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Strategically Locating Wildlife Crossing Structures for Florida Panthers Using Maximal Covering Approaches

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Abstract

Crossing structures are an effective method for mitigating habitat fragmentation and reducing wildlife-vehicle collisions, although high construction costs limit the number that can be implemented in practice. Therefore, optimizing the placement of crossing structures in road networks is suggested as a strategic conservation planning method. This research explores two approaches for using the maximal covering location problem (MCLP) to determine optimal sites to install new wildlife crossing structures. The first approach is based on records of traffic mortality, while the second uses animal tracking data for the species of interest. The objective of the first is to cover the maximum number of collision sites, given a specified number of proposed structures to build, while the second covers as many animal tracking locations as possible under a similar scenario. These two approaches were used to locate potential wildlife crossing structures for endangered Florida panthers (*Puma concolor coryi*) in Collier, Lee, and Hendry Counties, Florida, a population whose survival is threatened by excessive traffic mortality. Historical traffic mortality records and an extensive radio-tracking dataset were used in the analyses. Although the two approaches largely select different sites for crossing structures, both models highlight key locations in the landscape where these structures can remedy traffic mortality and habitat fragmentation. These applications demonstrate how the MCLP can serve as a useful conservation planning tool when traffic mortality or animal tracking data are available to researchers.

1 Introduction

Forman (2000) estimated that up to 20% of wildlife habitat in the U.S. is impacted by close proximity to roads. While transportation right-of-ways do provide suitable habitat to some species (Forman and Alexander 1998), the presence of roadways and other transportation networks, such as railways, usually negatively impacts animal populations. The effects of transportation networks on wildlife are far-ranging and include: habitat loss from new construction, soil erosion and hydrological flow alteration as a result of increased impermeable surfaces (Reid and Dunne 1984), disturbance caused by noise (Arisz 2005, Reijnen et al. 1997), habitat fragmentation that can restrict movements and isolate populations (e.g. Bienen 2007, Cameron et al. 1995, Clark et al. 2001, de Maynadier and Hunter 2000, Shepard et al. 2008), and the occurrence of wildlife-vehicle collisions.

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Wildlife-vehicle collisions are a major human health and safety risk not only in the U.S. but across the globe (Bruinderink and Hazebroek 1996, Inbar et al. 2002, Dussault et al. 2006, Jones 2000, Orlowski and Nowak 2004, Ramp et al. 2006). Wildlife collisions are a concern, because they often cause injury or death to vehicle passengers (Bashore et al. 1985, Biggs et al. 2004, Iverson and Iverson 1999) and result in considerable property damage (Finder et al. 1999, Mastro et al. 2008). However, collisions can also be a significant source of mortality for wildlife. Collisions with moose, elk, deer, bear, and other large mammals are the best documented, perhaps due to the abundance, size, and damage potential of these species (Braden et al. 2008, Farrell and Tappe 2007, Garrett and Conway 1999, Hubbard et al. 2000, Waller and Servheen 2005). Mortality caused by collisions is also well documented for a variety of smaller species, including other mammals (Clevenger et al. 2003, Fehlberg and Pohlmeyer 1993, Ford and Fahrig 2007, Orlowski and Nowak 2006, Philcox et al. 1999), birds (Orlowski 2005, Orlowski and Siembieda 2005), reptils and amphibians (Carr and Fahrig 2001, Eigenbrod et al. 2008, Langen et al. 2007, Roe et al. 2006, Sillero 2008), and insects (Elzanowski et al. 2009, Rao and Girish 2007). Collision-caused mortality is a particular conservation concern for endangered animal populations that are already at risk of extinction (Cook and Daggett 1995, Ferreras et al. 1992).

As transportation networks impose a variety of ecological impacts on animal populations, and also pose risks to human health and safety, research has focused on developing strategies for reducing these conflicts. While preventative measures such as fencing, warning signs, and other deterrents have been shown to reduce collisions in some situations (Cramer et al. 2006, Knapp 2005, Putman 1997), wildlife crossing structures – which allow animals to safely pass over or under roads – are a preferred solution since they can mitigate habitat fragmentation in addition to reducing roadway mortality (Cramer and Bissonette 2005, Kintsch et al. 2006). Crossing structures are typically implemented in locations where there is a known habitat disconnect, or where hot-spots of collisions occur as determined from accident reports or road-kill surveys (Clevenger 2005, Krisp and Durot 2007). However, Clevenger (2005) noted that strategic planning and integration of crossing structures into transportation systems is generally lacking. Proper siting of crossing structures is essential, because their placement determines wildlife utilization (Ruediger 2001). Additionally, since high construction costs limit the number of structures that can be implemented in practice, strategic landscape planning efforts should aim to identify potential crossing structure locations that yield the greatest conservation benefits given limited expenditures.

Downs and Horner (2012) suggested that location modelling can offer one approach for strategically siting wildlife crossing structures. Facility location models developed in operations research are widely used in GIS to strategically site facilities and other types of infrastructure. While there are many variants (see Revelle et al. [2008] and Murray [2010] for reviews), facility location models are designed to select the best locations for new facilities from a set of candidate sites by mathematically optimizing an objective function that is subject to any distance or other constraints. In the context of crossing structures, Downs and Horner (2012) developed two sets of spatial models for locating these facilities with the objective of connecting discrete, isolated habitats that are fragmented by roads. The first set of models minimizes the number of crossing structures required to connect all habitat patches in a landscape. The second set maximizes inter-patch connectivity given a fixed number of structures to locate. While these approaches are useful when target species occupy small isolated patches, they are not applicable for landscapes with more continuously distributed habitat where roads divide relatively large tracts of land. As such, this article describes alternative spatial modelling approaches that are based on collision records and animal tracking data rather than habitat configurations.

Specifically, the maximal covering location problem (MCLP) (Church and ReVelle 1974) is proposed as a method to strategically site wildlife crossing structures. Two approaches are used. The objective of the first is to 'cover' the maximum number of observed collision sites given the locations of existing structures and a specified number of proposed new structures. The second utilizes animal tracking data, rather than collision records, and attempts to cover as many animal locations as possible under a similar scenario. The models are explored in the context of locating potential crossing sites for endangered Florida panthers in three counties of Southwestern Florida. The goal is to identify optimal locations for future panther crossing structures under a variety of planning scenarios. The remainder of the article is organized as follows. Section 2 outlines the maximal covering approach and describes how it can be used to site wildlife crossing structures in road networks. Section 3 applies the model to locate crossing structures for Florida panthers. Finally, Section 4 discusses the limitations and applicability of this approach in the context of both panther recovery and GIScience in general.

