FINAL PROJECT REPORT

DEVELOPMENT AND EVALUATION OF DEVICES DESIGNED TO MINIMIZE DEER-VEHICLE COLLISIONS (PHASE II)

prepared by

David A. Osborn
William D. Gulsby
Daniel W. Stull
Bradley S. Cohen
Robert J. Warren
Karl V. Miller
George R. Gallagher

Daniel B. Warnell School of Forestry and Natural Resources
University of Georgia
Athens, Georgia

Department of Animal Sciences
Berry College
Mount Berry, Georgia

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D. A. Osborn, W.D. Gulsby, D.W. Stull, B.S. Cohen, R.J Warren, K.V. Miller (Univ. of Georgia), G.R. Gallagher (Berry College)

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We evaluated behavioral responses of captive white-tailed deer to visual and physical barriers designed to minimize deer-vehicle collisions, determined effects of exclusion fencing on movements of free-ranging deer, and further tested the visual capabilities of deer, as related to potential mitigation strategies. We tested the efficacy of several fencing designs and that of a layer of rip-rap rock for restricting movements of captive deer. Woven-wire fences <1.8 m tall, similar heights of opaque fencing, and rip-rap rock each were ineffective. Both 1.8-m and 2.4-m woven-wire fences were relatively more effective. Woven-wire fences >2.1-m tall and 1.2-m woven-wire fences with a top-mounted outrigger were most effective. We studied movements of free-ranging deer before and after construction of 1.6-km of 2.4-m woven-wire and 1.6-km of 1.2-m woven-wire with a top-mounted outrigger. Fencing did not affect deer home range size, and deer often circumvented fence ends. Daily deer movements in response to fencing were reduced by 98% and 90% for the 2.4-m and outrigger designs, respectively. The outrigger design has potential for reducing collisions because of its relative affordability and ability to function as a 1-way barrier. To further test deer vision, as related to deterrents to roadway crossing, we developed an automated system for training deer to associate a white-light stimulus with a food reward. Each of six captive deer correctly identified the positive reward in >75% of trials by Day 19. We will use this system to further characterize the visual thresholds of deer, and to test innovative roadside mitigation strategies.

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EXECUTIVE SUMMARY

This project was funded by Georgia Department of Transportation (GDOT) through the Governor's Office of Highway Safety and the National Highway Traffic Safety Administration. In 2004, Drs. Robert J. Warren and Karl V. Miller of the University of Georgia (UGA) and Dr. George R. Gallagher of Berry College initiated Phase I of this collaborative research, which resulted in the Ph.D. dissertation of Gino D'Angelo (2007) and the Master of Science thesis of Sharon Valitzski (2007). Phase I research findings were disseminated in 6 scientific publications, 19 presentations at professional meetings, and a final project report, which we submitted to GDOT on 2 July 2007.

Phase II of this collaborative effort began in 2007 to: (1) evaluate behavioral responses of captive white-tailed deer to visual and physical barriers designed to minimize deer-vehicle collisions (DVC), (2) determine effects of fences on roadway crossings and home range distribution of free-ranging white-tailed deer, and (3) generate additional information on the visual capabilities of white-tailed deer to further advance development of DVC mitigation strategies. This final project report is a compilation of the Master of Science theses of Daniel W. Stull (Stull 2009) and William D. Gulsby (2010); both documents are included in their entirety. Because a recently accepted publication (Stull et al. 2010) differed substantially in content and scope from Daniel Stull's thesis research, we've included it as part of this final report. In addition, we've included the Master of Science thesis proposal of Bradley Cohen (projected completion date May 2011). Bradley presented preliminary data from his research at a recent meeting of the Georgia Chapter of The Wildlife Society.

In Phase I of this research, we learned that sight- and sound-based deterrents were unreliable for modifying behavior of deer within roadway corridors in response to oncoming vehicles. Therefore, the primary focus of Phase II was to test the efficacy of various physical barriers for restricting deer access to roadways. A secondary focus was to determine how deer vision differed from human vision across the entire spectrum of visible light, so that the information could be used to develop innovative DVC mitigation strategies. Phase II findings to date are summarized as follows:

During January-December 2008, we evaluated the efficacy of a variety of fencing designs for restricting movements of captive deer; including standard woven-wire fencing (1.2-m, 1.5-m, 1.8-m, 2.1-m, and 2.4-m tall), opaque fencing (1.2-m, 1.5-m, and 1.8-m tall), and an outrigger fence (i.e., 0.6-m outriggers attached to a 1.2-m wire fence angled at 45º). Our findings suggest that woven-wire fences <1.8 m in height are ineffective for excluding deer from roadways and the cost of retrofitting existing fences with an opaque covering is unjustified. Efficacy of 1.8-m to 2.4-m woven-wire fences might be acceptable depending on the level of exclusion required along a particular roadway. Woven-wire fences $\geq$2.1-m tall and a 1.2-m woven-wire fence with a top-mounted outrigger angled toward the deer were most effective at restricting deer movements. Where exclusion fences of ineffective heights already exist along roadways, their efficacy might be improved by adding height with more woven-wire, or outriggers, to their tops. However, 1.8-m to 2.4-m woven-wire fences can potentially trap deer in the roadway, if they circumvent the fence ends. Shorter woven-wire fences with an outrigger angled away from the road might allow 1-way travel of deer from the roadway, thereby minimizing the potential for DVCs.

During November-December 2008, we tested a single layer of Type III rip-rap rock for restricting movements of captive deer. This tactile barrier did not prevent deer from crossing between 2 adjacent outside paddocks, and likely would be ineffective for excluding deer from roadways. Within weeks of construction, the rip-rap settled, collected debris, and plants became established among the rocks, which required repeated control by herbicides. We do not recommend this barrier to mitigate DVCs.

Because a 2.4-m woven-wire fence and a prototype outrigger fence (i.e., 0.6-m outriggers attached to a 1.2-m wire fence angled at 45º) were 100% effective at preventing crossings by captive deer, we evaluated the efficacy of these designs at preventing crossings by free-ranging deer at Berry College in northwestern Georgia. From January to April 2009, we fitted 14 adult does with GPS collars, programmed to collect ≥ 24 locations/day. In June 2009, we constructed a 3.2-km fence treatment that included a 1.6-km section of 2.4-m vertical-wire fence and a 1.6-km section of the outrigger fence. We retrieved collars between January and March 2010. We compared home ranges, core areas, fence crossings, and fence circumventions among deer that encountered the outrigger and 2.4-m fences, as contrasted to deer that did not encounter the fence (i.e., controls), before and after fence construction. Although home ranges and core areas changed among seasons, we found no effect of fencing on home range size. Deer with pre-treatment home ranges that approached or encompassed the end of the fence maintained a high degree of site fidelity by circumventing the fences. However, fence crossings were reduced by 98% and 90% for the 2.4-m and outrigger treatment groups, respectively. Although we recorded fewer crossings of the 2.4-m fence, the prototype outrigger fence may be a viable option for reducing DVCs because of its affordability and potential as a 1-way barrier. More importantly, we believe this study highlights the importance of using localized data on deer home range sizes to determine the minimum length of fencing necessary to prevent circumvention in high-risk areas.

In Phase I, D'Angelo (2007) examined morphological characteristics of the white-tailed deer eye to better understand what deer might see. In Phase II, Bradley Cohen's research is focused on recording behavioral measures of deer vision, particularly on the far ends of the visual light spectrum with the hope that the knowledge gained will be useful for developing more effective vision-related DVC-deterring devices. Few studies have focused on the cognitive perception of deer because of the logistical difficulty of training deer. To facilitate deer training, we have developed and validated an automated "deer-training-device" (DTD), which dispenses food; sounds a buzzer at the start of each trial; randomly assigns and activates a stimulus light over 1 of 2 food troughs; and records a deer's response during each trial. When a deer goes to the trough under the activated stimulus light to feed, a correct response is recorded by the DTD. An incorrect response is recorded when a deer goes to the trough beneath the inactivated light. Currently, 7 deer are trained to participate in the trials and each has correctly discriminated between activated and inactivated lights at $\geq$75% accuracy. By Day 25 of the trial, 6 deer responded correctly during 88.2 ± 3.9% of trials. Therefore, we will use the DTD to delineate the visual threshold (the smallest amount of intensity that can be detected at least 50% of the time at a specific wavelength) of these deer in light and dark conditions, and to determine how this knowledge might best be used for mitigation of DVCs.

