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Biological Conservation 118 (2004) 619–631
BIOLOGICAL CONSERVATION
www.elsevier.com/locate/biocon

Effectiveness of a barrier wall and culverts in reducing wildlife mortality on a heavily traveled highway in Florida

C. Kenneth Dodd Jr. [a,*], William J. Barichivich [a], Lora L. Smith [a,1]

[a] *Florida Integrated Science Centers, US Geological Survey 7920 NW 71st Street, Gainesville, FL 32653, USA*

Received 25 March 2003; received in revised form 5 October 2003; accepted 12 October 2003

Abstract

Because of high numbers of animals killed on Paynes Prairie State Preserve, Alachua County, Florida, the Florida Department of Transportation constructed a barrier wall-culvert system to reduce wildlife mortality yet allow for passage of some animals across the highway. During a one year study following construction, we counted only 158 animals, excluding hylid treefrogs, killed in the same area where 2411 road kills were recorded in the 12 months prior to the construction of the barrier wall-culvert system. Within the survey area lying directly in Paynes Prairie basin, mortality was reduced 65% if hylid treefrogs are included, and 93.5% with hylid treefrogs excluded. Sixty-four percent of the wildlife kills observed along the barrier wall-culvert system occurred at a maintenance road access point and along 300 m of type-A fence bordering private property. The 24 h kill rate during the post-construction survey was 4.9 compared with 13.5 during the pre-construction survey. We counted 1891 dead vertebrates within the entire area surveyed, including the ecotone between the surrounding uplands and prairie basin which did not include the barrier wall and culverts. Approximately 73% of the nonhylid road kills occurred in the 400 m section of road beyond the extent of the barrier wall-culvert system. We detected 51 vertebrate species, including 9 fish, using the 8 culverts after the construction of the barrier wall-culvert system, compared with 28 vertebrate species in the 4 existing culverts prior to construction. Capture success in culverts increased 10-fold from the pre-construction survey to the post-construction survey. Barrier wall trespass was facilitated by overhanging vegetation, maintenance road access, and by the use of the type-A fence. Additional problems resulted from siltation, water holes, and human access. These problems could be corrected using design modifications and by routine, periodic maintenance.
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Keywords: Barrier wall; Wildlife mortality; Roads; Highway mitigation; Culverts; Amphibians; Reptiles; Mammals

1. Introduction

Roads are an important feature in an animal's landscape, especially with regard to movement. Roads serve both as facilitators and barriers to dispersal, fragment habitats, and result in significant mortality (Case, 1978; Heine, 1987; Andrews, 1990; Fahrig et al., 1995; Ashley and Robinson, 1996; Forman and Alexander, 1998; Trombulak and Frissell, 2000; Gibbs and Shriver, 2002; Forman et al., 2003; Smith and Dodd, 2003). Numerous factors influence the number and species killed on a highway, including vehicle speed, volume, and traffic pulses, local topography, accessibility of cover, and structural features of a road, such as whether the roadbed is raised or level with the surrounding environment (Clevenger et al., 2003). Certain behavioral traits also may affect the probability of mortality on roads, such as active foraging (Bonnet et al., 1999), vagility (Carr and Fahrig, 2001) and inclination to cross open habitats (Gibbs, 1998; de Maynadier and Hunter, 2000). Most studies of the effects of roads on wildlife have focused on largely terrestrial or avian species, or semi-aquatic species moving between a breeding pond and terrestrial habitats (reviewed by Forman et al., 2003). Few studies, however, have examined highway effects on animal communities or potential mitigation

* Corresponding author. Tel.: 1-352-378-8181; fax: 1-352-378-4956.
E-mail address: ken_dodd@usgs.gov (C. Kenneth Dodd Jr.).
[1] Present address: Joseph W. Jones Ecological Research Center Route 2, Box 2324, Newton, GA 31770, USA.

0006-3207/$ - see front matter. Published by Elsevier Ltd.
doi:10.1016/j.biocon.2003.10.011

options when highway corridors cross large wetlands (Forman et al., 2003).

For the last few decades, biologists and engineers have grappled with ways to facilitate animal movement across transportation corridors, and developed a number of potential solutions (Langton, 1989; ALASV, 1994; Percsy, 1995; Duguet and Melki, 2003; Forman et al., 2003). A common mitigation measure provides for passage over or under a road or highway, usually with a type of fence channeling movement towards a tunnel or culvert. While culverts may be important in facilitating cross-road movements (Yanes et al., 1995; Clevenger and Waltho, 1999; Clevenger et al., 2001), follow-up studies have not systematically determined the effects of such mitigation efforts on the mortality of small vertebrates, particularly amphibians and reptiles.

Large numbers of animals have been killed on the section of US Highway 441 where it crosses Paynes Prairie State Preserve, Alachua County, Florida, since the highway was constructed in the early 1920s (Beck, 1938; Carr, 1940, 1974; Hellman and Telford, 1956; Kauffeld, 1957; Franz and Scudder, 1977; Smith, 1996; Smith and Dodd, 2003). High levels of wildlife mortality along the highway corridor bisecting this large, ecologically diverse wetland for nearly eight decades may have adversely impacted animal populations adjacent to the roadway by serving as a continuous drain on numbers. Collateral impacts also may extend far beyond the immediate vicinity of the actual roadway (Andrews, 1990; Fahrig et al., 1995; Findlay and Houlahan, 1997; Forman and Deblinger, 2000; Hels and Buchwald, 2001).

In addition, the many animals attempting to cross the highway (particularly alligators, large turtles, and medium-sized mammals such as Raccoons and Opossums) created human safety concerns as motorists collided with crossing animals or attempted to avoid them. Animal carcasses detracted from the beauty of the prairie and, because they were so numerous, sometimes caused the road surface to become slippery, creating an additional motorist safety hazard.

In 1996, the Florida Department of Transportation (FDOT) proposed constructing a wildlife barrier wall-culvert system (which FDOT terms an ecopassage) across Paynes Prairie to ameliorate the effects of the highway on wildlife populations. The barrier wall-culvert system consists of a concrete wall located on both sides of the highway parallel to, and 9–11 m from, the roadway. The wall is 1.1 m high with a 15.2 cm overhanging lip (Fig. 1(a)), and interconnects with eight prefabricated concrete culverts (two $2.4 \times 2.4 \times 44$ m partially submerged box culverts; two $1.8 \times 1.8 \times 44$ m usually dry box culverts; four cylindrical culverts 0.9 m in diameter $\times$ 44 m) which allow passage of water and wildlife underneath US Highway 441. The wall extends across the entire 2.8 km prairie wetland basin on the east side of the highway, but only for 2.5 km on the west side of the highway. In the