2 Maximal Covering Approach for Siting Wildlife Crossing Structures

The maximal covering location problem (MCLP) was originally described by Church and ReVelle (1974). The MCLP sites a specified number of facilities such that the selected facilities 'cover' as much demand as possible given each facility's potential service area. For example, the MCLP can be used to site hospitals such that they cover the largest amount of people within their service radii. The MCLP has been used to locate facilities in numerous urban and environmental planning situations. For example, this approach has been used to determine optimal locations for nature reserves (Church et al. 1996, Gerrard et al. 1997), health care facilities (Rahman and Smith 1995), ambulances and other emergency vehicles (Asiedu and Remsel 2009, Erdemir et al. 2010, Lim et al. 2011), businesses and many other types of public and private facilities (Chung 1986). The MCLP approach can be extended to site wildlife crossing structures in road networks based on patterns of either traffic mortality or observed animal locations. Herein, the goal was to select locations for crossing structures that cover the maximum number of either mortality or location data points.

The MCLP can be formulated as a linear integer programming problem using the following notation from Daskin (1995):

INPUTS:
h_i = demand at location i
p = ff number of facilities to locate
a_{ij} = 1 if candidate facility j can cover demand at location i; 0 otherwise

MAXIMIZE:

$$\sum_i h_i Z_i \tag{1}$$

SUBJECT TO:

$$\sum_j a_{ij} X_j - Z_i \geq 0 \qquad \forall i \tag{2}$$

$$\sum_j X_j = p \tag{3}$$

$$X_j = 1 \text{ if facility } j \text{ is selected; 0 otherwise} \qquad \forall i \tag{4}$$

$$Z_i = 1 \text{ if demand at node } i \text{ is covered; 0 otherwise} \qquad \forall i \tag{5}$$

Here, the objective function (1) maximizes the amount of demand covered by selected facilities. Constraints (2) ensures that for every demand node *i*, the demand is only covered if a

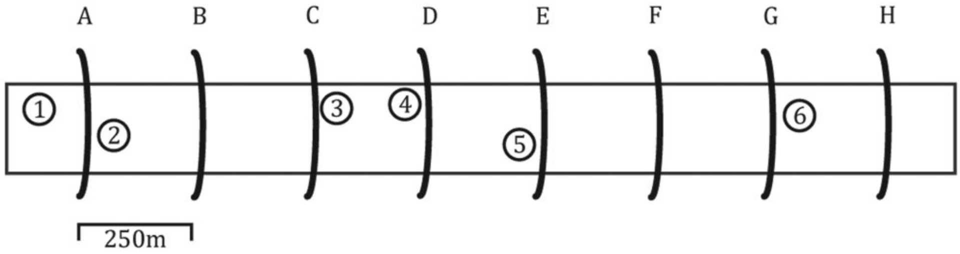

Figure 1 Sample roadway with wildlife traffic kills and potential crossing structure locations

facility capable of covering that demand is selected by the model. In other words, if all $a_{ij} = 0$ for node *i* are zero for the selected facilities, then the decision variable z_i is forced to also equal zero and not contribute to the objective function. In practice, values for a_{ij} are determined based on the proximity of the demand locations to the candidate facilities. Proximity can be measured in any number of ways, such as Euclidean or network distances. Constraint (3) specifies the p number of facilities the user wishes to locate. Finally, binary integer bounds (integrality conditions) are specified for decision variables X_j (4) and Z_i (5).

Figure 1 illustrates the first approach for siting wildlife crossing structures using a simple example with six collision sites along a road network. Here, each collision location is considered a demand point. For all points, the demand is equal to 1, since each represents mortality for a single animal. Then, potential crossing structure locations are identified along the roadway. In this case, candidate sites are arbitrarily defined every 250 m along the road and labeled A through H. If each crossing structure can cover a 250 m distance of roadway in either direction, then the MCLP for $p = 1$ can be written as shown in Table 1. This table displays the list of equations as coded in standard linear programming (lp) format, including the objective function (MAXIMIZE), constraints (SUBJECT TO), and bounds (BINARIES). Once the equations are written in that manner, the problem can be solved using optimization software. These ‘solvers’ use various search algorithms to find the optimal solutions. The sample problem from Figure 1 was solved using the commercial optimization package ILOG C-PLEX (IBM Corp). The output yields the values for the objective function and the decision variables, X_j and Z_i. In this scenario, the problem yields an objective value of 3, where $X_D = 1$, $Z_3 = 1$, $Z_4 = 1$, and $Z_5 = 1$, with all other decision variables equal to zero. In other words, candidate location D is selected as the single crossing structure, and it covers three collision sites – numbers 3, 4, and 5. This solution is intuitive, since location D is the only candidate site capable of covering three collisions and therefore provides the maximal amount of coverage. In the scenario of locating two crossing structures, then, candidate locations D and A are selected. They cover five collision sites in total, numbers 1 through 5. Finally, if a third crossing structure is added – either G or H – then all crossing sites are covered for an objective value of 6. Adding additional crossing structures would not increase the value of the objective, since all six collision sites are already covered.

Similarly, Figure 2 illustrates the second scenario where the goal is to site crossing structures such that they cover as many animal tracking data points as possible. This example uses the same road network and potential crossing structure locations as Figure 1, although here 35 tracking data points represent possible demand locations. If we assume a 1,000 m coverage distance (represented as dotted circles), then 22 of the 35 points are in need of coverage. Note that coverage distances are expressed using Euclidean, or straight-line, distances in this scenario. While in the first example distances between potential structures and collisions were measured according to lengths along the roadway (i.e. network distances), Euclidean distances

Table 1 Formulation of the MCLP for the scenario depicted in Figure 1

```
MAXIMIZE
lz_l + lz_2 + lz_3 + lZ_4 + lz_5 + lz_6

SUBJECT TO
lX_A + OX_B + OX_C + Ox_D + OX_E + OX_F + OX_G + OX_H - z_l >= 0
lX_A + lX_B + OX_C + Ox_D + OX_E + OX_F + OX_G + OX_H - z_2 >= 0
OX_A + OX_B + lx_C + lX_D + OX_E + OX_F + OX_G + OX_H - z_3 >= 0
OX_A + OX_B + lx_C + lX_D + OX_E + OX_F + OX_G + OX_H - z_4 >= 0
OX_A + OX_B + OX_C + lX_D +lX_E + OX_F + OX_G + OX_H - z_5 >= 0
OX_A + OX_B + OX_C + OX_D + OX_E + OX_F + lX_G + lX_H - z_6 >= 0

X_A + X_B + X_C + X_O + X_E + X_F + X_G + X_H =1

BINARIES
z_l
z_2
z_3
z_4
z_5
z_6

X_A
X_B
X_C
X_D
X_E
X_F
X_G
X_H

END
```

are used in this case, since tracking data points occur both on and off roads. In this case, coverage is specified according to the maximum distance that each crossing structure is expected to attract usage by wildlife. For example, solving the MCLP for $p = 1$ crossing structure yields an objective value of 12 where structure D is selected for construction; twelve tracking points occur within a 1,000 m radius of D, more than for any other candidate structure. If two structures are sited, then locations D and G are selected and cover a combined 18 tracking points. Three sites (D, G, and B) can cover 21 tracking points, while four (D, G, B, and F) can cover all 22. Similar to the first scenario, adding additional crossing structures would not increase the value of the objective, since all coverable tracking points are already served by four structures. The next section explores both of these approaches in the context of siting crossing structures for Florida panthers.