DISSERTATIONS AND THESES RESULTING FROM PHASE I AND PHASE II RESEARCH (PHASE II DOCUMENTS ATTACHED):

D'Angelo, G. J. 2007. Development and evaluation of strategies designed to minimize deer-vehicle collisions. Ph.D. Dissertation. University of Georgia, Athens, GA, USA.

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Valitzski, S. A. 2007. Evaluation of sound as a deterrent for reducing deer-vehicle collisions. M.S. Thesis. University of Georgia, Athens.

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Valitzski, S. A., G. J. D’Angelo, D. A. Osborn, G. R. Gallagher, K. V. Miller, and R. J. Warren. 2006. Evaluation of sound as a deterrent for reducing deer-vehicle collisions. Daniel B. Warnell School of Forestry and Natural Resources Graduate Student Symposium, Athens, Georgia.

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Valitzski, S. A., G. J. D'Angelo, D. A. Osborn, G. R. Gallagher , K. V. Miller, and R. J. Warren. 2007. Behavioral responses of white-tailed deer to vehicle-mounted sound-producing devices. 30th Annual Conference of the Southeast Deer Study Group, Ocean City, Maryland.

Valitzski, S. A., G. J. D'Angelo, D. A. Osborn, G. R. Gallagher , K. V. Miller, and R. J. Warren. 2007. Behavioral responses of white-tailed deer to vehicle-mounted sound-producing devices. Daniel B. Warnell School of Forestry and Natural Resources Graduate Student Symposium, Athens, Georgia.

Valitzski, S. A., G. J. D'Angelo, D. A. Osborn, G. R. Gallagher , K. V. Miller, and R. J. Warren. 2007. Evaluation of sound as a deterrent for reducing deer-vehicle collisions. International Conference on Ecology and Transportation, Little Rock, Arkansas.

BEHAVIORAL RESPONSES OF CAPTIVE DEER TO VISUAL AND PHYSICAL BARRIERS DESIGNED TO MINIMIZE DEER-VEHICLE COLLISIONS

by

DANIEL WILLIAM STULL

(Under the Direction of Karl V. Miller and Robert J. Warren)

ABSTRACT

As white-tailed deer (*Odocoileus virginianus*) and human populations expand and overlap, deer-vehicle collisions become a common occurrence. Although a variety of mitigation techniques have been studied, one of the most effective is exclusion fencing. I evaluated efficacy of exclusion fencing for preventing deer crossing into roadways. Fences were grouped into 3 categories: woven-wire fencing (1.2-2.4-m), opaque fencing (1.2-1.8-m), and fencing with a 45° outrigger. No deer crossed 2.4-m woven-wire fencing. Outrigger fencing angled toward deer and 2.1-m woven-wire fence had similar efficacy and were the next most effective. Efficacy between woven-wire fencing and opaque fencing at similar heights was not different. Outrigger fencing was more effective angled toward deer than away. Outrigger fencing along roadways may act as a one-way crossing instead of potentially trapping deer like 2.4-m woven-wire fence. I also evaluated efficacy of Type III rip-rap as a tactile barrier. Rip-rap was unsuccessful at preventing deer crossings.

INDEX WORDS: Deer, Deer-vehicle collisions, Fence, White-tailed deer

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by

DANIEL WILLIAM STULL

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by

DANIEL WILLIAM STULL

Major Professor:	Karl V. Miller Robert J. Warren
Committee:	John C. Maerz Craig A. Miller

Electronic Version Approved:

Maureen Grasso
Dean of the Graduate School
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CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

INTRODUCTION

Collisions with white-tailed deer (*Odocoileus virginianus*) present a significant hazard to motorists in the United States. Dense deer populations, coupled with a growing human population and concurrent expansion of the nation's roadway system, have increased the risk of deer-vehicle collisions. State Farm Insurance Company (2009) estimated that 1.5 million drivers are involved in deer-vehicle collisions each year, resulting in approximately 150 deaths and $1.1 billion in damage to personal property. Huijser et al. (2007) reported that the total number of vehicle crashes in the United States, when considering all causes, had remained relatively unchanged from 1990-2004. However, the proportion of wildlife-vehicle collisions in the annual total for the period has increased steadily by 6,769 each year with deer-vehicle collisions constituting 77% (5,212/yr) of the collisions with wildlife.

Many mitigation devices and strategies have been employed in an attempt to reduce the frequency of deer-vehicle collisions, including animal detection systems, deer whistles, roadside reflectors, roadway signage, population reduction, underpasses, overpasses, and fences. Animal detection systems and other roadway signage can alert drivers when or where an animal is likely to cross. However, roadway signage is often ignored by motorists as they become habituated to it, even if accompanied with flashing warning lights (Putman et al. 2004). Research conducted on white-tailed deer hearing and visual capabilities suggests deer whistles and roadside reflectors are ineffective in altering deer behavior so that a deer-vehicle collision would be avoided (D'Angelo et al. 2006, Valitzski et al. 2009). Although DeNicola and Williams (2008) were able to reduce deer-vehicle collisions of three suburban areas by 49-78% by reducing deer populations along roadways, sharpshooting may not be a viable option in many areas due to location and public opinion. Underpasses and overpasses are effective at providing safe passage for wildlife when designed specifically for the site and when accompanied by fencing, decreasing deer mortality 42.3% along a 4-lane highway and 36.8% along a 2-lane highway (Lehnert and Bissonette 1997). However, high construction cost ($173,000/4-lane and $92,000/2-lane) limits extensive use of this option for minimizing deer-vehicle collisions (Lehnert and Bissonette 1997). Tactile barriers such as cattle guards are also effective at prohibiting movement of hoofed animals, such as red deer (*Cervus elaphus elaphus;* Reed et al. 1974, Belant et al. 1998a, Peterson et al. 2003, Sebesta et al. 2003). Although long expanses of cattle guards are likely infeasible, alternative tactile barriers such as rip-rap (i.e., large pieces of crushed rock) have not been evaluated for effectiveness. Additionally, the effectiveness of tactile-fence combinations has not been studied.

Prohibitive fencing, often woven-wire fencing ≥2.4-m tall, effectively keeps deer out of roadways and reduces deer-vehicle collisions (Falk et al. 1978, Reed et al. 1980, Ludwig and Bremicker 1981, Clevenger et al. 2001, VerCauteren et al. 2006). Woven-wire prohibits deer from passing between individual wires. To be most effective at excluding deer from roadways, fencing should be installed on both sides of the road. However, even with effective exclusion fencing, deer may circumvent fence ends, enter the roadway at a new location (i.e., relocate the area of risk), and become trapped between the fences creating increased risk of a deer-vehicle collision (Conover 2002). To prevent a deer from circumventing fence ends, it may be necessary to extend the fence well beyond the targeted crossing site. However, long expanses of ≥2.4-m fence are expensive to build and maintain. To prevent deer from becoming trapped in the roadway, the fence should allow one-way crossing away from the road. Even with the cost of fence construction and maintenance, and the need for innovative fencing designs, exclusion fencing may be the most effective and practical method of reducing deer vehicle collisions (Feldhamer et al. 1986). The objective of this research was to evaluate the effectiveness of various heights and designs of fence and potential for rip-rap to slow deer movement.