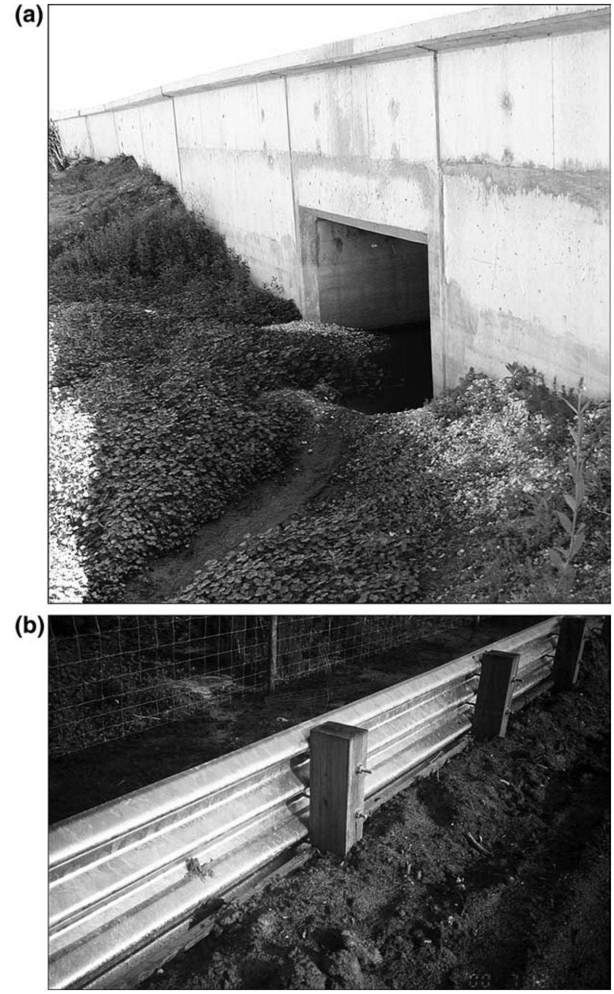


Fig. 1. (a). The barrier wall-culvert system on the northwest side of Paynes Prairie at culvert No. 2. The prefabricated concrete box culvert is 2.7×2.7 m. (b). Type A fence bordering 300 m on the northwest side of US 441 across the prairie basin. This fence was not effective in eliminating trespass.

northwest portion of the study area (~300 m in length), a "Type-A" fence was constructed. The Type-A fence consists of two guard rails (one on top of the other) with a hardware cloth barrier sunk below ground (Fig. 1(b)). Construction of the concrete barrier wall was prohibited in this section because the roadway abutted private land and because of concerns by FDOT about drainage.

In mid-1998, we began a study to assess the effectiveness of the barrier wall-culvert system. The first phase of the project (18 August 1998 to 13 August 1999) determined the level of pre-construction wildlife mortality, and how many and what types of animals used the existing four box culverts (Smith and Dodd, 2003). The results confirmed significant mortality on the highway and adjacent right-of-way, although some animals used the existing culverts to successfully traverse the highway. Construction of the barrier wall-culvert system was completed in February 2001. The post-construction phase of the study began on 14 March 2001 and continued until 5 March 2002. Our study objectives were to assess the effectiveness of the barrier wall-culvert system by measuring post-construction levels of wildlife mortality and the extent of culvert use. Based on our findings, we provide suggestions concerning modifications in the construction design and the need for regular maintenance of the barrier wall-culvert system.

2. Methods

2.1. Study area

Paynes Prairie is a large, highland freshwater marsh (18.3 m above mean sea level) on the central Florida Ridge in Alachua County. The prairie basin encompasses an area nearly 5000 ha. It is bordered by uplands ca. 4.5–7.5 m higher in elevation than the basin proper, and extends 13 km east to west and from 1.5 to 7 km from north to south. Highland marshes are shallow wetlands characterized by unstable drainage patterns (Kushlan, 1980). Depending on rainfall and drainage, Paynes Prairie may be a dry prairie, marsh, or shallow lake. Water on the prairie flows east where it drains into Alachua Sink and enters the Floridan Aquifer. Water levels are normally highest during the summer, and lowest in April, September, October and November. Drought conditions prevailed from April 2001 throughout the remainder of the year. In June 2001, water-table levels were 0.58–1.2 m below ground level (Jacobs et al., 2002). More details on the prairie's vegetation and hydrology are provided by Jacobs et al. (2002).

Paynes Prairie was designated as a State preserve in 1970. The prairie basin is transected by two major highways, Interstate 75 (I-75) and US Highway 441 (US 441), both of which are 4-lane divided highways. US 441 was built in 1923 and was expanded from two to four lanes in 1957. Fill for the roadway was taken from the adjacent marsh, which created shallow canals that parallel the highway. Prior to construction of the barrier wall-culvert system, the road sat on a gently sloping raised bed ca. 1.75 m above the surrounding wetlands. The highway corridor is 44 m wide (including a grassy right-of-way, paved highway and narrow bicycle lanes, and grassy median), and it traverses 2.8 km of the prairie basin. The current speed limit on US 441 is 97 km/h. Daily traffic volumes exceed 11,000 vehicles per day.

2.2. Road kill survey

The highway survey methods were similar to those employed during the pre-construction phase of data collection (Smith and Dodd, 2003). The highway was divided into 32 100 m sections for a total oneway length of 3.2 km. Section 1 was located on the north rim of the Paynes Prairie basin at the first private driveway (29.5874 °N, 82.3382 °W), and Section 32 was located on the south rim at the first private drive (29.5579 °N, 82.3305 °W). There were no barriers to wildlife entry onto the highway right-of-way in Sections 1, 2, 31, and 32 on the prairie rim, which were outside the boundaries of the state preserve. These four sections are in an ecotone between the prairie basin and surrounding uplands. They were monitored in order to assess whether animals used these ecotones as movement corridors. In addition, an increase in post-construction mortality in these ecotonal areas might reflect an attempt by wildlife to cross the highway at the first available area not fronted by the barrier wall. The type-A fence bordered the highway adjacent to the southbound lanes of Sections 3–6.

Surveys consisted of from one to four observers walking the 3.2 km survey area one time in each direction on each sampling occasion, for a total of 6.4 km. One observer walked along the highway in the grassy median, whereas the others walked in the east or west right-of-way. If only one observer was present, separate passes were made along the median and the north and south bound lanes to ensure complete coverage. In this manner, both the north and southbound lanes of the entire paved highway surface, extending 3–4 m onto the grassy shoulders (the right-of-way), and the entire grassy median between the north and southbound lanes, were surveyed.

A sampling period consisted of 3 consecutive 24 h sampling units, with one sampling period scheduled each week. The actual start day was chosen randomly using Julian calendar days. On day 1 (first sampling unit), researchers marked all dead animals found throughout the study site. On days 2 and 3 (sampling units 2 and 3), all road kills that had accumulated during the previous 24 h were recorded.