3 Locating Crossing Structures for Florida Panthers

The Florida panther (*Puma concolor coryi*) inhabits forest, wetland, and grassland habitats in southwestern Florida (Benson et al. 2008, Comiskey et al. 2002, Cox et al. 2006, Onorato

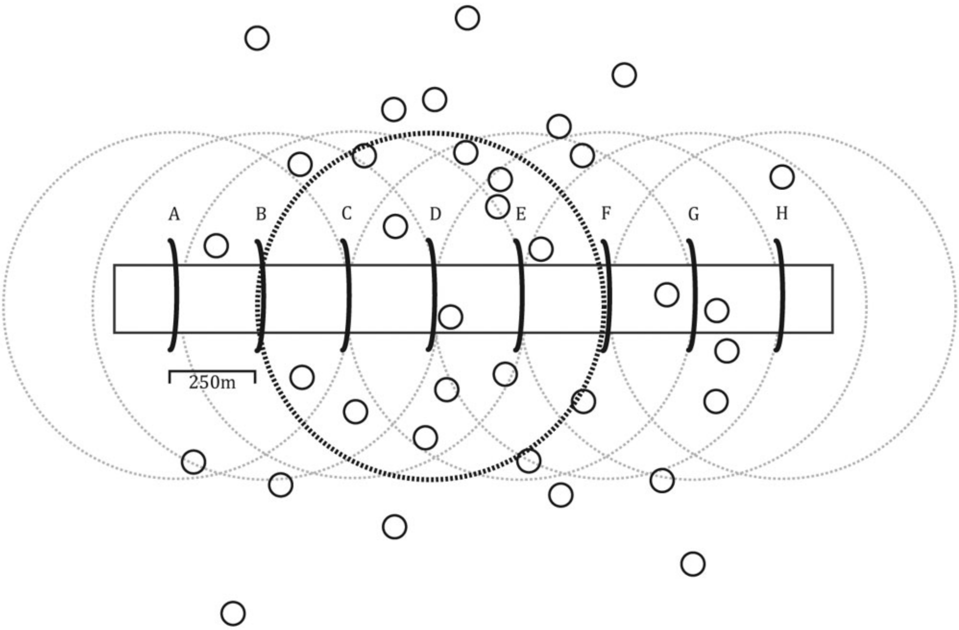

Figure 2 Sample roadway with wildlife tracking data and potential crossing structure locations

et al. 2011). This federally endangered large carnivore (Federal Register 1967) persists in a single, isolated population of 100–160 individuals (FWC 2010). Florida panthers occupy large home ranges, often hundreds of square kilometers in size (Belden et al. 1988, Kautz et al. 2006, Land et al. 2008), and habitat fragmentation is a major conservation concern (Meegan and Maehr 2002, Onorato et al. 2010). Since individuals can travel large distances in a diel period, roads pose a major threat to the population (Janis and Clark 2002, Schwab and Zandbergen 2011), and vehicle collisions have been documented as a significant source of panther mortality (Buergelt et al. 2002, Onorato et al. 2010, Taylor et al. 2002). Wildlife crossing structures have been implemented on some major roadways in an attempt to reduce traffic mortality and improve habitat connectivity within the panther's breeding range. Use of these structures by Florida panthers is well documented and studies have demonstrated reductions in traffic mortality rates after installation (Foster and Humphrey 1995, Jansen et al. 2010, Lotz et al. 1997). Although crossing structures have proven beneficial to the Florida panther, they are expensive to implement – on average $4 million plus $85/m of fencing according to 2008 pricing (Onorato et al. 2010) – and construction has been limited to a narrow region of southwestern Florida. Therefore, if only a limited number of crossing structures can be built in the future, it will be important to delineate candidate locations that can provide the greatest conservation benefit.

3.1 Study Area and Data

Three counties in southwestern Florida that comprise the largest portion of the Florida panther's current breeding range were included in the study: Lee, Hendry, and Collier (Figure 3). This area includes a large proportion of protected land, including the 107 km^2