LITERATURE REVIEW

Mitigation strategies for reducing deer-vehicle collisions have included altering deer behavior away from the road, influencing driver behavior, or prohibiting deer access to the road. Strategies involving altering behavior of either drivers (i.e., animal detection systems, reduced speed limits, and roadway signage) or deer (i.e., deer whistles and roadside reflectors) have been met with limited success (Huijser et al. 2007). Huijser et al. (2006) found that animal detection systems accurately detected 87% of elk (*C. e. canadensis*) crossings on a highway in Yellowstone National Park, Montana, USA. However, roadway signage and animal detection systems are often ignored by motorists as they become habituated to it and therefore are ineffective at mitigating wildlife-vehicle collisions (Putman et al. 2004, Meyer 2006). D’Angelo (2007) examined the physiological and morphological characteristics of white-tailed deer visual and auditory systems, and evaluated the effectiveness of Strieter-Lite® wildlife warning reflectors at altering deer behavior away from roadways. In experimental trials, these reflectors were ineffective at altering deer behavior in a manner that would reduce the incidence of deer-vehicle collisions (D’Angelo et al. 2006). Mule deer (*O. hemionus*)-vehicle collisions were not reduced in areas where Swareflex Reflectors were posted (Reeve and Anderson 1993). Ujvári et al. (1998) reported that fallow deer (*Dama dama*) became habituated to WEGU wildlife warning reflectors (Walter Dräbing KG, Kassel, Germany) over 17 nights. Most studies that report reflectors as being effective base their evaluations on deer carcass counts (Schafer and Penland 1985, Pafko and Kovach 1996) before and after installment or reflectors are covered and uncovered. These methods fail to consider seasonal movements, traffic patterns, changes in deer densities, or altered driver behavior in the presence of reflectors (D'Angelo 2007).

White-tailed deer hearing has the greatest sensitivity between 4-kHz and 8-kHz (D'Angelo et al. 2007). Valitzski et al. (2009) evaluated pure tones within this range as a potential deterrent to prevent deer-vehicle collisions and found that they were unsuccessful at altering deer behavior away from the road. Romin and Dalton (1992) reported mule deer were unaffected by Game Tracker or Sav-a-life wildlife warning whistles but did not determine if mule deer had the ability to hear the sound produced by either brand. Frightening devices such as motion-activated deer distress calls, propane exploders, and other electronic auditory devices have limited success reducing deer damage to crops (Belant et al. 1996, Belant et al. 1998b, Gilsdorf et al. 2006) and probably are not effective at reducing deer-vehicle collisions.

The standard fence used to prevent white-tailed deer damage is 2.4-m woven-wire fence. Ludwig and Bremicker (1981) evaluated 2.4-m fencing with one-way gates and reported that deer-vehicle collisions were reduced 60-93% over two fenced roadway segments. However, the length (4-km) of one the fences was considered too short and deer often circumvented the ends of the fence rather than using one-way gates. Falk et al. (1978) reported 2.3-m fencing was not high enough to prevent deer from crossing when startled by researchers.

Several studies have evaluated the efficacy of an array of alternate fencing designs (i.e., electric, woven-wire, barbed wire, and outrigger) to prevent deer damage, mostly in agricultural situations not associated with roadways. Electric fence designs are successful for preventing deer movement into exclosures (Tierson 1969, Palmer et al. 1985, Seamans and VerCauteren

2006). Tierson (1969) reported that deer behavior in response to making contact with the fence varied from appearing completely unaffected to reacting violently to the point of falling down. The addition of a 1.3-m, 5 stranded Electrobraid™ fence surrounding a preexisting 1.8-m snow fence reduced the number of deer gaining access to a corn feeder by 90% (Seamans and VerCauteren 2006). Webb et al. (2009) successfully prohibited deer movement with a 2.5-m, 15-strand high-tensile electric fence; however, white-tailed deer were still able to pass through water gaps and open places on uneven ground. Similarly, Leblond et al. (2007) reported that moose (*Alces alces*) roadway crossings were reduced by approximately 80% with the addition of a 1.5-m, 5 stranded Electrobraid™ in the Laurentides Wildlife Reserve, Quebec, Canada. Electrified fence requires continued maintenance to ensure the fence is working properly, limiting its applicability in many locations.

Fence designs with sections of overhanging fence, (i.e., outriggers) have also been tested. Goddard et al. (2001) reported equal success with a 0.9-m vertical fence with a 0.8-m, 90° outrigger and a 1.8-m vertical woven-wire fence at preventing crossings by red deer. Jones and Longhurst (1958) also reported that a 0.6-m vertical fence with an outrigger of 1.8-m angled at 25° and a 1.2-m vertical fence with 1.2-m outrigger angled at 45° were effective at prohibiting deer access to a Sudan grass pasture. A slanted fence design with a slope of 49° consisting of a 1.8-m roll of chicken wire also proved to be effective at restricting movement of mule deer and other ungulates (Jones and Longhurst 1958). Fenster (2006) reported that deer would enter an exclosure surrounded by a 45°, smooth-wire outrigger fence by climbing through the wires at the base, with the outrigger angled toward them, but would often jump over the top when the outrigger was angled away. Like electrified fence, 90° outrigger and slanted fences would require a significant amount of maintenance in a roadside setting as debris could accumulate on top of the fence that would need to be removed and mowing would become more difficult.

Currently, the fence used by the Georgia Department of Transportation (GDOT) in areas with a high potential for deer-vehicle collisions is 2.7-m tall and constructed in three sections (GDOT, personal communication). The bottom section consists of 22.9-cm of woven-wire with 7.6-cm of vertical spacing between strands, and a strand of barbed wire running along the ground. The middle section is 2.2-m of woven-wire with 20.3-cm of vertical spacing between strands. The top section consists of two strands of barbed wire spaced 15.2-cm apart and located 15.2-cm above the middle section of woven-wire. Although this fence is effective, it is presumably more costly to construct than a standard 2.4-m woven-wire fence due to the additional barbed wire. Deer are more likely to become ensnared and killed crossing a fence with barbed wire than a fence without (Harrington and Conover 2006). If a more cost effective alternative to this fencing design were discovered, fence mitigation strategies could be used over more extensive areas and in additional locations.

Few studies have considered characteristics of deer vision when testing efficacy of exclusion fencing. Jones and Longhurst (1958) found that deer were more likely to attempt to go under a fence 1.3-m high and slanted towards them at 45° rather than jump over it. It was likely that this modified fence-crossing behavior occurred because deer perceived they could not successfully jump the fence. Gallagher et al. (2003) showed that a 1.7-m vertical fence composed of hanging burlap (i.e., 100% visual barrier) prevented the majority of deer from crossing. Although deer had the ability to cross underneath the burlap, as the lower end was not fixed, and deer had prior knowledge that corn was available on the other side, they did not cross. Wild ungulates, cattle, and horses are more likely to respect a solid barrier as opposed to a woven wire barrier (Grandin 2007). Excited animals are more likely to run into a wire fence than a perceived solid barrier, which can be used to corral or move animals into a desired direction. A perceived solid barrier along roadways, such as existing fences retrofitted with an opaque covering, may minimize crossing attempts, although this has not been verified experimentally.

Barriers that exploit the anatomy of the ungulate hoof, hereafter referred to as tactile designs, have shown promise in preventing crossings. For example, grates of varying patterns (e.g., cattle guard) have been used in urban areas to successfully prohibit deer access (Reed et al. 1974, Belant et al. 1998a, Sebesta et al. 2003, Peterson et al. 2003). However, these barriers can still be breached if they are not spaced correctly or if the deer can reach the ground beneath the grate (Reed et al. 1974, Sebesta et al. 2003). Other tactile designs, such as the “slippery fence” design, also serve as effective barriers (Gallagher et al. 2005), but are not feasible for extensive use along roadways. Rip-rap (e.g., varying sized rock) has not been tested as a deer crossing barrier, although Austin and Garland (2001) and Cramer and Bissonette (2005) discuss how rip-rap was removed from wildlife underpasses and other passageways because it was prohibiting deer movement. Additionally, in 2004 a swath of rip-rap was used along the Christopher Creek Section of Arizona’s State Route 260 as an alternative to ungulate fencing, however the results were not reported (Dodd et al. 2005).

