junction. The data set included the following information: animal identification; point location; sex and age;

Fig. 4. Moose movement rules.



year, month, day, and hour of location data capture; and the distance traveled from the previous location (Dussault et al. 2007). The forest polygon vegetation data set, based on the Système d'information écoforestière database of the Ministère des Ressources naturelles et de la faune included the following information: forest polygon, slope category, forest composition and age, disturbance type and time, habitat type food category, and cover category (Dussault et al. 2006*b*). These data sets and the numerous scientific papers of the joint research team (Dussault et al. 2004, 2005, 2006*a*,*b*, 2007, Leblond et al. 2007*a*,*b*, Laurian et al. 2008*a*,*b*) provided a solid knowledge of moose behavior in the LWR and made it possible to develop an ABM model with some confidence.

Agent-based modeling platforms and model parameters

The model was built using the Java version of the open-source Recursive Porous Agent Simulation Toolkit, Repast J (North et al. 2006). It is considered a mature and flexible platform with many users in the scientific community and has good development support (Railsback et al. 2006, Tesfatsion 2008). Repast J also can read and write ArcGIS vector and raster data sets and be loosely coupled with ArcGIS so that the maps are refreshed as Repast J runs.

The spring and summer time period was chosen because this is when the moose are the most active visitors at salt pools (Leblond et al. 2007*b*). To match the GPS telemetry storage interval (Dussault et al. 2007), the model was set up to run from 1 May to 31 August on 2-hr time steps or Repast J "ticks," resulting in a total of 1476 steps.

A moose's daily activities can be divided into four parts: foraging for food, ruminating, resting, and traveling. Initially, a moose's 24-hr day was equally partitioned prior to model calibration, with 6 hr allotted to each activity based on Renecker and Schwartz (1998). After calibration, these four activities were assigned the following durations: foraging: 6 hr, ruminating: 6 hr, resting: 8 hr, and traveling: 4 hr (see below).

The distance a model moose moved while foraging in a 2-hr time step was determined to be 160 m by taking the average of the mean distance traveled

Table 4. Parameters for the 10 calibration runs. Run #8 was selected as best fitting the mean of the values for habitat use and total distance traveled by the corresponding 12 real moose.

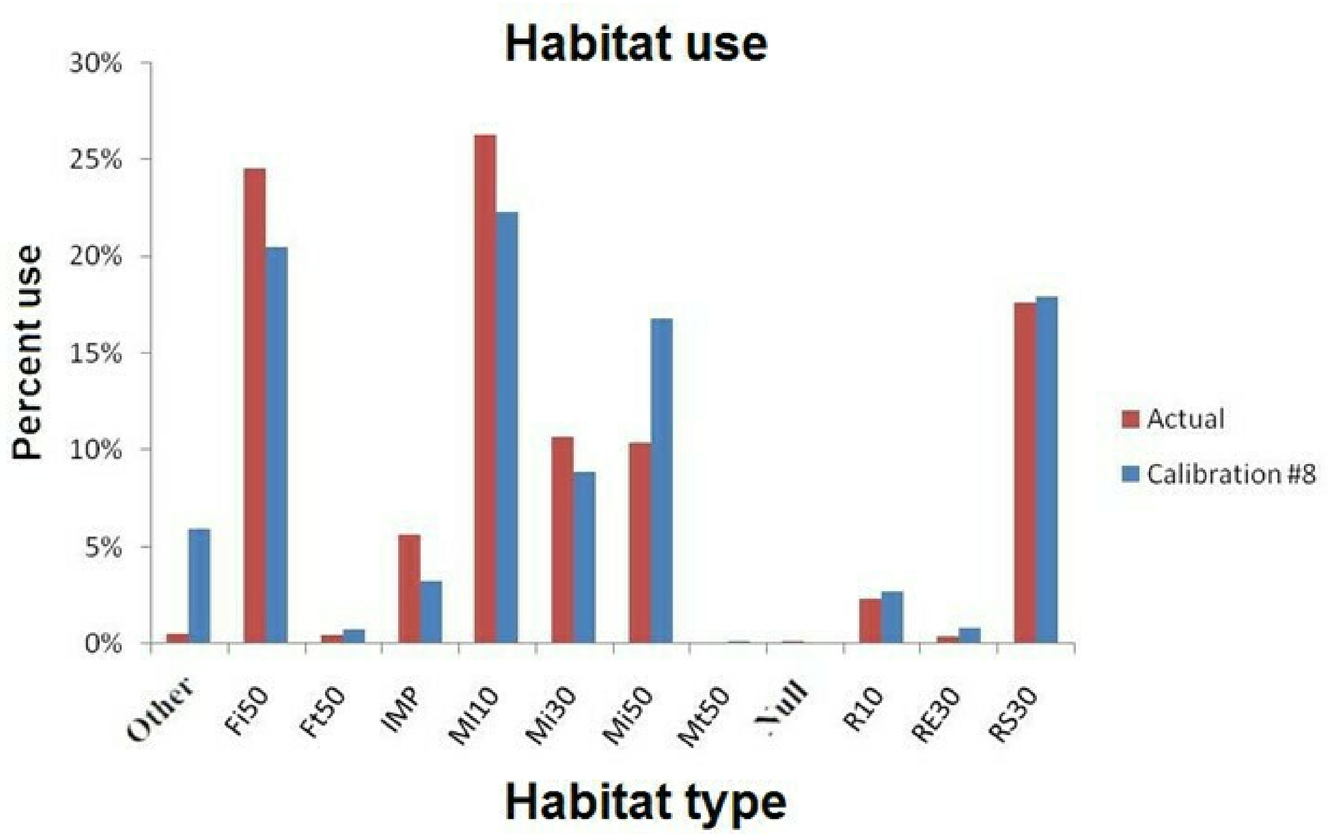
Table 4A. Time parameters for the 10 calibration runs.