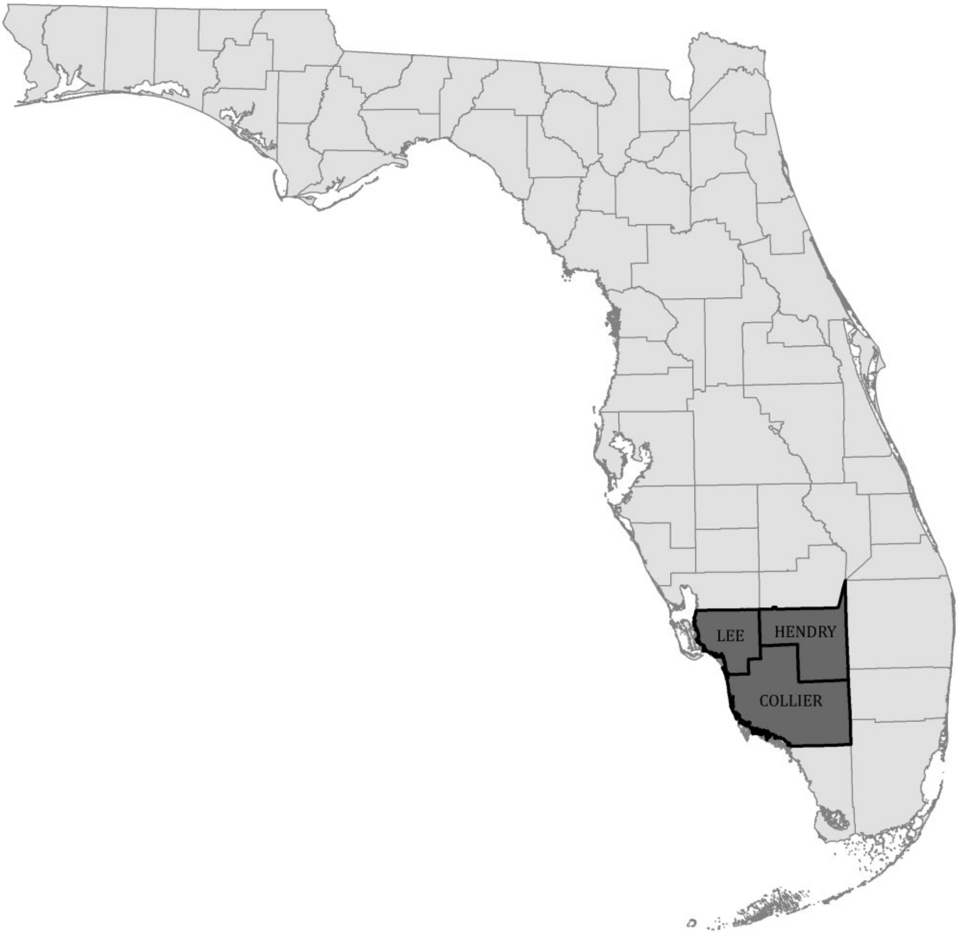

Figure 3 Location of Lee, Collier, and Hendry Counties in Florida

Florida Panther National Wildlife Refuge, 2,950 km^2 Big Cypress National Preserve, and portions of Everglades National Park. Spatial data layers documenting the locations of county boundaries, major roads, and existing wildlife crossing structures and associated lengths of fencing (updated as of 2010) were obtained from the Florida Geographic Data Library (FGDL) (http://www.fgdl.org). Panther-vehicle collision data from 1979–2010 were obtained from a detailed database of panther mortality maintained by the Florida Fish and Wildlife Conservation Commission (FWC). This updated dataset was previously analyzed by Buergelt et al. (2002) and Taylor et al. (2002) and is also archived by FGDL. Figure 4 illustrates the locations of the collisions with respect to major roads and the existing wildlife crossing structures in the three-county area. Approximately 86% (132 of 153) of the state-wide collisions occurred within the study area. Forty-six crossings have been built in this area to reduce panther mortality. They are primarily found along Interstate Highway 75 and State Road 29 in Collier County. Only five collisions are mapped within 250 m of a crossing structure, and all of these occurred during the 1980s on Interstate 75 before crossing structures were built.

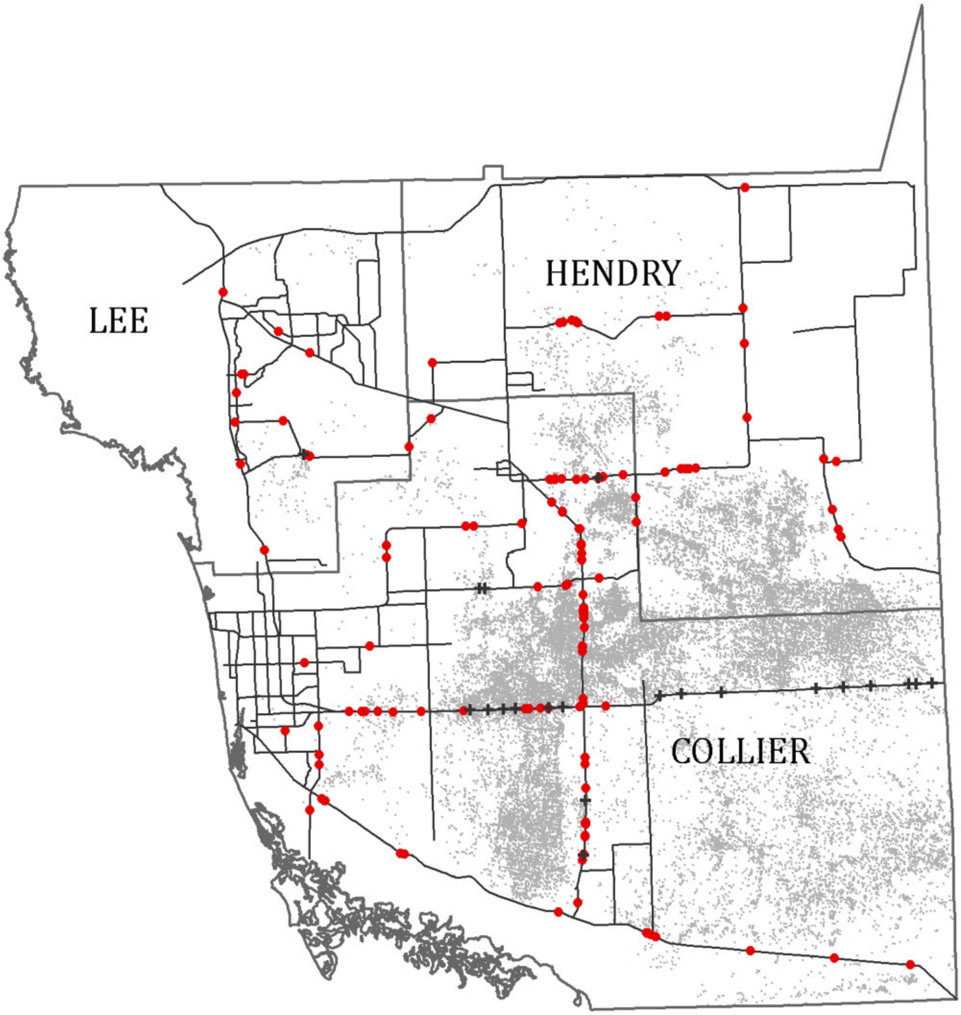

Figure 4 Locations of major roads, existing crossing structures (crosses), panther traffic kills (black circles), and radio-telemetry locations (grey dots) in the study area

While some crossings were placed near known panther traffic kills, most were placed at strategic points in the landscape (old logging trams, uplands, etc.) where panther movements between high quality habitats were previously documented or expected. A detailed description of the structures and their usage by panthers is provided by Foster and Humphrey (1995) and Jansen et al. (2010). A panther utilizing one of these structures is illustrated in Figure 5. Additionally, an extensive aerial VHF radio-tracking dataset was obtained from FWC, also illustrated in Figure 4. For the three study area counties, there are 41,644 locations for 94 unique panthers. Methods used to collect the data for each individual three times per week are detailed in Land et al. (2008), FWC (2010), and NPS (2009). We used the entire time spans of collision and tracking data in order to include areas that are both currently and historically important to the species.