A deer with previous success at crossing a barrier is more likely to attempt to cross it again. Therefore, it is important to understand a deer’s perception of roadside barriers and characteristics of those that minimize crossing attempts. Animals make decisions by assessing external stimuli and determining the level of risk associated with their desired actions (Blumstein and Bouskila 1996). External stimuli for a deer might include access to food and water, escape from a predator, or actions of a conspecific, such as a rutting buck, a doe in estrus, or a calling fawn. Behavioral patterns also vary among individuals. For example, white-tailed, black-tailed (*O. h. columbianus*), and red deer male fawns are bolder than female fawns (Guinness et al. 1979, Jackson et al. 1972, and Taber and Dasmann 1954). It seems logical for deer with bold personalities to be more prone to attempt risky behavior, such as crossing roadside fences. Wilson et al. (1994) described the shyness-boldness continuum as an axis of behavioral variation in a species. Animals living in groups often synchronize their behaviors in order to benefit from a mutual, external stimulus (Dostálková and Špinka 2007). If the boldest deer perceived a fencing design was "high risk", this likely would minimize crossing attempts by other members of the group and limit positive reinforcement associated with successful attempts.

Most prior research has focused on the efficacy of fence ≥2.4-m on mitigating deer-vehicle collisions. Few studies have actually evaluated fence height, fencing materials that limit visibility, or alternate fence designs for roadway usage. Therefore, I evaluated woven-wire fencing 1.2 to 2.4-m, opaque wove-wire fencing 1.2 to 1.8-m, and an outrigger style of fence from both directions. I also evaluated the ability of a 6.1-m swath of Type III rip-rap as a method of slowing deer movement.

OBJECTIVES

I compiled a list of barrier designs based on previous studies that have shown potential at preventing deer crossings and may be applicable along roadways. I constructed test sections of each barrier design within outdoor research paddocks at the Whitehall Deer Research Facility at the University of Georgia to accomplish the following objectives:

1. Evaluate woven-wire fence heights including 1.2-m, 1.5-m, 2.1-m, and 2.4-m.
2. Evaluate woven-wire fence with a 100% opaque covering at heights including 1.2-m, 1.5-m and 1.8-m.

3. Evaluate 1.2-m woven-wire fence with a 50% opaque outrigger angled at 45° in the direction toward deer and away from deer.
4. Evaluate Type III rip-rap as a prohibitive tactile barrier
5. Examine actions and behaviors associated with crossing barriers.

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CHAPTER 2

BEHAVIORAL RESPONSES OF CAPTIVE DEER TO VISUAL AND PHYSICAL BARRIERS DESIGNED TO MINIMIZE DEER-VEHICLE COLLISIONS

ABSTRACT

We evaluated the efficacy of a variety of fencing designs for the prevention of deer crossing including woven-wire fencing (1.2-m, 1.5-m, 1.8-m, 2.1-m, and 2.4-m), opaque fencing (1.2-m, 1.5-m, and 1.8-m), and a 0.6-m outrigger fencing installed at a 45° angle above a 1.2-m wire fence (towards and away from the deer). We recorded attempted crossings and successful crossings of fence barriers by captive deer to access a known feed source. No deer crossed the 2.4-m high woven-wire fence, whereas all deer successfully crossed the 1.2-m woven-wire fence. We observed no differences in successful crossings between the woven-wire fence and the opaque fencing. Outrigger fencing was more effective when the outrigger was angled towards the deer than away from the deer. The outrigger fencing angled towards the deer and the 2.1-m woven-wire fence had similar efficacy. Because orientation of the outrigger fence influenced effectiveness, this design may be useful along roadways because it may act as a one-way crossing to enable deer to exit the roadway unlike the 2.4-m fence.

INTRODUCTION

The frequency of deer-vehicle collisions in the United States has increased over recent decades. Increasing populations of white-tailed deer (*Odocoileus virginanus*), particularly in suburban and exurban areas, combined with an expanding human population and increased vehicular traffic has increased the risk of deer-vehicle collisions. There are an estimated 1.5 million deer-vehicle collisions reported each year causing approximately 29,000 injuries, 150-

200 human deaths (Conover et al. 1995), and $1.1 billion in property damage (State Farm Insurance Company 2009). Although the number of vehicle crashes from all causes remained relatively constant from 1990-2004, the number of wildlife-vehicle collisions has increased approximately by 6,769 /year with deer-vehicle collisions constituting 77% (5,212/year) of these additional collisions (Huijser et al. 2007).

Various mitigation devices and strategies have been employed in efforts to reduce the frequency of deer-vehicle collisions, including animal detection systems, deer whistles, roadside reflectors, roadway signage, population reduction, underpasses, overpasses, and exclusion fences. Construction of exclusion fences likely is the most effective strategy for prohibiting deer access to roadways and reducing the risk of deer-vehicle collisions (Falk et al. 1978, Feldhamer et al. 1986, Clevenger et al. 2001). Fencing ≥2.4-m in height is typically regarded as effective for excluding deer, but to maximize effectiveness, a fence needs to be located on both sides of the road and of sufficient length to extend beyond the home ranges of deer in the high risk area. Deer that circumvent the ends of a fence might become trapped within the roadway, thereby increasing the risk of a deer vehicle collision (Conover 2002). Thus, fencing that is effective at excluding deer while simultaneously enabling deer to escape from a roadway would be advantageous.

Few studies have utilized deer perception to develop effective barriers. Gallagher et al. (2003) reported that a 1.7-m vertical fence composed of hanging burlap (i.e., 100% visual barrier) prevented deer from entering an enclosure, suggesting that shorter (<2.4-m), opaque barriers may be as effective at preventing deer crossings as a taller woven-wire fence. When excited, wild ungulates are more likely to respect solid barriers than woven-wire fences, and are unlikely to run into them (Grandin 2007). Jones and Longhurst (1958) reported deer were more likely to attempt to go under a fence or outrigger angled towards them than over them. They were successful at keeping deer out of an exclosure using outrigger fencing (i.e., 0.6-m vertical fence with a 1.8-m 25° outrigger and 1.2-m vertical fence with a 1.2-m 45° outrigger) and slanted fencing (i.e., 1.8-m fence at 49°). Therefore, opaque and outrigger fencing may be more effective than woven-wire fences, although experimental trials are lacking.

Our objective was to evaluate the potential for deer to cross various heights and designs of fence to find an effective, and cost-effective, roadside barrier to reduce the incidence of deer-vehicle collisions.

STUDY AREA

We conducted our study at the Daniel B. Warnell School of Forestry and Natural Resources' Whitehall Deer Research Facility at the University of Georgia, Athens, Georgia, USA. The Facility spans 2.4-ha bordered by a 3-m high woven-wire fence, and is composed of 5 outdoor paddocks (0.4-0.8-ha), 3 sorting pens (15 x 20-m), a barn containing 19 roofed stalls (3 x 6-m), and a rotunda with movable walls to direct deer movement. Outdoor paddocks used in this study had a dominant cover of pine (*Pinus* spp.) and oak (*Quercus* spp.) of various ages. Experiments were conducted in smaller pens (0.1-0.2-ha), called treatment areas, built within the outdoor paddocks.

METHODS

We selected 18 adult ($\geq$1.5-$\leq$8.5 years old), healthy, female deer based on their reactions when a person approached them. We censored deer that remained calm when approached in favor of those with evoked flight responses. In addition, only does that successfully jumped a 1.2-m woven-wire fence (positive control fence) were included in the experiment. This fence is typical of the Georgia Department of Transportation fencing along roadways and is generally regarded as not effective in preventing deer crossings. We divided the deer into six, two-deer groups and fitted one deer in each group with a highly visible collar to differentiate between the two.

We constructed three (0.1 to 0.2-ha) treatment areas within two outdoor paddocks. The perimeter of each area was constructed of 2.4-m woven-wire fencing covered with 100% opaque shade cloth to limit external disturbances to the deer. We bisected each treatment area with the experimental fence designs. We provided deer with water ad libitum and on both sides of the test fence, while food was only available on one side. In each treatment area, we installed a 2.4-m solid gate to allow deer to pass unimpeded during the habituation portion of each experiment. To eliminate any pen effect, we tested each exclusion fence design in each treatment area with all two-deer groups.