Run #	Time spent (hr)			
	Foraging	Traveling	Resting	Ruminating
1	48	16	0	0
2	48	4	0	0
3	24	4	0	0
4	36	4	0	0
5	36	4	0	0
6	6	6	6	6
7	6	4	8	6
8	6	4	8	6
9	6	4	8	6
10	6	2	10	6

Table 4B. Habitat attribute weighting factors for the 10 calibration runs.

Run #	Habitat attribute				
	Cover	Food	Proximity to water bodies	Proximity to salt pools	Slope
1	0.200	0.300	0.100	0.350	0.050
2	0.200	0.300	0.100	0.350	0.050
3	0.200	0.300	0.100	0.350	0.050
4	0.200	0.300	0.100	0.350	0.050
5	0.225	0.325	0.100	0.300	0.050
6	0.200	0.300	0.100	0.350	0.050
7	0.200	0.300	0.100	0.350	0.050
8	0.100	0.400	0.100	0.350	0.050
9	0.100	0.450	0.100	0.300	0.050
10	0.100	0.400	0.100	0.350	0.050

Fig. 5. The habitat use of calibration run #8 compared to the actual habitat use of the 12 real moose. In calibration run #8, the top three habitat types were fairly close to actual moose habitat use. See Table 1 for a description of the habitat types.

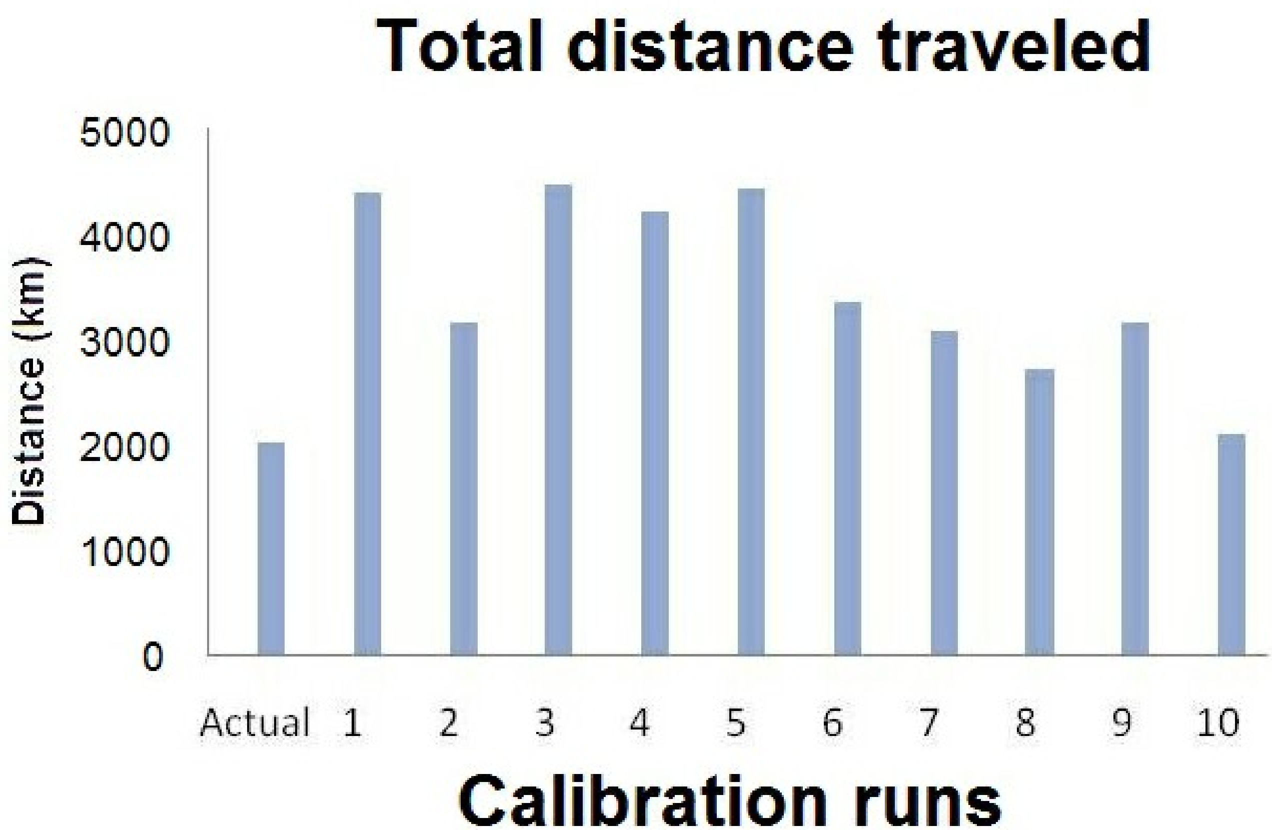


between successive locations for the spring and summer months (May: 159 m, June: 176 m, July: 172 m, and August: 134 m) for the 12 real moose that corresponded to the model moose.