Figure 5 A Florida panther utilizing a crossing structure

3.2 MCLP Applications

3.2.1 Collision-based approach

Since the majority of panther-vehicle collisions occurred in locations without crossing structures, future collisions might be prevented by constructing additional ones in problematic areas. The MCLP was used to find strategic locations for any new structures to be built within the three-county region. The MCLP for the collision-based approach was solved using seven different coverage distances: 500, 750, 1,000, 1,250, 1,500, 1,750, and 2,000 m. These distances can be assumed to represent the length of fencing – which prevents panthers from crossing – installed along the roadway on each side of the structure. For each coverage distance scenario, the model was solved for all values of p until all collisions were covered. First, candidate sites were identified along the major roads in the counties. This was accomplished by dividing the road network into segments approximately 0.15 km in length. The nodes, or endpoints, of these segments served as candidate locations. Then, locations of existing crossing structures were joined to the network layer so the coverage they provide (as determined from fencing lengths) could be included in the model. Next, network distances between each candidate or existing crossing structure (j) and each collision (i) were computed using a commercial GIS package, TransCAD v. 5.0 (Caliper Corp.). These measurements were used to determine the collisions each facility could cover based on the specified coverage distances (i.e. a_{ij} in Equation 2). These distance values were exported from the GIS as a text file. Then, a custom C++ script was written to read in the text file and output a new file with the MCLP for the scenario in lp format. The lp file contained the equations described in Section 2, along with an additional set of constraints that required existing crossing structures to be included in the model result. These constraints were written by setting $X_j = 1$ for all j representing existing structures. Finally, the lp files were solved using ILOG C-PLEX, with the results imported back into GIS for visualization.

3.2.2 Tracking-based approach

Since a large proportion of the Florida panther population has been consistently tracked over the years, these data provide an opportunity to site crossing structures in areas known to be frequented by the panthers. Here, the MCLP was applied using the radio-tracking dataset previously described with the same road network and candidate locations as for the first scenario. The MCLP was solved using one coverage distance of 1,000 m for $p = 1$ to $p = 8$ facilities; these distances and numbers of facilities were selected for brevity and to make the results most comparable to the emphasized output from the first scenario. First, GIS was used to reduce the tracking dataset to include only locations within 1,000 m of a major road; this yielded 4,032 coverable demand points. Next, Euclidean distances between each candidate or existing crossing structure (j) and each tracking point (i) were computed using TransCAD GIS. Finally, the same processing, scripting, and solving procedures as for scenario one were used to obtain and map the results.

3.3 Results

3.3.1 Collision-based approach

The resulting objective values for the MCLP applications for siting Florida panther crossing structures are summarized in the trade-off curves in Figure 6 and recorded in Table 2. The value for $p = 0$, or no new structures, indicates the number of collisions covered by existing facilities. For example, if an effective coverage distance of 1,000 m is assumed, then existing structures only cover 15 collisions. The trade-off curves illustrate the total number of collisions that are covered with the construction of each additional structure. For instance, if the 1,000 m coverage distance scenario is explored, constructing one new facility can cover eight more collisions for a total of 23, while a second can cover an additional seven for a total of 30. By examining the curves, it is evident that the number of collisions covered by each added crossing structure diminishes as the collision sites become more spatially dispersed from one another. For example, in the same coverage scenario, the third and forth structures cover four collisions each. Once eight structures are built, only three collisions are covered by each new structure. By the time 11 and 24 structures are sited each serves only two or one, respectively. Similar trends are observed for the remaining coverage distances.

In addition to the number of collisions covered, the MCLP output includes the specific structures selected by the model. For example, Figure 7 maps the top eight crossing structure locations for the 1,000 m coverage distance scenario. The first structure (i.e. solution for $p = 1$) is located on State Route 29 (SR-29). It is located north of four existing crossing structures built on the same road segment in Collier County. The second is also located in Collier County but on US-41, a highway without any existing crossing structures. The third is located on County Road (CR)-846 in Hendry County. The fourth is sited on SR-29, between CR-846 and CR-858, a road segment which has no existing crossing structures. The fifth is also located on

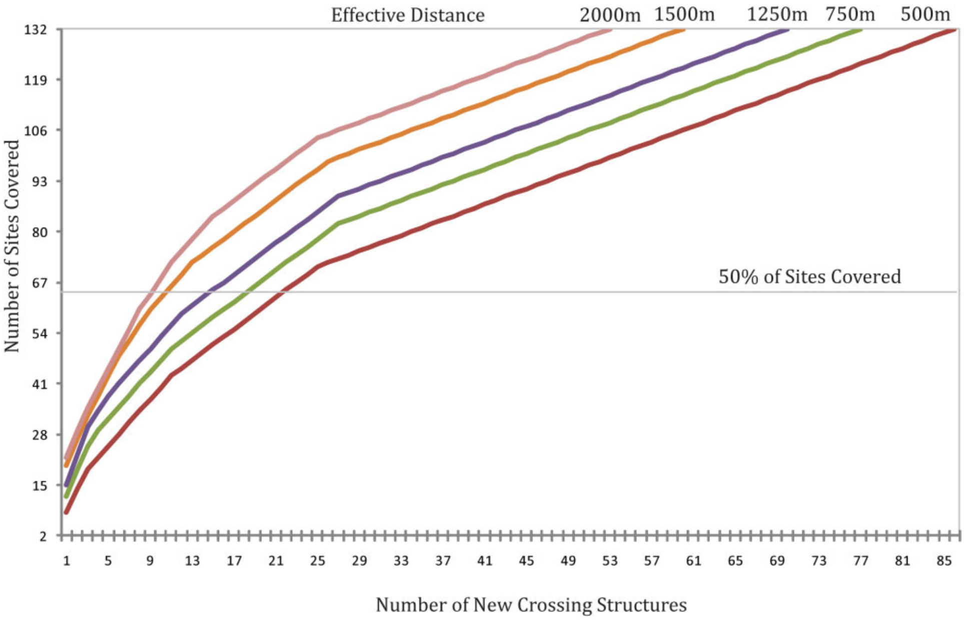

Figure 6 Trade-off curves for solutions of the MCLP for the collision-based approach

SR-29, along an unfenced portion of roadway between two existing structures. Remaining sites include Interstate 75 (I-75) and CR-846 in Collier County as well as CR-832 in Hendry County.