Our experimental fence designs included: 1) woven-wire fencing (Solidlock® Fixed-Knot) of various heights (1.2-m, 1.5-m, 1.8-m, 2.1-m, and 2.4-m) with a 5.1-cm strip of white polytape (LACME Electric Fencing Systems) attached along the top; 2) woven-wire fencing (1.2-m, 1.5-m, and 1.8-m) covered with a 100% opaque woven landscape fabric (DeWitt Ultra Web 3000 Groundcover); and 3) 1.2-m woven-wire fence with a 0.6-m 50% opaque plastic outrigger attached to the fence top and angled at 45°. When testing fencing heights we began our trials at a height of 1.2-m and increased fence height in subsequent trials by intervals of 0.3-m. We tested the outrigger fence with the outrigger facing either towards or away from the deer. Because we anticipated that experimental deer would learn to jump the fences, we included an additional three two-deer groups of naïve deer in a separate trial of the outrigger fence. For all trials, each two-deer group was rotated through each of the three treatment areas without any group encountering the same fence design twice. At the start of each new trial, groups were assigned randomly to each treatment area and then rotated through the remaining treatment areas

To stimulate desire to cross the barriers, we limited feed (Meadow's Edge Deer Feed, Meadow's Edge, Millen, GA and Omolene 300 Growth Horse Feed, Land O'Lakes Purina Mills, Gray Summit, MO) intake to 1.4-kg/deer/day. Before each trial, each two-deer group had 48 hours of unrestricted access throughout the treatment area via the gate. After the habituation period, deer were separated from their food by the experimental exclusion fence for 25 hours (i.e., treatment period), or until they jumped the fence. If a deer had not jumped the experimental fence within 24 hours, we applied light pressure to evoke a flight response, further encouraging it to attempt a crossing. Initial pressure was the presence of a human at the back of the test pen. Increasing levels of pressure included adding clapping and shouting and walking while clapping and shouting. We discontinued pressure once both deer had attempted to jump the experimental fence (successfully or unsuccessfully), it was apparent that the deer would not attempt, or 15 minutes had passed since the researcher entered the pen. Following the trials, deer were moved into barn stalls and had access to water ad libitum and an increased supply of food (1.6-kg/deer/day).

During the 25-hr trials we monitored the deer continuously with an infrared day/night camera (Model No. PC1771R-6; Supercircuits Inc., Austin, TX) recording to an ARCHOS 504 Digital Media Player (160 GB) with a digital video recorder station (Archos Inc., Greenwood Village, CO) housed in a waterproof container. Digital video files were stored on hard drives and transferred to computers for review. Videos were reviewed using Videolan-VLC media player 0.8.6 (videolan.org). We characterized and quantified deer behavior in relation to the experimental exclusion fence, defining crossing behaviors as Rearing 1, Rearing 2, Failed

Attempts, and Crosses. Rearing 1 was recorded when a deer faced towards the fence and lifted one foreleg towards the fence. Rearing 2 was recorded when a deer faced towards the fence and reared up on both hind legs. A failed attempt was recorded when all four feet left the ground but the fence was not breached successfully. We recorded time and duration for each crossing attempt. Once a deer successfully crossed the fence its actions were no longer recorded. The first half hour and last half hour were separated from the remainder of the food restriction period as this was the time that was more likely to have been influenced by human interaction, either by shutting the gate or through the light pressure applied at the end of the trials. We compared the mean number of attempts per hour by the motivational period in which they occurred (i.e., gate shutting, food restriction, and light pressure). Deer that had successfully crossed during one motivational period were excluded from analysis in the subsequent motivational periods. The percentage of deer that crossed during each motivational period for each fence type was found by combining all treatment periods into a single 75-hr period. Deer with multiple crossings had only their first crossing, and the motivational period it occurred in, used in the analysis.

We used statistical package R v. 2.9.2 (The R Foundation for Statistical Computing 2009) to analyze our data. We used orthogonal contrasts, though our groups were not independent of each other, to compare the relative efficacy of each fence design and height to a 1.2-m woven-wire fence, and to rank efficacies of the various experimental exclusion fences. A binomial logistic regression model was used to determine the probability of fence effectiveness in an odds ratio using the efficacy of 1.2-m woven-wire fence as a baseline as it was the least effective fence design. An odds ratio reports the probability of the likelihood of an occurrence compared to the likelihood of another occurrence. Naïve deer were not included in the orthogonal contrasts or binomial logistic regression. All animal use and handling procedures were approved by the

Institutional Animal Care and Use Committee of the University of Georgia (AUP# A2007-10127-0).

RESULTS

From 21 January 2008 through 14 November 2008 we recorded 1,210 actions directed at attempting or successfully crossing experimental exclusion fencing during 233 observation periods of 25 hours each. The rates of Rearing 1 and Rearing 2 attempts decreased as height of the woven-wire fence increased (Figure 2.1). The rates of Failed Attempts increased as fence height increased and the percentage of crossings decreased (Table 2.1). Successful crossings occurred most often during the gate shutting and light pressure periods. The number of deer that crossed decreased at each height from 1.8 to 2.4-m. As the height of the woven-wire fence increased the percentage of crossings during food restriction decreased and most crossings occurred during the period of light pressure. The 1.5-m and 1.8-m woven-wire fences had similar efficacy ($P = 0.226$; Table 2.2). The 2.4-m woven-wire fence had significantly higher efficacy compared to other heights of woven-wire fences (1.2-m: $P = <0.001$; 1.5-m: $P = <0.001$; 1.8-m: $P = <0.001$; 2.1-m: $P = 0.006$). We removed two deer after the 2.4-m experiment, one from injury and one from becoming habituated to the researchers. The remaining two deer from the dismantled groups were then paired together. As expected, the odds ratio from the binomial logistic regression reported the 2.4-m woven-wire fence had the lowest probability to be crossed (Figure 2.4).

Opaque fencing had more uniform distribution of crossings through the motivational periods than the woven-wire fencing (Figure 2.2). Attempts during the food restriction period decreased as fence heights increased while attempts occurring during the gate shutting and light pressure periods increased. Efficacy between opaque fences and woven wire fences of the same height were not different (1.2-m: *P* = 0.23; 1.5-m: *P* = 0.498; 1.8-m: *P* = 0.766). The 1.5-m opaque fencing had similar efficacy as 1.2-m woven-wire fence as well (*P* = 0.072). Percentages of deer that successfully crossed the opaque fences were equal (90%).

During the experiments with the outrigger angled toward the deer Rearing 1 and Rearing 2 attempts were similar in all motivational periods however the rate of Failed Attempts was significantly higher (Figure 2.3). The outrigger angled away from the deer had fewer interactions than when the outrigger was angled toward the deer. Outrigger fencing angled towards the deer had higher efficacy than the outrigger fencing angled away from the deer (*P* = 0.012). Efficacy of a 2.1-m woven-wire fence and an outrigger fence angled towards the deer were not different (*P* = 0.46). The odds ratio reported the 2.1-m woven-wire fence and the outrigger fence angled towards the deer had similar probabilities of not being crossed.

Naïve deer had lower rates of activity than trained deer in all motivational periods during the outrigger experiments. When including the naïve deer groups (*n* = 3 for a total *n* = 8) in the contrast between the directions the outrigger angled, the outrigger angled towards the deer was still more effective than the outrigger angled away from the deer (*P* = 0.014). When contrasting successful crossings of naïve and trained deer, trained deer were more likely to cross the outrigger fences in both directions (*P* = 0.02). Combined percentage of trained and naïve deer that crossed the outrigger fence angled towards the deer (36%) were similar to the percentage of trained deer that crossed the 2.1-m woven-wire fence (41%). Each motivational period during the experiments with the outrigger angled away from the deer had similar percentages of deer crossings when trained and naïve deer were combined. Most of the crossings that occurred during the experiments with the outrigger angled towards the deer occurred with light pressure.