Road kill surveys began at first light and all live and dead animals were recorded. Dead animals were marked with Day-Glo® orange spray paint so that they were not counted more than once. The paint was free of lead and toluene. Locations of all animals were recorded, that is, whether the animal was in the north or southbound lane, the right-of-way, or the grassy median, and in which 100 m section it was found. Freshly killed, undamaged specimens were collected and deposited in the Florida Museum of Natural History at the University of Florida.

Beginning 5 September 2001, our sampling protocol was adjusted so that treefrogs (Family Hylidae) were counted only in the southbound lanes of three randomly selected Sections (3, 14, and 23). We made this change because of the large volume of morning commuter traffic and associated safety concerns. The large volume of traffic quickly obliterated hylid carcasses, and we chose to rigorously sample three highway sections rather than to underestimate hylid mortality over the entire study length. In the results that follow, hylid totals are thus for the entire 3.2 km survey area from 14 March to 4 September 2001, but only for the 3 100 m sections from 5 September to the end of the survey.

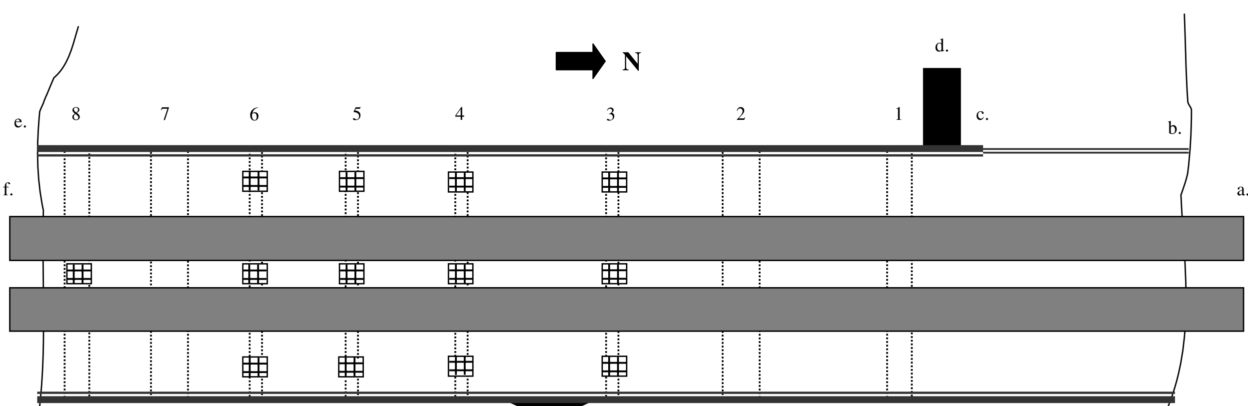
2.3. Culvert survey

The eight culverts that underlie US 441 also were monitored for wildlife use. Culverts were numbered one to eight from north to south (Fig. 2). Culverts 1 and 8 were usually dry with an earthen substrate, whereas culverts 2 and 7 were inundated throughout the study. Culverts 3–6 were installed as part of the new barrier wall-culvert system. Culvert 4 was usually wet, whereas the other culverts (3, 5, and 6) were dry or wet depending on prairie water levels. These culverts also had earthen substrates.

Wire screen-mesh funnel traps (see Fig. 15 in Karns, 1986) were installed in the four box culverts to sample amphibians, reptiles, and small mammals. In both 1.8 × 1.8 m box culverts (1 and 8), 10 square hardware-cloth funnel traps were placed flush with the sides of the culverts. We installed 10 floating screen funnel traps in the remaining two 2.4 × 2.4 m box culverts (2 and 7) in the center of the culvert under the roadway. The latter two culverts were monitored until they became unsuitable for sampling because of high water levels or the presence of alligators.

Each of the four recently-constructed 0.9 m diameter culverts (3, 4, 5, and 6) were sampled using two commercial crayfish traps (Lee Fisher, Inc., Tampa, FL; Darby et al., 2001) placed in each of two light boxes located in the right-of-way, for a total of four traps per culvert. The trapping schedule coincided with the road surveys, although it was adjusted to include two additional sampling units; thus, all culverts were sampled five nights per week.

A sand track station (1.8 m long by 1.0 m wide) occasionally was set up in the center of the northern, dry culvert (number 1). TrailMaster TM1500® Active Infrared monitors and cameras (Goodson and Associates,



Symbol		Distance from 0 (m)	Culvert size(m)
a.	Beginning of survey area	0	
b.	Start of type-A fence, start of west concrete barrier, North Rim	200	
c.	End of type-A fence, beginning of east concrete barrier	650	
d.	Cattle gate	675	
1	Culvert 1	700	1.8 x 1.8
2	Culvert 2	1200	2.7 x 2.7
3	Culvert 3	1600	0.9 dia
4	Culvert 4	2000	0.9 dia
5	Culvert 5	2300	0.9 dia
6	Culvert 6	2600	0.9 dia
7	Culvert 7	2800	2.7 x 2.7
8	Culvert 8	3000	1.8 x 1.8
e.	End of east west concrete barriers South Rim	3015	
f.	End of survey area	3200	

	Width (m)
West ROW	10
South travel lanes	9
Median	6
North travel lanes	9
East ROW	10
Total	44

Fig. 2. Schematic representation of US Highway 441 across Paynes Prairie State Preserve. The road is bordered by a prefabricated concrete barrier wall and underlain by 8 culverts. Light boxes (squares) occur across the road only in the new small culverts (g, h, i, j) to allow light; a small grate is in culvert l. An access road enters on the southbound lane near the northern prairie rim (d), and a visitor turn out is located between culverts g and h. A type-A fence borders private property along the southbound lanes on the north prairie rim (b to c).

Inc., Lenexa, KS) were installed at the center of the north and south box culverts (1 and 8) to record the use of these culverts by larger vertebrates. To be recorded, an animal had to pass through the infrared light beam; thus, animals less than ca. 30 cm in height were not recorded. The track station and cameras were monitored five days per week, weather and water conditions permitting.

3. Results

3.1. Live animals on highway

Only 13 live vertebrates were observed on the highway during the year-long post-construction survey: 2 Eastern Narrow-mouthed Toads (*Gastrophryne carolinensis*), 1 unidentified Treefrog (*Hyla* sp.), 2 Green Treefrogs (*Hyla cinerea*), 1 Squirrel Treefrog (*H. squirella*), 1 Southern Leopard Frog (*Rana sphenocephala*), 1 Eastern Mud Turtle (*Kinosternon bauri*), 3 Brown Anoles (*Anolis sagrei*), 1 Broad-headed Skink (*Eumeces laticeps*), 1 Eastern Glass Lizard (*Ophisaurus ventralis*), 1 Southern Watersnake (*Nerodia fasciata*), 1 Coyote (*Canis latrans*).