The curves can also serve as a reference guide in terms of the number of structures required to meet specific conservation goals for each coverage distance. For example, 69 structures are required to cover all collisions at the 1,000 m threshold. If coverage of 50% of the collisions is desired, then the appropriate number of covered collisions – 66 in this case – can be determined for each scenario; 22 additional crossings would be needed assuming a 500 m threshold, 15 for 1,000 m, 10 for 1,500 m, and nine for 2,000 m. Likewise, a threshold can be specified in terms of the minimum number of collisions a new structure must protect in order to be built. For example, if each crossing structure must cover at least four collisions to be considered worthwhile, then the number of crossing structures to implement in a study area can be determined. In this case, the ideal number of crossing structures selected for installation would be between two and nine, depending on the specified coverage distance. This type of strategy would be useful in situations where planners decide it is economically infeasible to build structures that do not provide a large enough conservation benefit.

3.3.2 Tracking-based approach

Solving the MCLP with the radio-tracking data as demand points identifies different locations for crossing structures than the collision-based approach when using a similar distance of 1,000 m for up to eight new facilities (Figure 8). Existing crossing structures protect nearly half of the telemetry data near roadways (2,008 of 4,032 points), indicating they are well-placed with respect to known panther movements. The addition of one new structure – located in an unfenced area between two structures on SR-29 – can cover 131 points (from 19 unique

Table 2 Number of panther mortality sites covered by p number of crossing structures using coverage distances of 500 to 2,000 m

p	500 m	750 m	1000 m	1250 m	1500 m	1750 m	2000 m	*p*	500 m	750 m	1000 m	1250 m	1500 m	1750 m	2000 m
0	8	12	15	17	20	20	22	43	90	99	106	114	116	119	123
1	14	19	23	25	27	27	29	44	91	100	107	115	117	120	124
2	19	25	30	32	33	34	35	45	92	101	108	116	118	121	125
3	22	29	34	37	38	39	40	46	93	102	109	117	119	122	126
4	25	32	38	42	43	44	45	47	94	103	110	118	120	123	127
5	28	35	41	47	48	49	50	48	95	104	111	119	121	124	128
6	31	38	44	51	52	54	55	49	96	105	112	120	122	125	129
7	34	41	47	55	56	58	60	50	97	106	113	121	123	126	130
8	37	44	50	59	60	62	64	51	98	107	114	122	124	127	131
9	40	47	53	62	63	66	68	52	99	108	115	123	125	128	132
10	13	50	56	65	66	69	72	53	100	109	116	124	126	129	
11	45	52	59	68	69	72	75	54	101	110	117	125	127	130	
12	47	54	61	71	72	75	78	55	102	111	118	126	128	131	
13	49	56	63	73	74	77	81	56	103	112	119	127	129	132	
14	51	58	65	75	76	79	84	57	104	113	120	128	130		
15	53	60	67	77	78	81	86	58	105	114	121	129	131		
16	55	62	69	79	80	83	88	59	106	115	122	130	132		
17	57	64	71	81	82	85	90	60	107	116	123	131			
18	59	66	73	83	84	87	92	61	108	117	124	132			
19	61	68	75	85	86	89	94	62	109	118	125				
20	63	70	77	87	88	91	96	63	110	119	126				
21	65	72	79	89	90	93	98	64	111	120	127				
22	67	74	81	91	92	95	100	65	112	121	128				
23	69	76	83	93	94	97	102	66	113	122	129				
24	71	78	85	95	96	99	104	67	114	123	130				
25	72	80	87	96	98	101	105	68	115	124	131				
26	73	82	89	97	99	102	106	69	116	125	132				
27	74	83	90	98	100	103	107	70	117	126					
28	75	84	91	99	101	104	108	71	118	127					
29	76	85	92	100	102	105	109	72	119	128					
30	77	86	93	101	103	106	110	73	120	129					
31	78	87	94	102	104	107	111	74	121	130					
32	79	88	95	103	105	108	112	75	122	131					
33	80	89	96	104	106	109	113	76	123	132					
34	81	90	97	105	107	110	114	77	124						
35	82	91	98	106	108	111	115	78	125						
36	83	92	99	107	109	112	116	79	126						
37	84	93	100	108	110	113	117	80	127						
38	85	94	101	109	111	114	118	81	128						
39	86	95	102	110	112	115	119	82	129						
40	87	96	103	111	113	116	120	83	130						
41	88	97	104	112	114	117	121	84	131						
42	89	98	105	113	115	118	122	85	132						

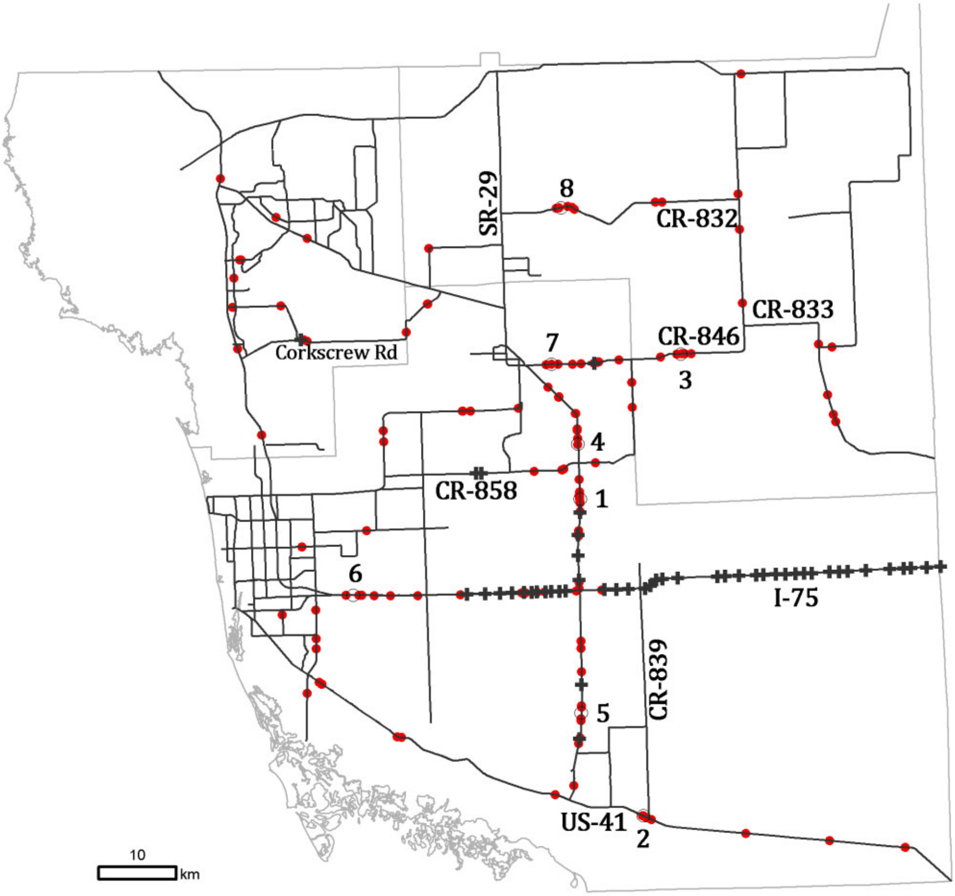

Figure 7 Top eight (numbered) selected crossing structure sites for the collision-based approach

panthers). The second structure, located on a segment of CR-858 that lacks crossing structures, can cover 127 (13). The third and fourth structures, covering 96 (19) and 78 (10) points, are also located in the unfenced area among existing structures on SR-29. The fourth, which was ranked first using the collision-based approach, is the only location selected by both models. The fifth and sixth protect 77 points each (10, 14) and are both located on CR-839. The seventh is located on I-75, just west of an existing crossing structure, and covers 51 (9) points. Finally, the eighth structure is sited on CR-858, 2 km west of the second selected site, and covers an additional 40 (8) points for a total of 2,762, or 69% of the coverable telemetry points.