DISCUSSION

In our study, no deer crossed a 2.4-m woven-wire fence. Presumably, trained deer would be the most apt to cross woven-wire fences, although from the height of 1.8-m and higher there were significantly fewer crosses at each increasing height. Sauer (1984) reported white-tailed deer could jump a 2.1-m fence from a standing start and could jump a 2.4-m fence from a running start. In contradiction, Fitzwater (1972) indicates that a 2.4-m fence is sufficient to prevent deer from jumping. Ludwig and Bremicker (1981) concluded that 2.4-m fencing was effective at keeping deer out of roadways as long as the length of the fence is extended well beyond the high-risk area for deer-vehicle collisions.

Opaque fencing had similar efficacy as woven-wire of the same height. Similarly, the number of attempts and/or crossings decreased as fence height increased for opaque fencing. However, the percentage of deer that crossed the opaque fences remained the same at each height. Crossing attempts by deer for the opaque fencing may have been influenced by the deer having prior knowledge of the other side of the fence; however, Gallagher et al. (2003) reported that free-ranging deer did not cross a 1.7-m high burlap fence to access a corn feeder, even though the deer had gained access to the feeder at lower heights by jumping the fence. Deer in our opaque fencing study successfully crossed more often under human motivation during the gate shutting and light pressure periods. Increased motivation levels in our captive deer compared to free-ranging deer may responsible for the differing crossing rates between our study and Gallagher et al. (2003).

In our study, deer had prior experience on the other side of the opaque fence. Solid barriers are used in deer handling facilities to prevent deer from colliding with fencing by visually emphasizing the fences (Matthews 2007). How deer will react to a solid barrier fence without prior experience to the other side of the fence is unknown. In a roadway situation, solid fencing may prove more effective at restricting access to roadways by naïve deer, although experimental evaluation is necessary.

Because deer often attempt to go through fencing rather than over it (Jones and Longhurst 1958), we evaluated leaving the lower section of fencing uncovered and using a 50% opaque material as an outrigger. We hypothesized that when deer confronted the fence, they would see the outrigger above them and therefore not attempt to jump. Similarly, we assumed a deer encountering the outrigger facing in the opposite direction would perceive it as little more than a 1.5-m fence. Our observations indicated that the outrigger fencing had similar effectiveness as a 2.1-m woven-wire fence, even though the vertical portion of the outrigger fence was only 1.2-m. Three deer that did not cross the fence when angled towards them did cross when the outrigger angled away from them. In our trials using naïve deer, none crossed the outrigger fence when angled toward the deer, and only one crossed in the opposite direction. As such, outrigger fencing may have potential application along roadways. Because deer were more likely to cross when outriggers were angled away from the animal, if a deer became caught on the roadway between fences, it may be more likely to escape over an outrigger fence as opposed to a 2.4-m fence. In areas where lower heights of fencing are already in place, outriggers could be retrofitted to existing fence.

Jumping ability could be considered a learned skill through both the acts of doing (i.e., learning) and watching the actions of others (i.e., observational modeling). Our deer were tested in pairs to allow for any group dynamic when crossing a barrier. The responses of the herd are often influenced of the behavior of the lead animal (Matthews 2007); however, in our study, there were no differences in the efficacy of barriers when considering whether one deer or both deer crossed the barrier.

Experiments evaluating the effectiveness of fences in prohibiting white-tailed deer access often do not consider the behaviors and motivation of the deer. Studies have been conducted which examined the effectiveness of a fence by evaluating reduction in crop damage (Jones and Longhurst 1958) or the decrease in the number of carcasses along a roadway (Ludwig and Bremicker 1981) rather than the actual deterring ability of the fence. If the motivational factor to cross a barrier is not sufficiently strong, then a deer may select an alternate resource. Although this might indicate a fence was effective, it does not mean that a deer could not successfully cross it given the proper motivation. We attempted to pressure our deer to cross while also avoiding injury to themselves or us in the process. Most successful crossings occurred when the deer were influenced by human activity and not during the 24-hr food restriction period.

Deer often panic when confronted by stressful circumstances that which may hinder their ability to assess a situation. Deer in our study appeared to remain calm throughout the food restriction period; however, during any interaction with humans (i.e., gate shutting or light pressure) they became alert. When excited, deer may not react to a fence the same way as if they approached it without being stressed. Wilson et al. (1994) describes a shy-bold continuum as it relates to optimal risk-taking strategies. Therefore, deer on the boldness side of the continuum may be able to breach a fence without being pressured, whereas deer on the shyness side may need to be pressured to elicit a flight response in order for them to cross.

MANAGEMENT IMPLICATIONS

We concluded that the 2.4-m woven-wire fence may be the best choice for prohibiting deer access to roadways, but could trap deer that circumvent the ends of the fence and is likely the most expensive to build. Depending on how frequent deer-vehicle collisions occur on a particular roadway, it may be as cost-effective to construct a 2.1-m woven-wire fence or outrigger fence. Outriggers allow movement in one direction reducing risk of trapped deer and could be retrofitted to existing fencing 1.2-m and higher to enhance efficacy. Further experiments should be conducted to assess the application of these fence designs under field conditions with free-ranging deer.

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Figure 2.1. Mean (+/- SE) attempts per hour prior to a successful crossing by captive white-tailed deer in experiments comparing various heights of woven-wire fencing: (a) 1.5-m fence, (b) 1.8-m fence, (c) 2.1-m fence, and (d) 2.4-m fence. Note: The y-axis has a maximum of 2.2-attempts/deer/hr.