3.2. Species killed

We counted 1891 dead vertebrates (1647 frogs; 1 alligator; 7 turtles; 4 lizards; 149 snakes; 83 mammals) during the post-construction phase of the study (Table 1). The total includes all of the dead animals observed during 152 road kill surveys over the entire 3.2 km study area within the prairie basin and on the adjacent rim. With the exception of hylid treefrogs, which easily trespass the barrier system by climbing up the barrier wall and adjacent vegetation, the mean number of vertebrate kills per 24-h sampling period was 4.9 (SD = 17.4; range = 0–162). Monthly means ranged from 0.75 to 33.2 vertebrates killed per 24-h period (Fig. 3). The mean number of animals killed per month was less than 10 throughout the study except for September 2001 when large numbers of *G. carolinensis* were killed (see below).

Hylid treefrogs ($n = 1301$) accounted for 68.8% of all road kills counted throughout the post-construction survey. In survey Sections 3, 14, and 23 where the sampling protocol was the same between pre- and post-construction surveys, 149 hylids were counted during the pre-construction survey versus 194 during the post-construction survey. Most treefrogs could not be identified to species because of the extent of body damage, although *H. cinerea* ($n = 135$) accounted for at least 10.4% of the hylids. The second most abundant species found dead on the highway, also an amphibian, was *G. carolinensis* (10.9%; $n = 218$). One hundred sixty-two Eastern Narrow-mouthed Toads were counted on a single day (6 September 2001) in the northbound lane in Section 1 (on the prairie rim) beyond the barrier wall (represented by the extended bar in Fig. 3).

DeKay's Brownsnakes (*Storeria dekayi*; $n = 54$) and Southern Watersnakes (*N. fasciata*; $n = 21$) were the most commonly killed snakes (Table 1). Most *S. dekayi* also were killed on the north and south prairie rims ($n = 28$). However, this small, semifossorial species also may have colonized the highway right-of-way, based on the number killed ($n = 26$) that were rather evenly distributed across the prairie basin. Most *N. fasciata* were killed within the prairie basin (81%), but the relatively large percentages killed in front of the prairie access gate (33%; Section 7) and type-A fence (19%; Sections 3–6) suggest that trespass within the basin was opportunistic rather than a failure of the wildlife barrier to deter movement. Only 12 other individual reptiles were counted dead during the study.

The Rice Rat (*Orozomys palustris*) was the most common mammal observed dead on the highway, with Opossums and Armadillos next in abundance. Few individuals of other mammal species were found (Table 1). Rice Rats trespassed the fence by climbing adjacent vegetation, whereas Opossums, Armadillos and other large mammals were usually found dead on the prairie rims.

3.3. Time and location of kills

Most post-construction mortality was recorded in August and September (729 and 727, respectively, or 132 and 224 if hylid treefrogs are excluded; Fig. 4). Approximately 73% of road kills, excluding hylid treefrogs, occurred in the ecotonal areas on the prairie rim beyond the extent of the barrier wall-culvert system (Table 2, Fig. 5). A total of only 158 dead amphibians, reptiles, and mammals was counted within the prairie basin. Most of the dead animals on the roadway within the prairie basin were found in sections adjacent to the type-A fence (Sections 3–6; $n = 62$; 39%) and in front of the prairie access gate (Section 7; $n = 39$; 25%).

Mortality was higher on the north rim than the south rim of the prairie beyond the barrier wall during the post-construction phase of the survey (Table 3). The majority of kills were *G. carolinensis* during September 2001 (203 of 302 [67%] recorded kills). Mortality on the south rim of the prairie beyond the barrier wall also increased during the post-construction phase of the survey. Unlike the north rim, mortality on the south rim resulted mostly from kills of Southern Toads (*Bufo terrestris*) and was more evenly distributed throughout the year.

Most carcasses were located in the outside lanes (46.5%) and contiguous bicycle lanes (28.5%), followed by the inside lane (11.1%) and grassy right-of-way (9.9%, Table 3). Very few animals were found in the

Table 1
Vertebrate roadkills on US 441 at Paynes Prairie State Preserve from 14 March 2001 through 5 March 2002

Scientific name	Common name	Within prairie basin	Rim	Total
Frogs				
Bufo terrestris	Southern Toad	7	71	78
Gastrophryne carolinensis	Eastern Narrow-mouthed Toad	4	214	218
Hyla cinerea	Green Treefrog	101	34	135
Hyla squirella	Squirrel Treefrog	7	6	13
Hyla sp.	Unidentified Treefrog	763	390	1153
Rana sphenocephala	Southern Leopard Frog	6	6	12
Rana sp.	Unidentified Ranid	5	7	12
Scaphiopus holbrookii	Eastern Spadefoot		7	7
Unidentified frog		6	13	19
Crocodilian				
Alligator mississippiensis	American Alligator		1	1
Turtles				
Chelydra serpentina	Snapping Turtle	2		2
Kinosternon bauri	Striped Mud Turtle		2	2
Kinosternon sp.	Unidentified Mud Turtle		1	1
Pseudemys nelsoni	Florida Red-bellied Turtle	1	1	2
Lizards				
Anolis sp.	Unidentified Anole	1		1
Ophisaurus sp.	Unidentified Glass Lizard	2		2
Ophisaurus ventralis	Eastern Glass Lizard	1		1
Snakes				
Agkistrodon piscivorus	Cottonmouth		1	1
Coluber constrictor	Eastern Racer	4		4
Diadophis punctatus	Ring-necked Snake	1	1	2
Elaphe guttata	Cornsnake	2		2
Elaphe obsoleta	Yellow Ratsnake	5	11	16
Farancia abacura	Red-bellied Mudsnake	7	1	8
Lampropeltis triangulum	Milksnake		1	1
Nerodia fasciata	Southern Watersnake	18	3	21
Nerodia floridana	Florida Green Watersnake	2	1	3
Opheodrys aestivus	Rough Greensnake		1	1
Seminatrix pygaea	Black Swampsnake	10	2	12
Storeria dekayi	DeKay's Brownsnake	26	28	54
Thamnophis sauritus	Eastern Ribbonsnake	2	1	3
Thamnophis sirtalis	Common Gartersnake	7	5	12
Unidentified snake		5	4	9
Mammals				
Blarina carolinensis	Southeastern Short-tailed Shrew		1	1
Canis familiaris	Domestic Dog	1		1
Canis latrans	Coyote		2	2
Dasypus novemcinctus	Nine-banded Armadillo	2	8	10
Didelphis virginianus	Virginia Opossum	1	14	15
Lutra canadensis	River Otter	1		1
Odocoileus virginianus	White-tailed Deer	1	2	3
Oryzomys palustris	Rice Rat	17	8	25
Peromyscus gossypinus	Cotton Mouse	1	1	2
Procyon lotor	Raccoon		5	5
Sigmodon hispidus	Hispid Cotton Rat	1	1	2
Sylvilagus palustris	Marsh Rabbit	1	1	2
Sylvilagus sp.	Unidentified rabbit	1		1
Urocyon cinereoargenteus	Gray Fox	1		1
Unidentified bat		2	3	5
Unidentified mammal		3	4	7
Total		1028	863	1891

Nomenclature of amphibians and reptiles follows Crother (2000).