Habitat use rules

The habitat use rules to determine which forest polygon to move to in the next time step were based on the five most significant parameters determined from the current scientific literature on moose in the LWR (Dussault et al. 2004, 2005, 2006*a*, 2007). These were food quality, cover quality or protection from predators and thermal stress, minimal slope, proximity to water bodies and streams, and proximity to roadside salt pools. Moose require 3–8 kg of food daily to maintain a positive energy balance and can spend 6–9.5 hr/day in the summer foraging (Renecker and Schwartz 1998, Dussault et al. 2005). The lower limit of 6 hr for foraging was chosen based on the model's calibration results because this time allotment gave the closest results when the model moose's habitat use and total distance traveled were compared to those of the 12 real moose. Moose seek protection from predators such as wolves (*Canis lupus*) and black bears (*Ursus americanus*) by selecting denser forests that provide habitat with lower visibility as well as shade for protection from solar radiation. Mature conifer stands typically offer the best cover against both predators and thermal stress (Dussault et al. 2005). These two parameters, food quality and cover quality, were coded for each forest polygon based on habitat type (Table 1). Moose when traveling

Fig. 6. The mean distance traveled in the 10 calibration simulations compared to the actual distance traveled by the 12 real moose. Calibration run #8 was the second-best match.



tend to seek flat terrain; they can travel along streams and also along hill ridges but tend not to move up and down slopes, probably to conserve energy (Dussault et al. 2006*a*). Slope was reclassified as a numerical value in the model for the purposes of scoring the neighbors of a forest polygon (Table 2). For proximity to water bodies, forest polygons bordering water bodies were given the highest score (5), those within a distance of 200 m received a score of 3, and any distance greater than 200 m was classified as 0. Proximity to salt pools was chosen because of the animal's essential nutritional need for sodium in its diet (Table 3). Each parameter was given a weight reflecting its relative importance for habitat use (Dussault et al. 2004, 2005, 2006*a*, 2007); the sum of these weights equaled 1.

The habitat quality ranks were initially set as follows: score of 5 = 0.60 chance of selection, 4 = 0.25 chance of selection, 3 = 0.125 chance of selection, 2 = 0.08 chance of selection, and 1 = 0.01 chance of selection. Rather than have the moose agent always select the neighboring polygon with the highest weighted score, these rankings were used to assign a likelihood that any particular score from 0 to 5 should be selected.

Moose movement rules

To apply the moose movement rules for traveling, a text file was generated prior to model execution using the GeoDa software program (Anselin 2004), which lists each forest polygon identification and its neighboring forest polygons. This file was then

Fig. 7. Location of the 36 roadside salt pools and their 18 compensatory salt pools in the model's study area along Route 175 in the Laurentides Wildlife Reserve.