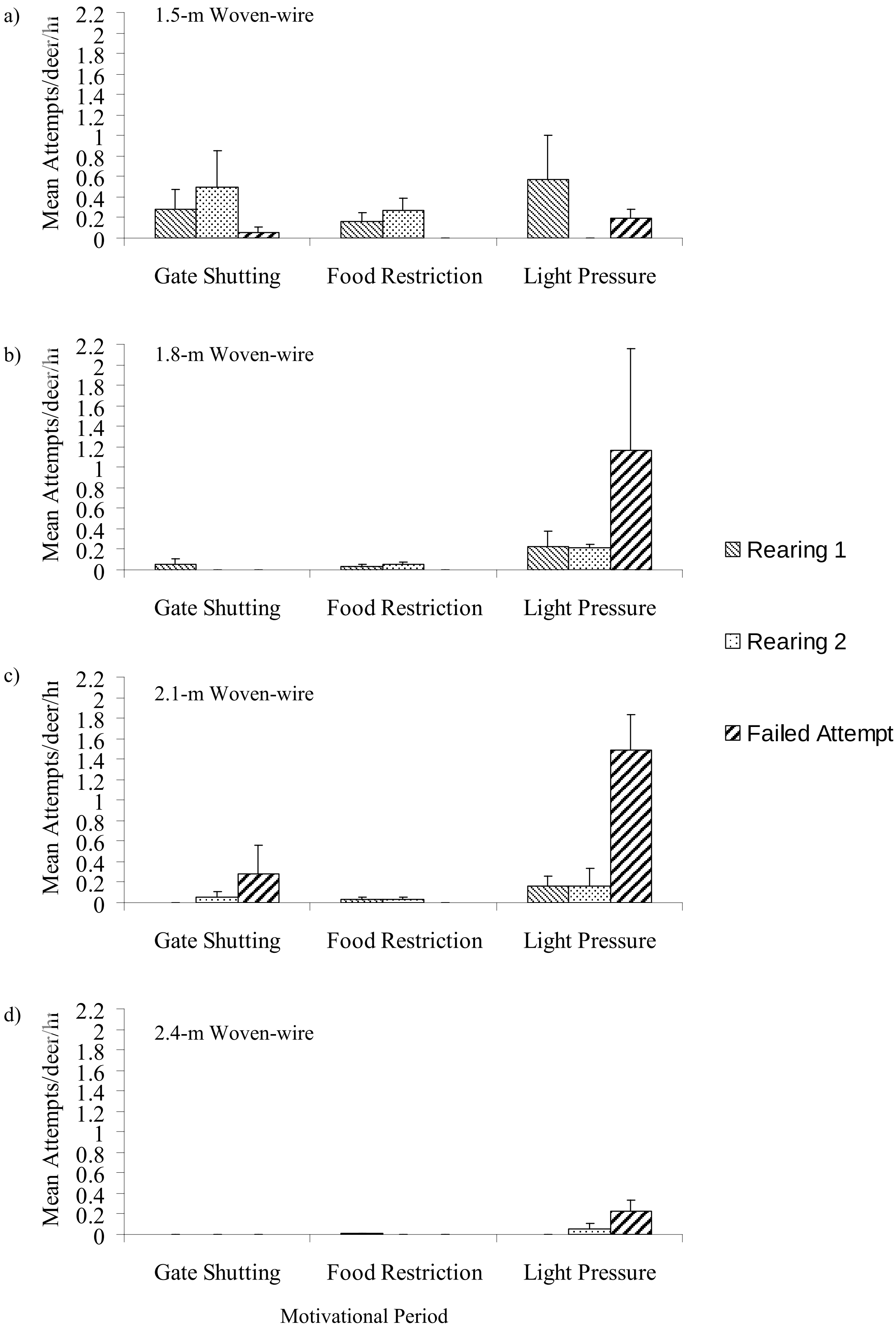

a)
1.5-m Woven-wire
b)
1.8-m Woven-wire
c)
2.1-m Woven-wire
d)
2.4-m Woven-wire
Mean Attempts/deer/hr
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Gate Shutting
Food Restriction
Light Pressure
Motivational Period
▧ Rearing 1
⬚ Rearing 2
▨ Failed Attempt

Figure 2.2. Mean (+/- SE) attempts per hour prior to a successful crossing by captive white-tailed deer in experiments comparing various heights of opaque fencing experiments: (a) opaque 1.2-m, (b) opaque 1.5-m, and (c) opaque 1.8-m. Note: The y-axis has a maximum of 0.8-attempts/deer/hr.

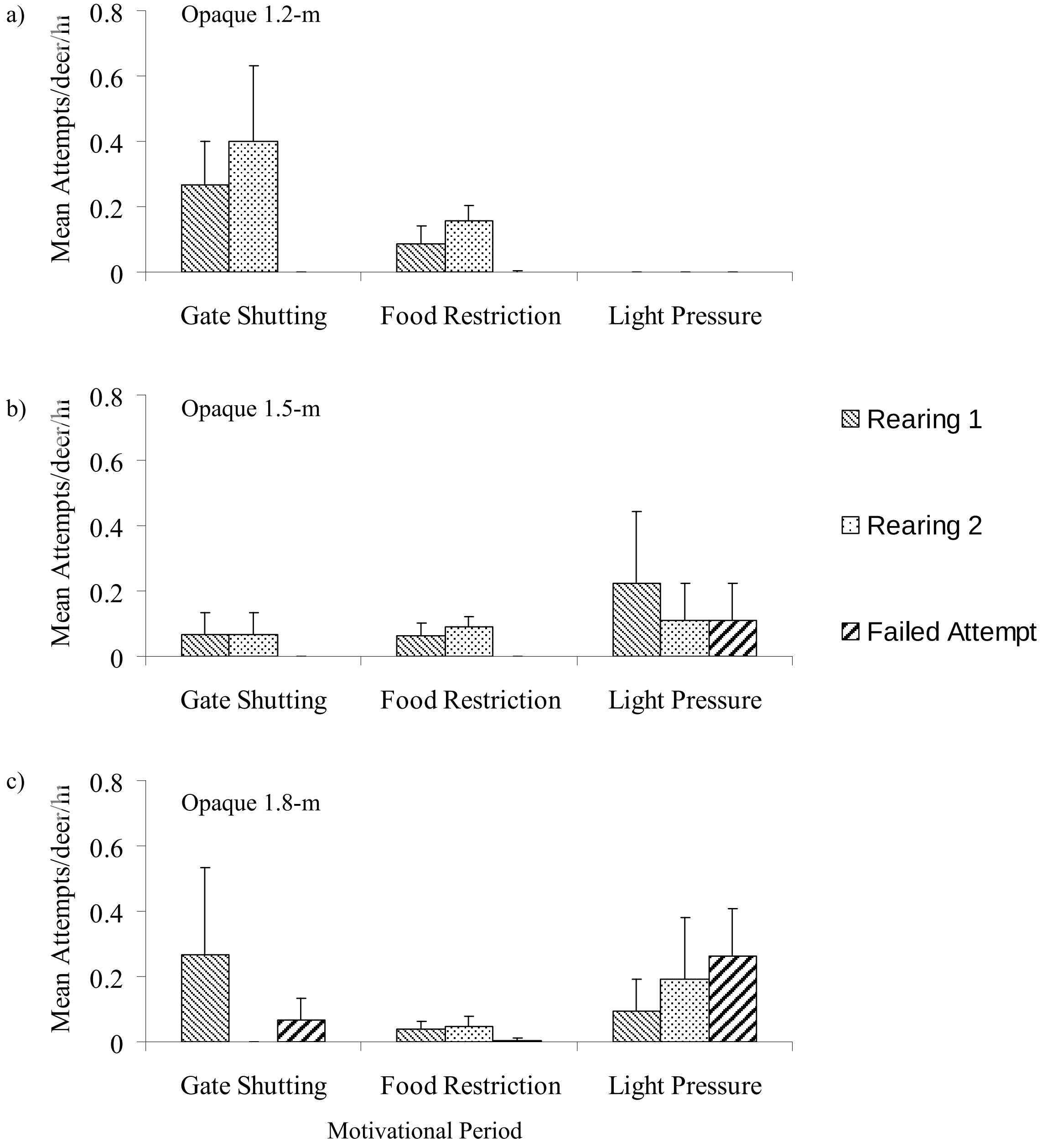

a)
Opaque 1.2-m
b)
Opaque 1.5-m
c)
Opaque 1.8-m
Mean Attempts/deer/hr
0.8
0.6
0.4
0.2
0
Gate Shutting
Food Restriction
Light Pressure
Motivational Period
▧ Rearing 1
⬚ Rearing 2
▨ Failed Attempt

Figure 2.3. Mean (+/- SE) attempts per hour prior to a successful crossing by captive white-tailed deer in outrigger fencing experiments: (a) outrigger angled towards trained deer, (b) outrigger angled towards naïve deer, (c) outrigger angled away from trained deer, and (d) outrigger angled away from naïve deer. Note: The y-axis has a maximum of 0.8-attempts/deer/hr.