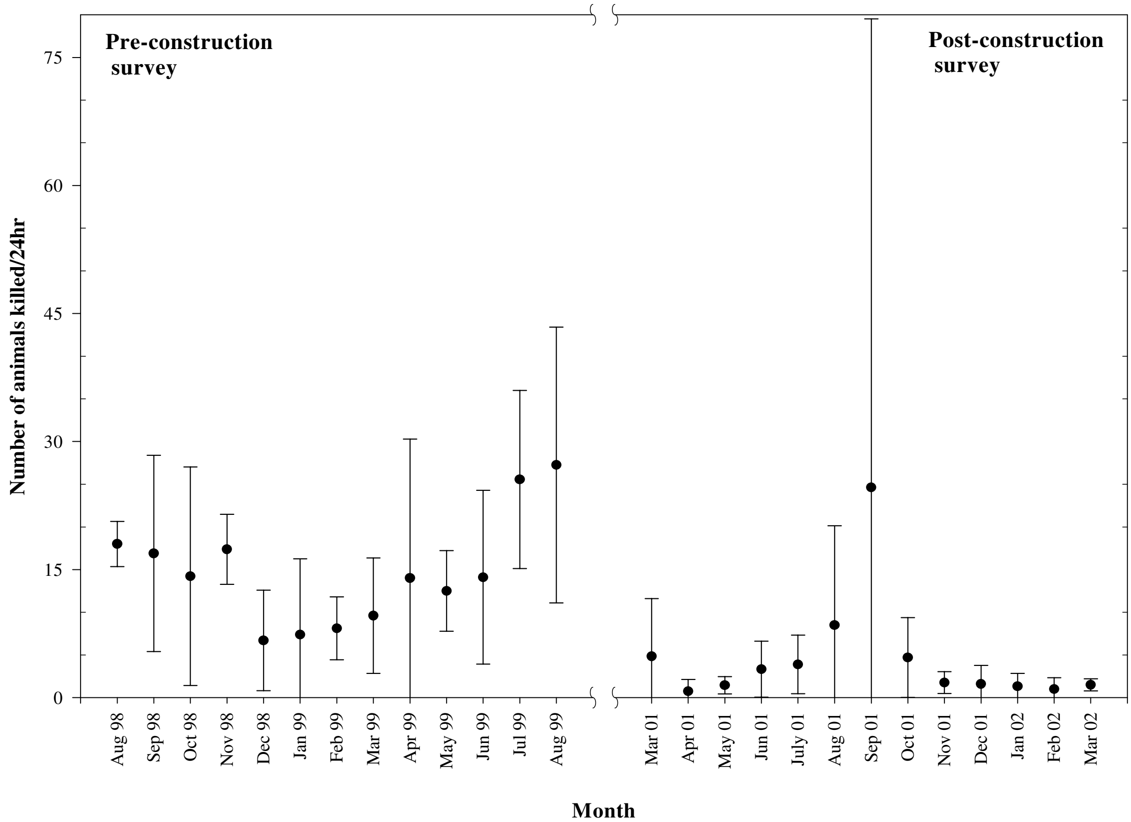


Fig. 3. Monthly roadkill totals on US Highway 441 across Paynes Prairie State Preserve, Alachua County, Florida one-year prior to and after construction of the barrier wall-culvert system.

median (3.6%) and directly on the centerline between lanes (0.4%) (Table 3). Wildlife mortality in the northbound lanes was 1.75 times that of southbound lanes (Table 3).

3.4. Culvert use

We recorded 51 vertebrate species using the culverts during post-construction monitoring (Table 4). We recorded 1046 captures during 7580 trap-nights (13.8% capture success) in funnel traps. Most captures occurred from mid-June to early July, when large numbers of juvenile Southern Leopard Frogs (40.5%) passed through culvert 8. Captures of Rice and Hispid Cotton Rats (*Oryzomys palustris* and *Sigmodon hispidus*, respectively) were most numerous in the dry culverts (culverts 1, 3, 5, 6, 8; Table 4) during the summer. Tracks of Ninebanded Armadillo (*Dasypus novemcinctus*), River Otter (*Lutra canadensis*), Virginia Opossum (*Didelphis virginianus*), and Raccoon (*Procyon lotor*) often were observed in the dry north culvert (number 1). These four species also were repeatedly photographed with the motion sensor cameras. Two species previously undocumented from the culverts, the Marsh Rabbit (*Sylvilagus palustris*) and American Alligator (*Alligator mississippiensis*), were photographed in culvert 1.

The newly installed rounded culverts often contained considerable amounts of water, and appeared to be used readily by fish, when inundated, and small mammals, when dry. Amphibians and reptiles were captured or observed less often (Table 4), perhaps because they were able to travel through or around the commercial crayfish traps. Because of the small diameter of these culverts and their sometimes wet environs, we were unable to use motion cameras or track stations to monitor culvert use. Other vertebrate species may have used the culverts and not been captured in the specialized traps.

4. Discussion

4.1. Is the barrier wall-culvert system effective?

Judging the effectiveness of a mitigation project of the magnitude of the Paynes Prairie barrier wall-culvert system is fraught with interpretive problems. Under ideal conditions, the pre- and post-construction surveys should have been carried out under exactly the same circumstances. The surveys should have begun and ended on the same dates, carcass detection probabilities should be equal among taxa, and the environmental conditions (temperature and precipitation patterns,