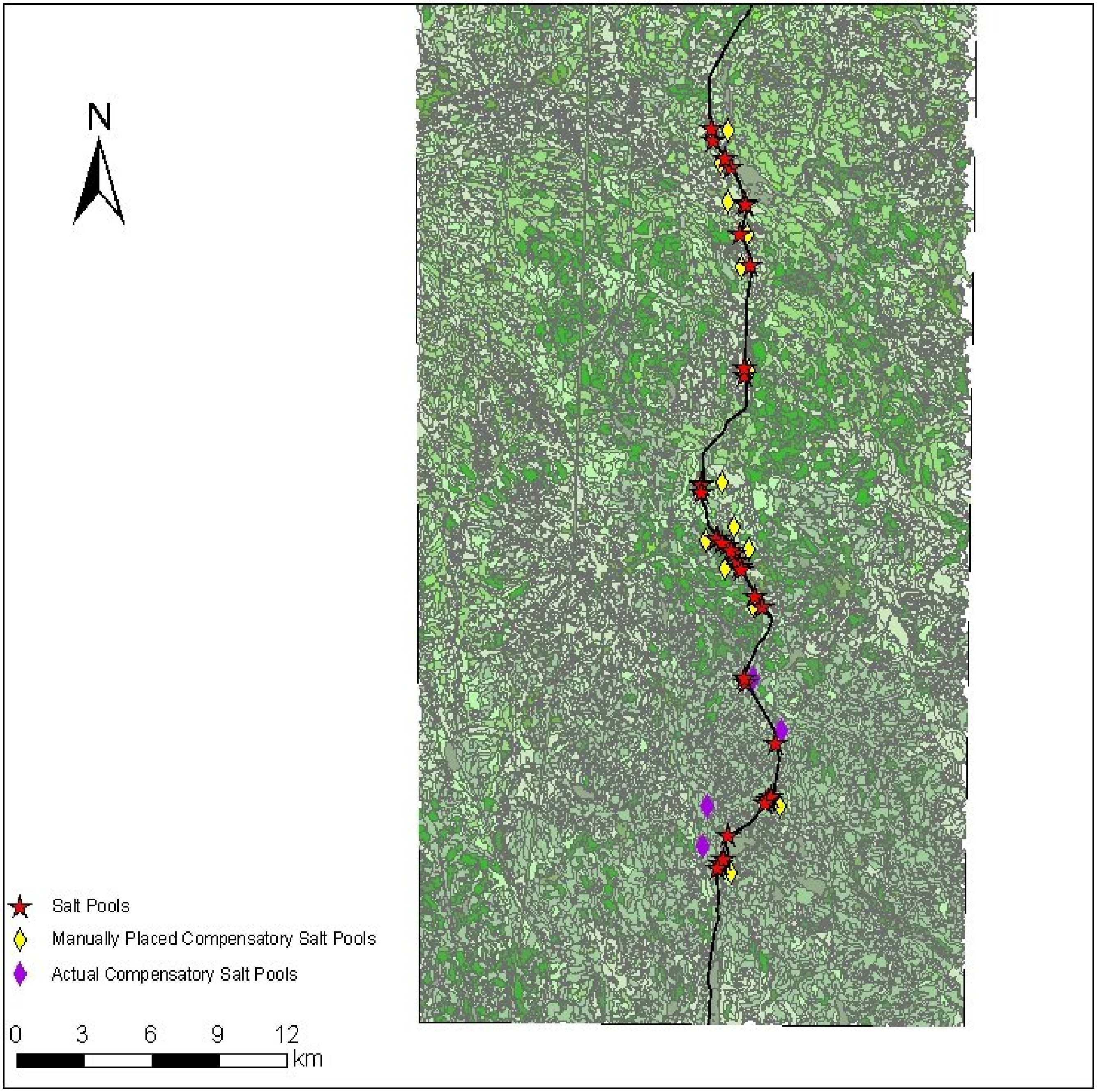


Table 5. Number of road crossings by model moose while traveling during the summer period according to five different modeling scenarios. Modeling scenarios differed from each other with respect to the degree of salt pool removal and the creation of compensatory salt pools. We conducted 100 runs per scenario. Standard error is equal to the standard deviation divided by the square root of the sample number.

Scenario	Mean	Standard deviation	Standard error	Reduction	One-sided *p*-value
1 (current situation)	45.58	22.79	2.28	...	...
2 (no salt pools)	23.14	13.18	1.32	49.24%	< 0.001
3 (no salt pools with compensating salt pools)	37.55	19.03	1.90	17.62%	0.004
4 (two-thirds of salt pools removed)	38.27	16.52	1.65	16.05%	0.005
5 (two-thirds of salt pools removed with compensating salt pools)	38.06	17.04	1.70	16.50%	0.004

used when the moose was traveling to determine the immediate neighbors of a given forest polygon.

If the moose is foraging, it moves to a new point within its current forest polygon (Fig. 4). The new point is constructed from its current location by multiplying the forage distance parameter, initially set to 112 m because $112 * \sqrt{2} = 160$ by two randomly selected numbers between -1 and +1 and adding these to the *x* and *y* coordinates of the current location. If the new point is outside the current forest polygon, the calculation is redone until a new point within the current forest polygon is obtained. When the moose is resting or ruminating, it does not move. If the moose is traveling, a stochastic approach is used to choose the highest-valued neighboring polygon rather than always selecting the highest-scoring neighboring polygon in a completely deterministic manner (Appendix 1).

Model calibration

A comparison of the distance of the 12 real moose GPS locations from the roadside salt pools vs. random points on the road showed no significant statistical differences (*t*-test: one-sided p-values ≥ 0.10). Therefore, the model calibration was done using habitat use by the 12 real moose and the total distance they traveled instead of using the number of salt pool visits. Ten simulations of 10 runs each were executed with various sets of moose daily activity budgets (Table 4A) and the model parameter weights (Table 4B). The mean habitat use and the mean distance traveled of the model moose were then compared to the habitat use and distance traveled totals of the 12 real moose for one summer. Run #8 fitted the habitat selection best and fitted the total distance traveled second-to-best (Figs. 5 and 6). These parameter weights and daily activity budget were chosen for the scenario runs.

Scenarios

The following five scenarios were tested with the model:

1. Current situation: no salt pools removed, no compensation salt pools;

2. 100% salt pool removal, no compensation salt pools;

Fig. 8. Road crossings by 12 real moose for the time period 1 May–31 August. Of the 72 paths that intersected the 45-m road buffer, 53 paths actually crossed the road. L53, L19, L46, L05, and L17 are the moose GPS telemetry collar identifications.