4 Discussion and Conclusions

The results of this research illustrate how maximal covering approaches can be used to strategically site wildlife crossing structures based on spatial patterns of animal-vehicle collisions or

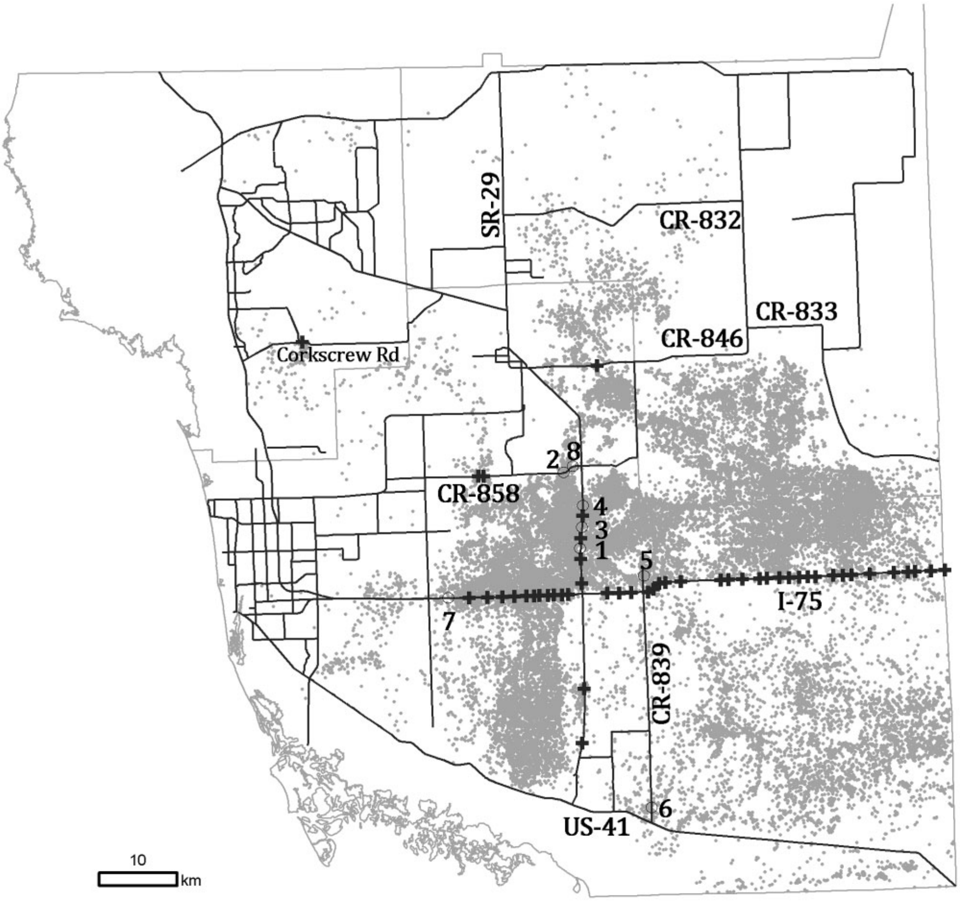

Figure 8 Top eight (numbered) selected crossing structure sites for the tracking-based approach

radio-tracking data. While other authors (e.g. Clevenger 2005, Krisp and Duret 2007) have proposed similar strategies based on mapping hotspots of traffic mortality (see Ramp et al. 2005, 2006), the main advantage of applying the MCLP is that the results explicitly identify the best locations for crossing structures – in rank order – as well as directly quantify the number of demand sites that can be protected by each additional structure under different coverage scenarios. Since funding to build new crossing structures is often difficult to encumber, the associated costs are most effectively incorporated into road building or widening projects during their initial planning stages as opposed to retrofitting crossings into existing roads (Onorato et al. 2010). Knowing the locations of priority crossing sites in advance of road construction projects invariably improves the likelihood that wildlife and funding issues will be assessed, and the maximal covering approaches described in this article can be used to identify location in early planning stages.

In the context of endangered Florida panthers, these maximal covering approaches identified a number of sites for placing new crossing structures given the locations of ones already installed within the study area. While these results can be used to develop a strategy for siting future crossing structures in Florida, there are a number of important issues – from both GIS and ecological perspectives – that need to be considered before any site selections are finalized. First, and perhaps most importantly, the output is directly dependent on the quantity and quality of information used in the analysis, and the results must be evaluated or ground-truthed by experts familiar with the sites before any construction is recommended. In this case study, the inputs included publicly available GIS layers representing major roads, existing crossing structures with associated fencing, traffic mortality locations, and panther tracking data. While this information was sufficient to apply the MCLP to generate two ranked lists of priority crossing structure locations, there are other factors that might assist with planning decisions. Examples might include the monetary or environmental costs influenced by topography, road properties, habitat or soil conditions. For example, constructing a structure on a major interstate – like I-75 – would entail larger costs and more logistical issues than one constructed on a county road. Although the coverage models could be weighted according to these or other factors (see Amaldi et al. 2008, Farhan and Murray 2006, Oxendine et al. 2012), other site-specific factors are also relevant and can ultimately determine the success of a wildlife crossing project. As such, the following paragraph provides an on-the-ground assessment of the sites selected to identify any practical considerations before any model results are used to make planning recommendations for Florida panther conservation.