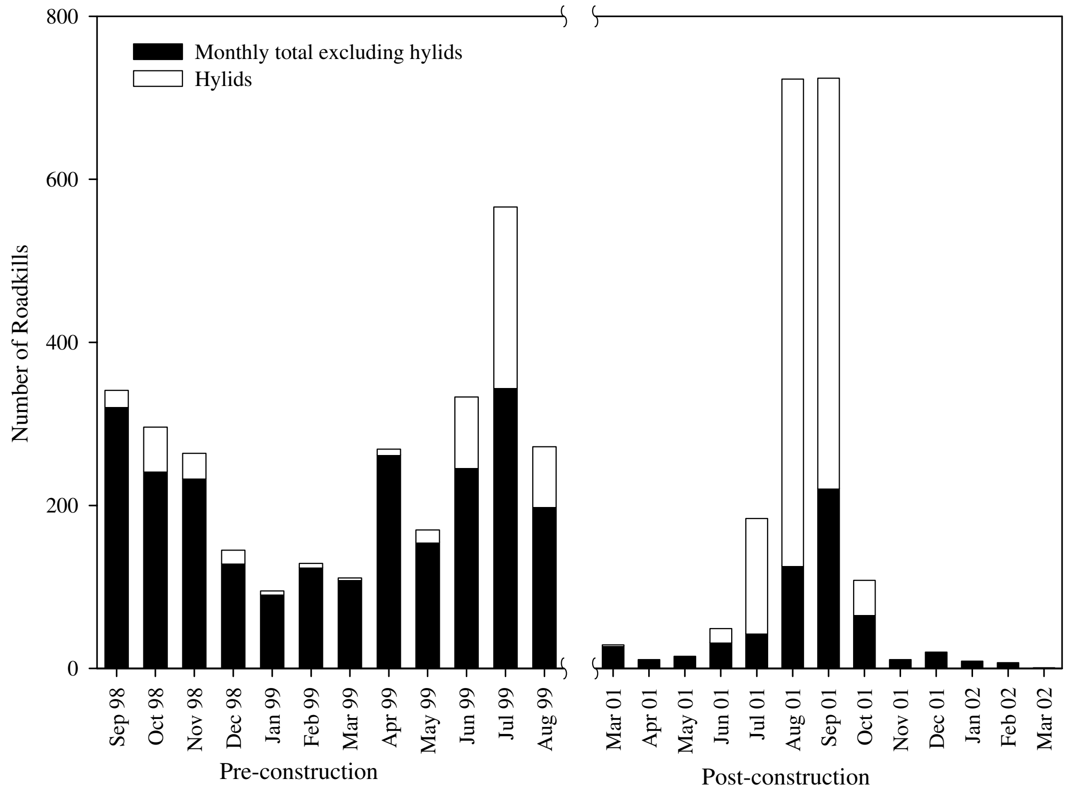


Fig. 4. Mean number of roadkills per 24 h period, exclusive of hylid treefrogs, on US Highway 441 across Paynes Prairie State Preserve, Alachua County, Florida one-year prior to and after construction of the barrier wall-culvert system. One standard deviation is expressed by the error bars. The large number of kills recorded in September 2001 results from an anomalous event whereby 162 Eastern Narrow-mouthed Toads were on a single day. In contrast, the kills in August 2001 were more evenly distributed throughout the month.

Table 2
Pre- and post-construction highway-related mortality on US Highway 441 in sections bordered and not bordered by the concrete barrier wall

Sections	Pre-construction mortality	Pre-construction mortality w/o hylids	Post-construction mortality	Post-construction mortality w/o hylids
1 and 2	146	85	595	302
3–30	2863	2411	1029	158
31 and 32	92	64	267	130
Total	3101	2560	1891	590

Sections 1, 2, 31 and 32 had no barriers to highway access by wildlife; Sections 3–30 were bordered by the concrete barrier wall.

water levels) should be controlled experimentally. It would also have been desirable to avoid possible observer biases, such as by using the same experienced observers, and to control for human-caused variables, such as traffic volume and noise. Given the scale of the project and limitations imposed by construction and environmental stochasticity, however, this was not possible. If the magnitude of highway mortality was similar between surveys, judging the effectiveness of the barrier wall-culvert system might be extremely difficult.

Forman et al. (2003) discussed six criteria for determining the success of barrier-related mitigation projects. If the objectives in constructing the barrier wall-culvert system were to reduce the mortality of vertebrates, especially the larger vertebrates, and to allow the passage of some animals across the highway in order to maintain habitat connectivity and gene flow between populations on opposite sides of the roadway corridor, we suggest that three lines of evidence argue for the success of the Paynes Prairie project.

4.1.1. *Mortality greatly decreased, especially for large species*

In the 12 months prior to construction of the barrier wall-culvert system, 2411 road kills were recorded in the study area (Smith and Dodd, 2003), whereas only 158 animals were killed during the post-construction surveys. Within the survey area lying directly in the Paynes Prairie basin, mortality was reduced 65% if hylid treefrogs are included, and 93.5% with hylid treefrogs ex-

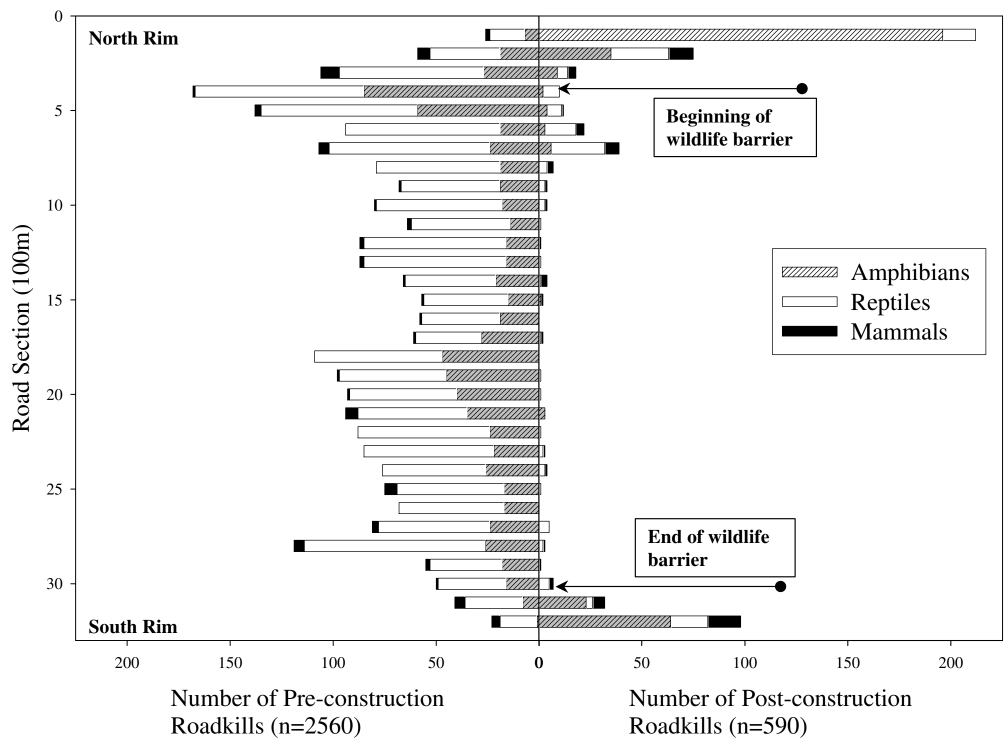


Fig. 5. Number of roadkills, excluding hylid treefrogs, per 100 m-section of US Highway 441 across Paynes Prairie State Preserve, Alachua County, Florida. The survey area commenced at the first private drive on the north rim of the prairie (Section 1) and extended 3.2 km to the first private driveway on the south rim (Section 3.2). Pre-construction data were collected from 18 August 1998 through 13 August 1999, and post-construction data were collected from 14 March 2001 to 5 March 2002. The concrete barrier wall adjacent to the roadway extends from Section 3 to Section 30.