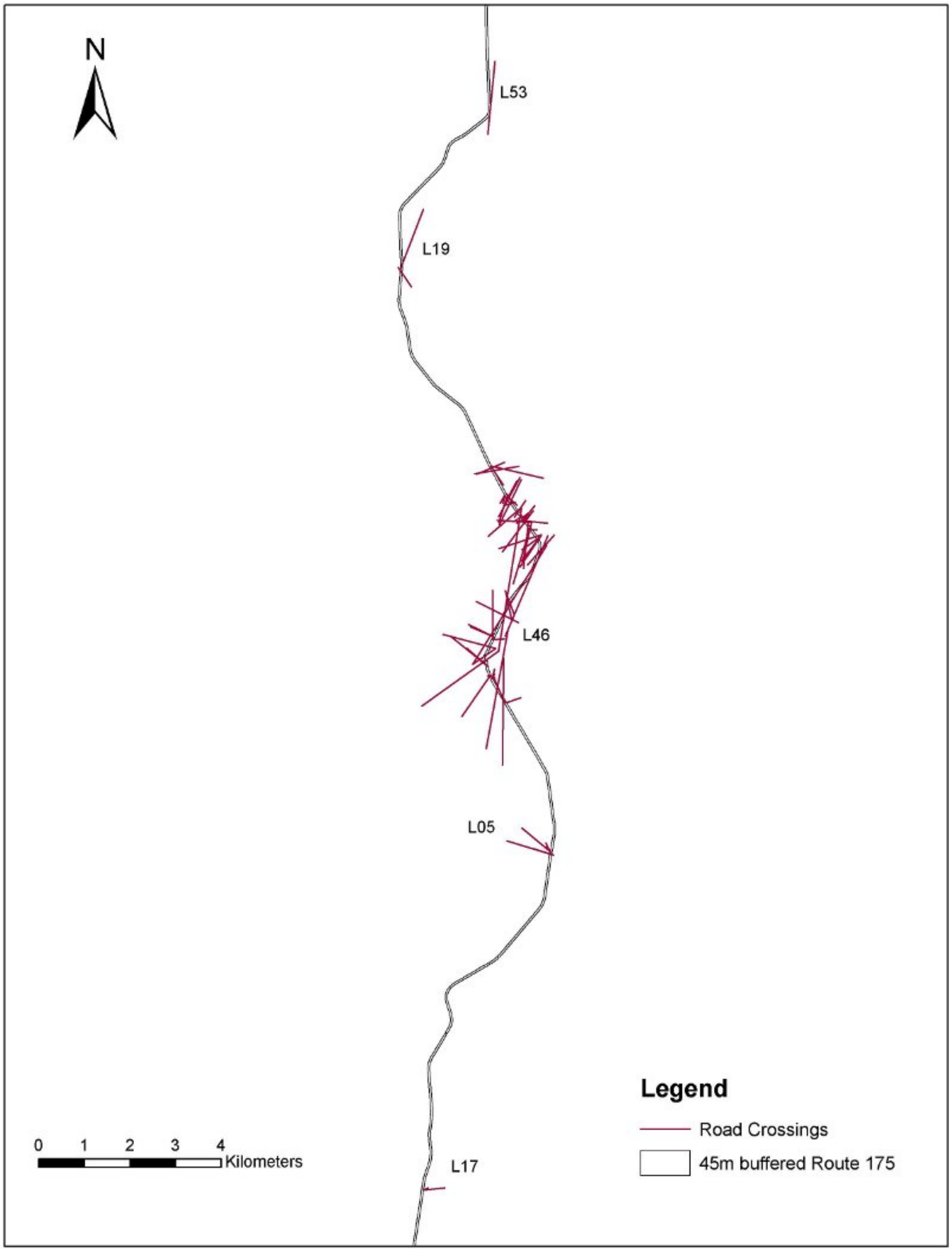


Table 6. Total distance traveled by model moose while traveling during the summer period according to five different modeling scenarios. Modeling scenarios differed from each other with respect to the degree of salt pool removal and the creation of compensatory salt pools. We conducted 100 runs per scenario. The “Change” value means change compared to the current situation.

Scenario	Mean	Standard deviation	Standard error	Change	Two-sided *p*-value
1 (current situation)	2724	308	31	...	...
2 (no salt pools)	2972	291	29	+9.10%	< 0.01
3 (no salt pools with compensating salt pools)	2725	247	25	+0.02%	0.99
4 (two-thirds of salt pools removed)	2693	262	26	-1.15%	0.44
5 (two-thirds of salt pools removed with compensating salt pools)	2756	304	30	+1.150%	0.47

3. 100% salt pool removal, 100% compensation salt pools;

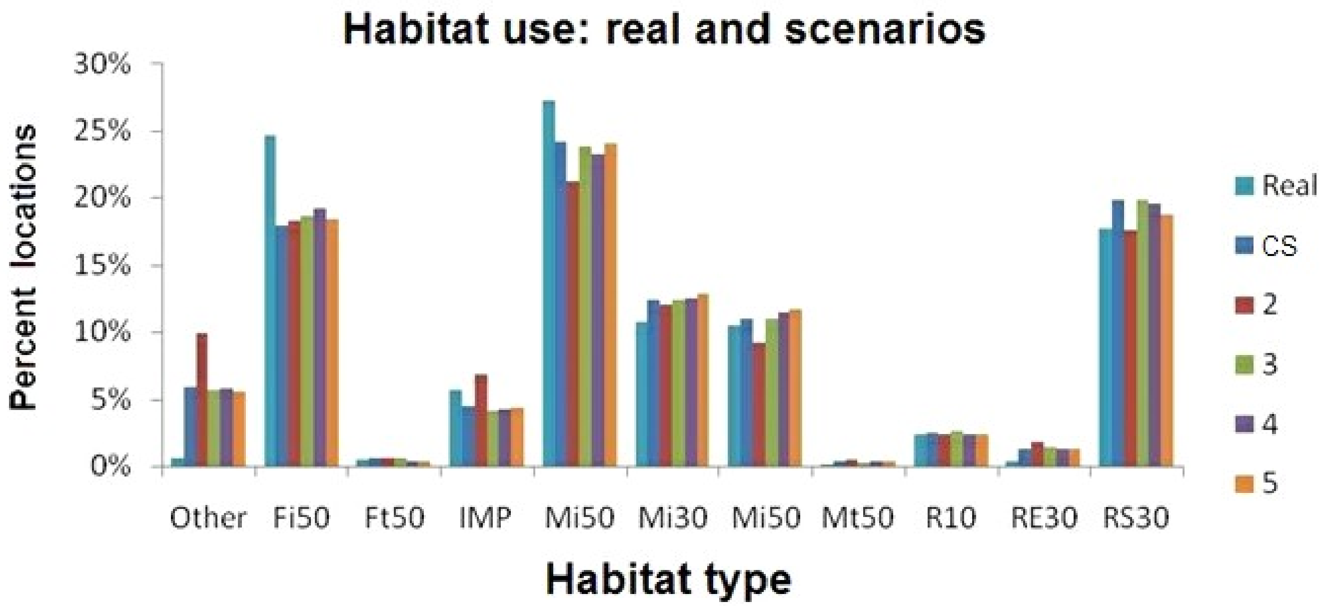
4. Two-thirds salt pool removal, no compensation salt pools;