The proposed structure on SR-29 ranked first based on collisions and fourth based on tracking data, suggesting it as the highest priority site overall. An assessment of on-the-ground conditions finds that fencing stops almost abruptly at the existing crossing structure approximately 2 km to the south. Since this northern stretch of roadway is currently unprotected, it is an ideal place for an additional crossing structure, as it is located in prime panther habitat and has been a site of repeated collisions. However, the first and third priority sites according to the tracking model – located between existing structures immediately south of the area just discussed – are less of a priority than their ranks suggest. In particular, there is a canal on one side of the road and intermittent fencing recently installed on the other side, and these in combination provide a current barrier to panther movements. Much of this fencing was not included in the GIS database, as it is not directly connected to the existing crossing structures. Another issue presented by the two sites on CR-839, ranked fifth and sixth by the tracking-based approach, is that while this road is included in the data layer for major roads, in reality it is a dirt road that receives very little traffic; as such, it is not in need of urgent protection. However, of note is that the latter of these sites is in very close proximity to the site on US-41 that the collision-based model identified as rank two. This adds further support to the US-41 location, which already has been discussed as a candidate site by conservationists in Florida. Our on-the-ground assessment of this and the remaining sites selected by the models suggests they are viable candidates for future crossing installations. In particular, the tracking-based model suggests a problematic area on CR-858, where it selected the second and eighth ranked sites. In practice, one crossing structure with extended fencing might be adequate to protect this segment of road, which also experienced two collisions, and our results suggest it is a high priority location. Other important sites include two on CR-846, two on SR-29, two on I-75, and one on CR-832. Interestingly, a least cost pathway analysis (Lundqvist 2007) based on habitat configurations predicted that movements of Florida panthers are likely to intersect SR-29, CR-846, I-75, CR-832, and US-41 (Swanson et al. 2008), further supporting the recommendation for crossing structure installation at these locations.

Beyond the site-specific issues, there are a number of other issues worthy of discussion. First, in the application for Florida panthers, the MCLP was solved using a range of plausible coverage distances, ranging from 500 m to 2 km representing fence lengths, without concluding which value was most appropriate. Wildlife usage of structures increases when fences are incorporated into projects, as they can prevent wildlife from traversing the roads on either side (Mata et al. 2005) of the wildlife crossing. Knowing the length of fencing necessary to maximize the benefits of a wildlife crossing can improve planning strategies. Spacing of neighbouring panther crossings within the study area is somewhat variable, ranging from approximately 750 m to 8 km. The lengths of fencing associated with these structures are also variable and include a 64 km section of I-75 with continuous fencing at one extreme. In our case study, we focused our discussion for the 1,000 m fencing scenario, since it represents about the average fence length for existing structures. Determination of fencing lengths is critical to the success of a crossing structure project, as there are both economic and ecologic trade-offs associated with the decision. From a purely economic perspective, constructing fewer crossing structures with longer lengths of fencing would be advantageous to constructing a greater number of structures with shorter fences, as the structures are more costly to implement. However, from an ecological perspective, fencing can be both beneficial to wildlife – by funneling their movements towards safe passage across roads – and detrimental to their movements by acting as a physical barrier if the lengths are too long. Ideally, crossing structures should have associated fencing that facilitates movements of target and non-target species through the crossing structure but without over-restricting their movements.

In terms of spatial analysis, there are concerns related to the measurement of distances between the demand points and the candidate crossing structures. The collision-based application utilized network distances computed using actual lengths of the road segments instead of straight-line distances, since the demand points are always located on-network, while the telemetry-based approach utilizes Euclidean distances, as the points mostly occur off-network. However, in both cases the MCLP can possibly produce misleading results if the distance measurements are not used carefully. If the coverage distance specified is relatively too large for a given road network structure, then it is possible that collisions on different roads (or telemetry locations separated by multiple roads) can be considered covered by a single structure. This can create a situation where an animal at one location must actually cross a road to utilize a crossing structure located on an adjacent road, although the model output considers it covered since it is within the specified coverage distance (Figure 9). This can be problematic if the construction of the crossing structure increases movements on an unprotected road segment. However, this was not a concern in this research as collisions and telemetry points tended not to be clustered around major intersections and appropriate coverage distances were specified. In situations where this artifact is problematic, a simple solution is to correct constraints in the model to ensure coverage is accurately represented. In this way, crossing structures can be modeled to cover only demand points on the same segment of road.

A third consideration is that some problem instances have multiple optimal solutions, especially in the case of the collision-based approach. In other words, for a given scenario, multiple crossing structures could be selected to achieve the same maximum objective, and the solver will output one randomly. For example, for the 1,000 m coverage distance, constructing a third, fourth, and fifth crossing structure each results in the protection of five additional collision sites. So, in terms of selecting the best site for the third structure, there are three possible locations – all of which contribute the same amount to the objective function. Therefore, if only a third structure is built, planners might want to further examine the three similar locations rather than choosing one randomly. For instance, the candidate location that is on average closest to the collisions, nearest telemetry data points, or nearest to the most recent collision might be prioritized.

In conclusion, the MCLP described in this article provides a useful planning tool for strategically locating wildlife crossing structures in road networks. Crossing structures reduce the

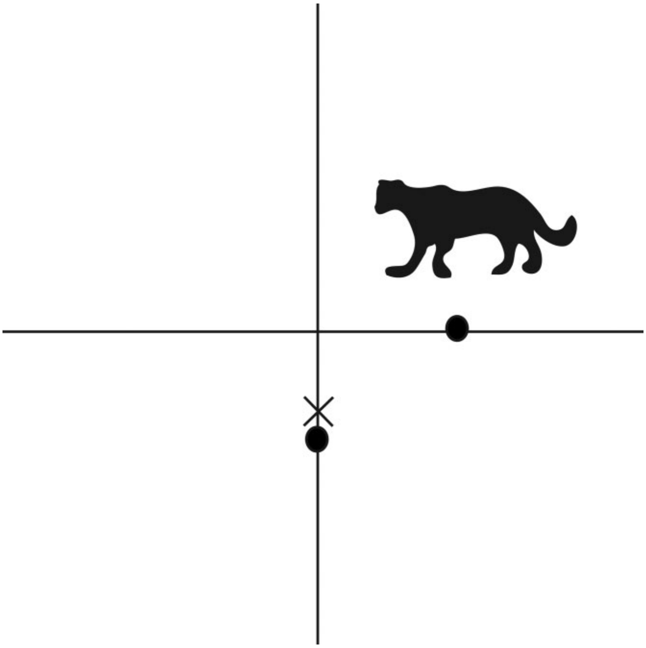

Figure 9 Coverage scenarios for traffic mortality sites located on adjoining roads

harmful, fragmenting effects of roads by enhancing habitat connectivity, which facilitates animal movements and reduces traffic mortality. The advantage of using the MCLP is that its output allows planners to objectively choose the best locations for new crossing structures as well as to quantify the benefits of building each successive facility. This strategy can be used to help prioritize funds such that the greatest conservation gains can be made with limited resources.

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