Table 3
Location of wildlife kills (excluding hylid treefrogs) on the road surface, right-of-way, and median of US 441 at Paynes Prairie State Preserve, Alachua County, Florida

	Location	Northbound	Southbound	Median	Total
Amphibians	Right-of-way		1		1
	Bike lane	89	15		104
	Outer lane	136	38		174
	Centerline				0
	Inner lane	5	8		13
	Median			2	2
	Total	230	62	2	294
Reptiles	Right-of-way	10	16		26
	Bike lane	11	12		23
	Outer lane	11	30		41
	Centerline				0
	Inner lane	5	6		11
	Median			3	3
	Total	37	64	3	104
Mammals	Right-of-way	4	2		6
	Bike lane	3			3
	Outer lane	7	4		11
	Centerline	1			1
	Inner lane	7	8		15
	Median			5	5
	Total	22	14	5	41
Lane total		289	140	9	439

Surveys were conducted from 15 March 2001 through 5 March 2002. The data presented represents the two 24 h sampling units (2 and 3) collected weekly throughout the study.

Table 4
Vertebrates observed in culverts under US Highway 441 across Paynes Prairie, Alachua County, Florida, 14 March though 5 March 2002

Scientific name	Common name	Culvert no. (*N*)
Fish (*n* = 9)		
Ameiurus nebulosus	Brown bullhead	2(1), 4(1)
Elassoma sp.	Pygmy sunfish	2(5), 7(21)
Etheostoma fusiforme	Swamp darter	7(1)
Fundulus chrysotus	Golden topminnnow	7(1)
Gambusia holbrooki	Mosquitofish	2(12), 7(88)
Heterandria formosa	Least killifish	2(1), 7(19)
Lepisosteus platyrhincus	Florida gar	2(3), 3(4), 4(1), 5(2), 6(1)
Lepomis gulosus	Warmouth	4(16), 6(1)
Lepomis macrochirus	Bluegill	4(2)
Salamanders (*n* = 2)		
Amphiuma means	Two-toed Amphiuma	4(1), 6(2)
Siren lacertina	Greater Siren	4(2), 5(1)
Frogs (*n* = 11)		
Acris gryllus	Southern Cricket Frog	8*
Bufo terrestris	Southern Toad	1(9), 8*(36)
Gastrophryne carolinensis	Narrow-mouthed Toad	1(3), 6*, 8*(7)
Hyla cinerea	Green Treefrog	1(4), 3*, 4*, 5*, 6*, 7*, 8*(34)
Hyla femoralis	Pine Woods Treefrog	8(1)
Hyla squirella	Squirrel Treefrog	4*, 5*, 8(6)
Rana catesbeiana	American Bullfrog	6(1)
Rana clamitans	Green Frog	8*(1)
Rana grylio	Pig frog	4*, 6(1)
Rana sphenocephala	Southern Leopard Frog	1(14), 2(12), 3*, 5*, 7(85), 8*(424)
Scaphiopus holbrooki	Eastern Spadefoot	8(1)
Crocodilians (*n* = 1)		
Alligator mississippiensis	American Alligator	1*, 2*, 4*(6), 7*, 8*
Turtles (*n* = 4)		
Apalone ferox	Florida Softshell	3*, 4(3)
Kinosternon baurii	Striped Mud Turtle	8*(2)
Pseudemys nelsoni	Florida Red-bellied Turtle	2(1)
Sternotherus odoratus	Stinkpot	4(1)
Lizards (*n* = 1)		
Anolis carolinensis	Green Anole	1*
Snakes (*n* = 11)		
Agkistrodon piscivorus	Cottonmouth	1(4), 3*, 5*, 7*, 8(3)
Coluber constrictor	Eastern Racer	1(1)
Diadophis punctatus	Ring-necked Snake	4*
Elaphe guttata	Cornsnake	1(1)
Elaphe obsoleta	Yellow Ratsnake	8(1)
Farancia abacura	Eastern Mudsnake	8*
Nerodia fasciata	Southern Watersnake	1(4*), 3(1), 4*, 5*, 6*, 7*, 8*
Nerodia floridana	Florida Green Watersnake	1(2)
Storeria dekayi	Dekay's Brownsnake	1(1), 3*
Thamnophis sauritus	Eastern Ribbonsnake	1(4)
Thamnophis sirtalis	Common Gartersnake	1(1)
Mammals (*n* = 12)		
Blarina carolinensis	Southeastern Short-tailed Shrew	1(6), 8(4)
Dasypus novemcinctus	Nine-banded Armadillo	1*, 8*
Didelphis virginianus	Virginia Opossum	1*, 8*
Lutra canadensis	River Otter	1*, 6*
Lynx rufus	Bobcat	1*
Myotis austroriparius	Southeastern Bat	8*
Neofiber alleni	Round-tailed Muskrat	1(1), 6(1), 8*(4)
Oryzomys palustris/*Sigmodon hispidus*	Rice Rat/Hispid Cotton Rat	1*(17), 3(29), 5(19), 6(20), 8(19)
Peromyscus gossypinus	Cotton Mouse	1(2), 3(3), 5(2)
Procyon lotor	Raccoon	1*, 8*
Sylvilagus palustris	Marsh Rabbit	1*

*indicates photo, track, or incidental observation.

cluded. Snake (1,291 vs. 149), turtle (374 vs. 7), and alligator (29 vs. 1) mortality also was notably lower in the post-construction survey as well. We suggest that this decrease in highway-related mortality cannot be attributed solely to changes in water level. The species killed during the post-construction survey were mostly small vertebrates that either climbed over the wall or trespassed the barrier at the maintenance road access ramp or at the inadequate barrier formed by the type-A fence. In contrast, more larger vertebrates were killed during the pre-construction survey, and many were killed throughout the basin on the highway. Snake, turtle, ranid frog, and alligator mortality declined dramatically with the construction of the barrier wall-culvert system, yet treefrog mortality appears to have increased (149 to 194 in the road sections monitored in the same manner from pre- to post-construction).

The apparent increase is most likely a result of differences in water levels on the prairie between pre- and post-construction surveys. Increased levels of amphibian mortality observed in the post-construction survey may be related to the decreasing water levels on the prairie, which caused animals to move to terrestrial habitats. During the period of high water in the prairie basin during part of the pre-construction survey, hylids may have been less likely to move than they did when water receded during the drought associated with much of the post-construction survey. In any case, mortality is undoubtedly underestimated for amphibians since small treefrogs are quickly obliterated by vehicles. The large number of hylids killed on the highway indicates that some animals likely will be killed on US 441, despite the presence of a barrier. At this time, we know of no practical, effective way to reduce hylid mortality.

4.1.2. Use of culverts increased

In addition to a decrease in highway-related mortality of most vertebrates, we observed an increase in culvert use by many species. Capture success increased tenfold between the pre- and post-construction surveys. The increase was most pronounced in the number of individual amphibians using the culverts (0.006–0.085 captures per trap-night, respectively). For example, the huge decline in the number of ranid frogs killed on the highway, combined with an increase in the use of culverts by these species, provides evidence of the effectiveness of the wall-culvert system to prevent mortality of certain amphibians while allowing passage under the highway.