5. Two-thirds salt pool removal, two-thirds compensation salt pools.

Each scenario was run 100 times. Because the 36 roadside salt pools have a clustered distribution, they were randomly divided up into six sets of six; the 18 compensatory salt pools were divided up into three sets of six based on which roadside salt pools they were compensating for. Four of the 18 compensatory salt pools used in the model were real, created by Transport Quebec personnel, and located in the field with a GPS (Leblond et al. 2007*b*). The other 14 were created only in the computer model and placed near existing roadside salt pool locations that had no real compensatory salt pools near by (Fig. 7). Thus, each compensatory salt pool replaced two neighboring roadside salt pools. The compensatory salt pools were placed at a distance of 300–1700 m from Route 175.

In the second scenario only, the moose should revert to the sodium-rich aquatic environment because there are no salt pools in the GIS landscape (Leblond et al. 2007*b*). Accordingly, the weight of the parameter “proximity to salt pool” was reduced to zero, and that of the parameter “proximity to water bodies” was correspondingly increased to 0.45; for the other four scenarios, all the weights were kept identical to the results of the model calibration. The data logs for each scenario were combined and summarized to determine the number of moose road crossings while traveling, the total distance traveled by the model moose, and their habitat use. Student’s *t* tests were performed on the 100 runs of scenarios #2 through #5 against the 100 runs of scenario #1 to verify if roadside salt pool removal and displacement led to a statistically significant reduction in moose crossings and in total distance traveled. We considered effects significant with p values ≤0.05 in all statistical analyses.

Fig. 9. Habitat use by moose for the time period 1 May–31 August as determined using GPS-collared individuals (real) and as predicted with the five different modeling scenarios for the Laurentides Wildlife Reserve. See Table 1 for a description of habitat types.



RESULTS

Road crossings

In each test, there was a statistically significant reduction in road crossings compared to the scenario reflecting the current situation (one-sided *p*-values varying from <0.01 to 0.01). In this scenario, the moose crossed Route 175 a mean of 45.6 times from 1 May to 31 August. When roadside salt pools were removed with or without compensatory salt pools, the number of road crossings by moose was reduced 18–49% (Table 5).

However, only three of the 12 real moose crossed the road for a total of 53 times: two did so twice, and the other, whose home range was bisected by Route 175, crossed 49 times (Fig. 8). This was determined using Hawth's Analysis Tools for ArcGIS (Beyer 2004).

Total distance traveled

In the current situation scenario, the 12 moose traveled a mean total of 2724 km from 1 May to 31 August. When roadside salt pools were removed with and without compensatory salt pools, the total distance traveled by moose varied from a reduction of about 1% to an increase of 9% (Table 6).

Total distance traveled by moose only differed from the current situation scenario when all the salt pools were removed and no compensatory salt pool was created (two-sided *p*-value <0.01). In comparison, the corresponding set of 12 real moose traveled 2018 km over the same time period, which was 26% less than in the current situation scenario.

Habitat use

Moose habitat use in the model did not vary between scenarios, which all represented quite well the habitat use of the real moose (Fig. 9). Relative rankings of habitat type appeared to be consistent between the scenarios and the real set of moose. The higher percent location for the “Other” habitat type for scenario #2 reflects the result of the increased weighting for proximity to water bodies as the model moose search for water bodies instead of salt pools. The higher percent location for the “Fi50” habitat type for the real moose compared to all the scenarios in the model could be because most of the “Fi50” forest polygons are located in the northern half of the model study area whereas there are more salt pools in the southern portion, and half of the model moose’s starting locations are in the southern portion as well.

DISCUSSION

The model results showed that the removal and displacement of roadside salt pools leads to a statistically significant reduction in road crossings by model moose. Thus, such an intervention in the field should reduce MVC probability depending on road crossing dates and times and traffic volumes at these times. Regardless of potential improvements that can be made to this model, as discussed below, we conclude that roadside salt pool removal should reduce the number of MVC by reducing moose visits to roadside salt pools.

The greatest reduction in road crossings occurred in the second scenario in which all the salt pools were removed and no compensatory ones were created. For this scenario only, because there were no salt pools of either type, the weight of the parameter “proximity to salt pools” was reduced to zero. Smaller reductions in moose crossings occurred in the other three scenarios that had salt pools. The scenario with no roadside salt pools but 18 compensatory ones had a greater reduction in road crossings than did the scenarios with one third of roadside salt pools remaining. This is in agreement with the empirical findings of Leblond et al. (2007*b*), who conducted a study of 12 roadside salt pools over three consecutive summers. Seven salt pools were drained and filled with stone, and five were left alone. The managed salt pools had a reduction in visits of 90% in the second and third years compared to the unmanaged pools, thus decreasing the risk of moose–vehicle collisions. Leblond et al. (2007*b*) recommended longer studies to assess the efficacy of this management strategy.

Habitat use by the model moose generally agreed well with that of the real moose (Dussault et al. 2005), particularly in terms of habitat rankings. Therefore, the habitat selection rules that were based on the weighted average of the five parameters of food, cover, slope, proximity to salt pools, and proximity to water bodies with stochastic variability appeared to give reasonable results. However, the total distance traveled by the model moose was consistently greater than that of the real moose. For future modeling studies, some of the moose movement rules need to be redesigned (see below). The scenario with no salt pools had a statistically significant increase in distance traveled, and this may be attributed to the model moose searching for water bodies (Leblond et al. 2007*b*).

Suggestions for future improvements

There are several possible avenues for improvements to the ABM model that are currently being investigated: home range enforcement, the consideration of the road avoidance behavior of the moose (Laurian et al. 2008*b*), spatial memory of roadside salt pools, and the calculation of MVC probabilities as a function of traffic volumes (e.g., Van Langevelde and Jaarsma 2004).

Most of the home ranges of the real moose appeared to be quite distinct from each other in the GIS data (Fig. 2). An enforcement of their limits is likely to improve the results by keeping the moose from moving out of their own home ranges, particularly to areas that are on the opposite side of the road. It appears that a road avoidance effect is operating on the moose home ranges (Dodd et al. 2007, Dussault et al. 2007, Laurian et al. 2008*b*). This is probably the change that could improve the model the most. It is clear from the GIS data that most of the home ranges of the 12 moose come up to the road but do not extend beyond it. Riley et al. (2006) studied the barrier effect of the Ventura Highway on the local coyote and bobcat populations and found that, even though there were numerous crossings, there was a lack of reproductive success by the individuals that crossed. The authors attributed this to the barrier effect of the road, which created a “home range pile-up” against the road that did not allow immigrants to establish a home range for themselves (Riley et al. 2006). To reduce foraging time in the vicinity of the road, a new road buffer could be used that represents the degraded habitat (food and cover) on and near the road (Dussault et al. 2007). This would likely discourage the moose from choosing forest polygons that are closer to the road than other neighboring ones.

The decay of salt pool attraction to zero at distances greater than 1000 m may be rather unrealistic; it is likely that the moose remember the roadside salt pool locations from year to year and do not have to rely on rediscovering them with their sense of smell (Leblond et al. 2007*b*). Periodically, moose would travel directly to roadside salt pools at the edge of their home ranges but then return to the interior.

These improvements will likely affect the outcomes of the model. Both home range enforcement and road avoidance are expected to reduce the number of road crossings with and without salt pools present, but the net effect is difficult to predict. Including a memory of salt pools will probably lead to a more pronounced decrease in the number of road crossings because moose will access salt pools on a more regular basis when they are present and no longer go to those locations after the pools have been removed. This may include a time lag in the reaction of the moose to the removal of salt pools because of learning, as suggested by Leblond et al. (2007). Higher traffic volumes are likely to increase the number of MVC and the absolute reduction of MVCs because of salt pool removal, but will not necessarily change the relative reduction of MVCs.

Speculation

It must be acknowledged that salt pools are more a road safety issue than a population viability issue for moose. Although it has been shown that there is a direct relationship between moose road-crossing sites and salt pools (Dussault et al. 2006*a*, 2007), MVCs are not a significant mortality factor for moose in the LWR. To increase traffic safety, salt pool removal could be a better alternative to the more expensive fences in areas in which moose are present and may be more socially acceptable because of the negative visual impact of fences. However, roadside salt pools and salt pool removal still have effects on the population level and the landscape level as well as on landscape function. One reason is that MVCs are a density-independent factor that kills healthy individuals and therefore affects population composition in a different way than predators. In areas with higher road densities and hunting pressure and with relatively high predator densities, mortalities on the road could make the difference between a stable and a declining population. This is certainly the case with some other ungulate species that are also attracted to roadside salt pools. A small Charlevoix herd of woodland caribou (*Rangifer tarandus caribou*), for example, is listed as a Canadian threatened species (COSEWIC 2002) and as a vulnerable species under the *Quebec Act Respecting Threatened or Vulnerable Species* (MRNF 2007). This herd is estimated at only 117 individuals (Courtois et al. 2002), some of which cross the southern portion of Route 175 entering the Parc national de la Jacques-Cartier (Lefort et al. 2006). Only a few woodland caribou–vehicle collisions would result in reduced population viability for the entire herd, and salt pool removal could slow this decline.