Additionally, the number of species using the culverts increased from 28 to 42 (excluding fish), and was most apparent in the number of amphibian species using the culverts (from 5 to 13 species). Because of sampling limitations, we were unable to quantify culvert use. Nonetheless, movements through culverts by at least some individuals, as observed in this study, should be sufficient to maintain habitat connectivity and gene flow between the east and west sides of the prairie. Hypothetically, only a few individuals need to cross a barrier per generation to maintain heterozygosity (Meffee and Carroll, 1997; Forman et al., 2003), although roads have effectively altered the population structure of some small vertebrates living on different sides of a highway (Reh and Seitz, 1990; Gerlach and Musolf, 2000).

4.1.3. Use of ecotones increased for some species

Terrestrial vertebrates commonly use topographic features or ecotones as movement or dispersal corridors (e.g., Healy, 1975). Vertebrate mortality on US 441, particularly of the mammals and certain terrestrial amphibians, increased at the ecotonal areas on both prairie rims after construction. This suggests that the barrier wall directed animals along the bottom of the barrier to the first place where they could cross, the end of the wall. The fence also likely directed animals to the culverts, as evidenced by the increase in culvert use post-construction.

Five of the six criteria outlined by Forman et al. (2003) to judge success appear to be met along the US 441 barrier wall-culvert system at Paynes Prairie: a reduction road-kill rates post-construction, maintenance of habitat connectivity, maintenance of genetic interchange, allowance for dispersal and recolonization (see 4.2), and maintenance of metapopulation processes and ecosystem function. The Florida Park Service has been working to re-establish natural water flow regimes on the prairie since the area became a state preserve. Old dikes have been removed, ditches have been filled, and prescribed fires have helped to restore the prairie's hydrology. However, little is known concerning the population size and structure for most species occurring within the prairie basin, except for a few large mammals and alligators. Call surveys and road counts suggest that populations of many amphibians, reptiles, and small mammals may be very large on the vast wetland. Until more precise data are available, however, the last of Forman et al.'s criteria, the ability to ensure that biological requirements are met, cannot be evaluated.

4.2. Mortality patterns and season

We observed noticeable differences in wildlife mortality, depending on highway direction. A small number of carcasses were found in the median suggesting that few animals made it that far. Differences in mortality between the north and southbound lanes could result from the large volume of traffic moving toward Gainesville during the very early morning hours, when nocturnal and crepuscular animals were still active. In the late afternoon during the heat of the day, fewer animals were likely to be active and thus encountered on the highway when motorists working in Gainesville return to their homes south of the Prairie.

Highway-related mortality was greatest during the late summer months in both surveys, and this pattern is consistent with the results from the most systematic previous survey (Franz and Scudder, 1977). Some animals also may have been moving in a particular direction at a certain time of the year, such as when juvenile frogs disperse after metamorphosis. For example, large numbers of juvenile *R. sphenocephala* were captured moving from east to west in culvert funnel traps in July 2002, presumably as the dispersed away from the drying wetlands on the eastern side of the highway.

5. Recommendations

Patterns of mortality observed in the study revealed several maintenance and design problems in the Paynes Prairie barrier wall-culvert system that may be fixed in this system and avoided in ecological passage projects elsewhere. Early in the study, we observed small mammals, snakes and treefrogs climbing vegetation along the barrier wall. The vegetation offered access to the highway right-of-way and some of the animals observed dead on the roadway undoubtedly obtained access in this manner. Once we identified the problem, FDOT responded by applying herbicide along the barrier wall, which temporarily resolved the problem. However, to minimize trespass, vegetation must be removed from barriers regularly, particularly during the growing season.

We documented a peak in the numbers of animals killed on the roadway adjacent to a maintenance road access ramp in the northwest part of the study area (Section 7). A second access road is located in the southeast part of the prairie. We did not observe high mortality in this area because it does not ascend to the level of US 441. In wet years, this access road may allow animals to trespass onto the roadway by funneling them toward the south rim beyond the barrier wall. Widely spaced cattle grates could be used to prevent small animals from accessing the roadway, while allowing service vehicle access to the prairie.

Significant trespass occurred at the type-A fence on the northwest edge of our study area. Gaps developed beneath the barricades as a result of erosion of the top soil, allowing snakes, turtles, and frogs free access to the highway. We recommend burying galvanized tin or aluminum flashing to a depth of at least 20 cm below barricades to prevent access. However, this method will require regular maintenance because mammals are likely to attempt to dig under barriers and over time, sheet flow associated with heavy rain could still cause erosion. Since the type-A fence occurs in an area where many animals were killed in the pre- and post-construction survey, more permanent structures should be used, accompanied with ample culverts to act as underpasses.

Culverts require regular maintenance. During heavy rain, flow through culverts in our study increased dramatically causing silt to accumulate. Although a natural substrate on the floor of the concrete culverts might enhance their use by some animals (Yanes et al., 1995), a heavy build-up of silt would eventually diminish the area available for wildlife passage. Also, during construction, deep pools were created outside six of the eight culverts. These pools attracted alligators, which could discourage movement of animals through the culvert. Animals exiting a culvert into these pools might be subject to an increased risk of predation, although we did not see evidence of this (also see Little et al., 2002). These pools should be filled in to match the grade of the surrounding prairie.

Finally, once in place, the barrier wall-culvert system received an unanticipated amount of public interest. Modifications to the right-of-way during construction created space for people to park and observe wildlife on the prairie. During the post-construction survey, water levels on the prairie were low and alligators were concentrated in the canals adjacent to the wall. Although illegal, people stopping along the wall regularly fed the alligators and often climbed down to the prairie to do so, creating a safety concern. Eventually, the FDOT erected a fence in the right-of-way restricting public access to the barrier wall. The fence seems to have eliminated safety concerns, but is an obstruction to what was once a scenic view of the prairie. Such issues may arise in other barrier wall-culvert projects and could perhaps be resolved in the planning process. Ideally, an barrier wall-culvert system should be designed to not only mitigate for wildlife mortality and public safety, but also to allow public access and appreciation for the resource being protected.

Acknowledgements

This study was funded by the Florida Department of Transportation; we thank Gary Evink and Pete Southall for their support of the project. We are grateful to Jack Gillen, Dan Pearson, and Jim Weimer of the Florida Department of Environmental Protection for providing mortality data for Paynes Prairie. We also thank Dick Franz and Sylvia Scudder for making their unpublished data available to us. Kelly Keefe, Audrey Owens, Kristina Sorensen, Jennifer Staiger, and Maya Zacharow assisted in field surveys. Tom Webber, Candace McCaffery, and Laurie Wilkens helped with the identification of small mammals. Dick Franz, Russell Hall and two anonymous reviewers provided helpful comments on the manuscript. This work was carried out under Florida Fish and Wildlife Conservation Commission Permits WS98348 and WS01511.

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