Salt pools are also responsible for specific moose movements, sometimes of several kilometers, across the landscape. Results from the study by Laurian et al. (2008*a*) indicate that moose make directional trips toward salt pools at increased movement rates and that visits are more frequent during spring and early summer before aquatic vegetation is available (see elongation of the summer home ranges in Fig. 1), and also during the night, which is the time of increased MVC risk. This emphasizes the need to incorporate a salt pool memory parameter in the model.

The model could also be used in conjunction with a population dynamics model to evaluate different management scenarios if the probability of a moose being hit by a car when crossing the road could be estimated. Finally, Laurian et al. (2008*b*) showed that roads are avoided by moose all year long except during the spring, when the need for sodium is highest. All these results indicate that there is a behavioral adaptation of moose to a landscape-level human-induced habitat modification, i.e., paved roads. This is even more obvious in areas like the LWR in which highways are not uniformly distributed in the landscape and moose have to travel to reach them. This illustrates that roads affect landscape connectivity for moose, which is an example of landscape function.

CONCLUSION

Our results suggest that the most effective strategy is to remove all salt pools with no compensatory ones and to let the moose return to foraging for aquatic plants to satisfy their sodium dietary requirement. The results also highlight a strong potential for the use of ABM in road mitigation planning and wildlife management (see also Kramer-Schadt et al. 2004, Malo et al. 2004, Frank et al. 2005, Jaeger 2006). If ABM can be used to test our assumptions about wildlife behavior with regard to roads, it can certainly be useful to road ecologists, wildlife biologists, and transportation planners seeking ways to reduce wildlife–vehicle collisions and re-establish wildlife habitat connectivity. Mitigation measures such as fences, overpasses, and underpasses could be placed in the model and simulations run to determine likely usage over time. The model could thus be used to help determine the best locations for mitigation measures such as wildlife underpasses. Changes to habitat composition by human or natural disturbance such as clear-cutting, fires, and climate change could also be introduced into the model to evaluate potential changes to the animal movement behavior.

In addition to being useful for traffic planners, such models can also serve as an important means to communicate increasing ecological issues related to human population growth to the general public who live in urban settings and have little direct experience with wildlife. Such models can be used for education in schools and as part of exhibitions such as the exhibition about the function of wildlife passages at the Whyte Museum in Banff in 2006. Viewing wildlife–vehicle collisions as indicators of deeper ecological conflicts would contribute to a broader perception of such human–wildlife encounters rather than the current narrow focus on issues of traffic safety.

Responses to this article can be read online at: *http://www.ecologyandsociety.org/vol14/iss2/art17/responses/*

Acknowledgments:

This article has benefited from the constructive suggestions made by the subject editor and the two anonymous reviewers. This study was funded by the Ministère des Transports du Québec, the Ministère des Ressources naturelles et de la Faune du Québec, and the Université du Québec à Rimouski. The first author was supported with funding from the Université du Québec à Rimouski and the Ministère des Ressources naturelles et de la Faune.

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APPENDIX 1. MOOSE TRAVELING PROCEDURE

First, all the neighboring forest polygons next to the currently occupied one were scored using the weighted parameters. For example, say that a neighboring polygon had the following values: food quality = 4, cover quality = 1, slope = 5, proximity to water bodies = 1, and proximity to roadside salt pools = 3. Then its score would have been equal to the following:

score = (food weight) * (food quality) + (cover weight) * (cover quality) + (slope weight) * slope + (proxWB weight) * (proximity to water bodies) + (proxSP) * (proximity to roadside salt pools)
= 0.40 * 4 + 0.10 * 1 + 0.05 * 5 + 0.10 * 1 + 0.35 * 3 = 3.10.

Next the scores were turned into preferences by determining the two habitat quality ranks on either side of the score and applying a linear interpolation to obtain a precise preference value. For example, the score 3.10 obtained above fell between the habitat quality rankings of 3 and 4, which had values of 0.125 and 0.25 respectively. Consequently, the score 3.10 became 0.125 + (3.10 -3) * (0.25 -0.125) = 0.1375.

These preferences were normalized to 100%. The normalized preferences were laid out along a line from 0 to 1, a random number was selected between 0 and 1, and the preference that bound the selected random number was determined and its corresponding polygon chosen. If, however, this chosen polygon was the one previously visited or the one before that, the process was repeated until a new polygon was selected. This was to avoid the moose returning too soon to a previously visited forest polygon. If the current polygon had only one or two neighbors, the first neighbor was selected in both cases. If the polygon had no neighbors, the moose returned to the forest polygon it had visited before the previous one. It was anticipated that at that point the moose would pick a different neighboring forest polygon and not end up in the same dead end.

It was clear that individual moose had distinct home ranges from the moose movement GPS data. Each moose's starting location was assumed to be the center of its circular home range, the radius of which was entered into the moose location shape field. All moose ranges were given a radius of 10 km, a value somewhat larger than the 6 km of Voigt et al. (2000) but which approximated the real study-area moose. This radius was used when the moose was traveling to check if it exceeded its home range limit. If this happened, then the moose had to choose a different polygon to move to. This rule was relaxed to just a warning in the final version of the model, because otherwise the moose tended to get stuck on the perimeter of its home range.