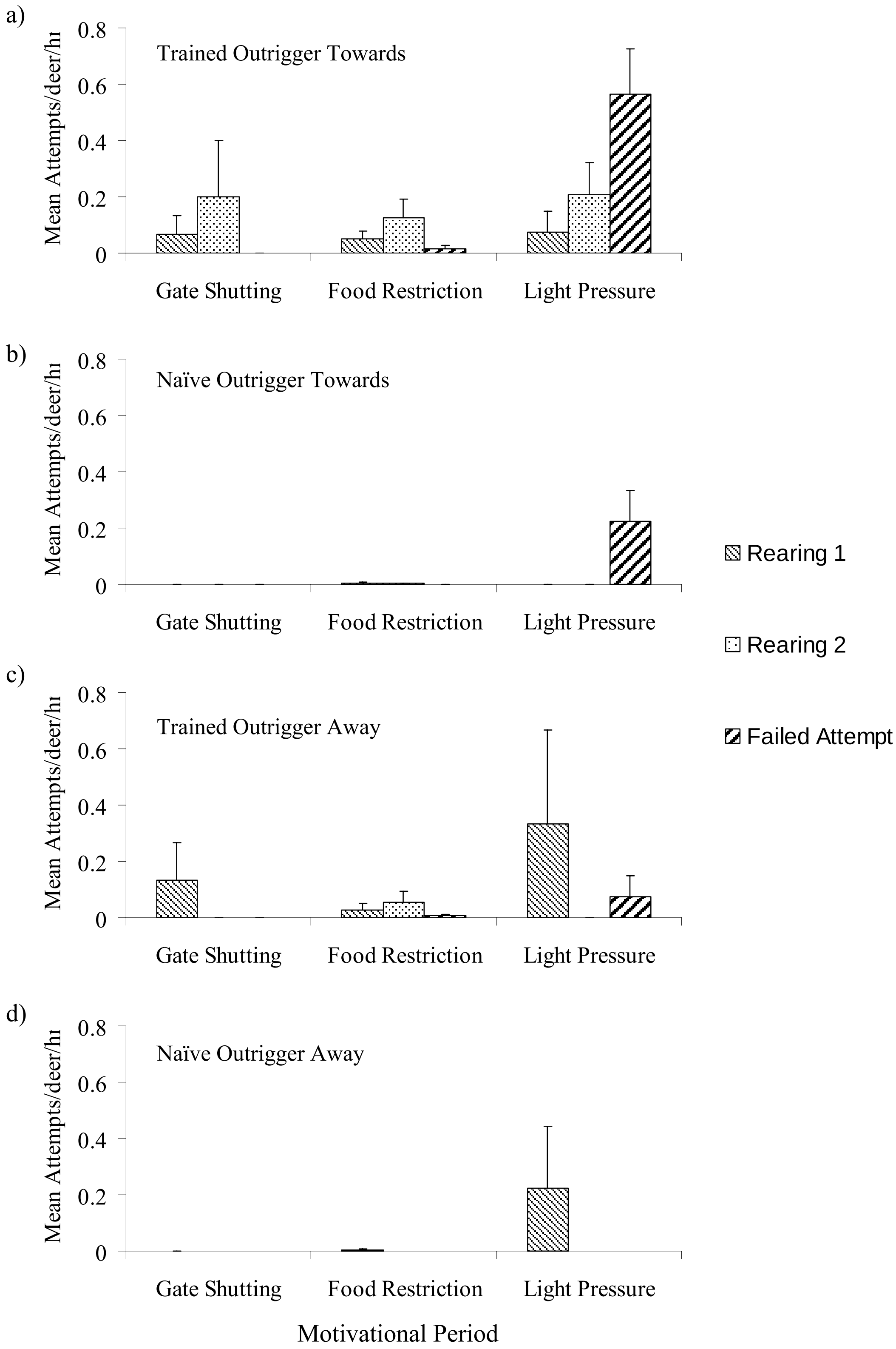

a)
Trained Outrigger Towards
b)
Naïve Outrigger Towards
c)
Trained Outrigger Away
d)
Naïve Outrigger Away
Mean Attempts/deer/h
0
0.2
0.4
0.6
0.8
Gate Shutting
Food Restriction
Light Pressure
Motivational Period
▧ Rearing 1
⬚ Rearing 2
▨ Failed Attempt

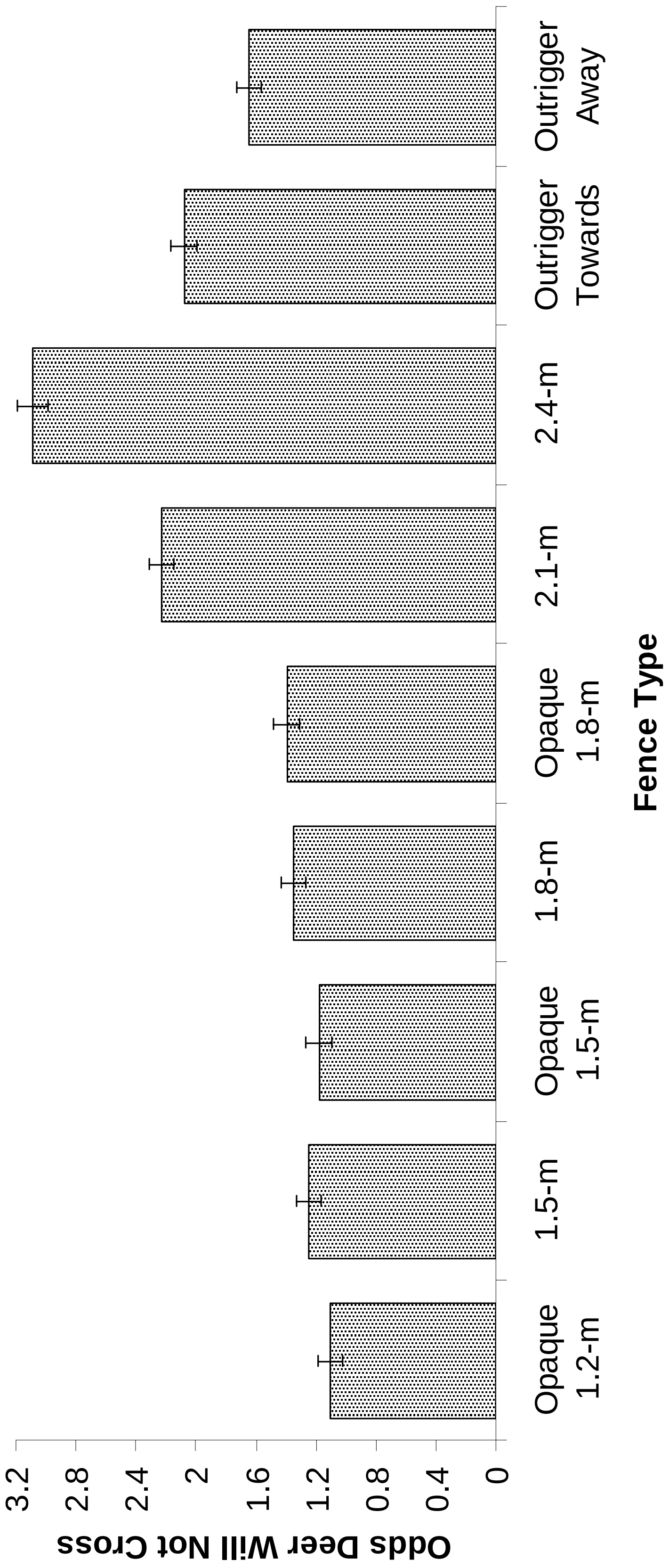
Table 2.1. Percentage of captive white-tailed deer that successfully crossed, by motivational period, in all fencing experiments when treatment periods for each fence type were combined into single 75-hr periods.

Fence Type	***n***	**Percentage Crossed**			
		Gate Shutting	**Food Restriction**	**Light Pressure**	**Total**
1.2-m	12	33	50	17	100
1.5-m	12	25	25	42	92
1.8-m	12	25	8	42	75
2.1-m	12	8	0	33	41
2.4-m	12	0	0	0	0
Opaque 1.2-m	10	40	30	20	90
Opaque 1.5-m	10	20	50	20	90
Opaque 1.8-m	10	30	20	40	90
Trained Outrigger Towards	10	0	10	50	60
Trained Outrigger Away	10	30	30	20	80
Naïve Outrigger Towards	6	0	0	0	0
Naïve Outrigger Away	6	0	0	17	17
Combined Outrigger Towards	16	0	6	31	37
Combined Outrigger Away	16	19	19	19	57

Table 2.2. Contingency table of orthogonal contrast p-values for comparing the effectiveness of two types of fence at prohibiting captive white-tailed deer crossings. The 1.2-m fence was used as a control and compared across all fence types.

	1.2-m	**Opaque 1.2-m**	**1.5-m**	**Opaque 1.5-m**	**1.8-m**	**Opaque 1.8-m**	**2.1-m**	**2.4-m**	**Outrigger Towards**	**Outrigger Away**
1.2-m		0.23	0.006	0.072	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Opaque 1.2-m	0.23			0.442		0.008				
1.5-m	0.006			0.498	0.266		<0.001	<0.001		
Opaque 1.5-m	0.072	0.442	0.498			0.046				
1.8-m	<0.001		0.266			0.766	<0.001	<0.001		
Opaque 1.8-m	<0.001	0.008		0.046	0.766					
2.1-m	<0.001		<0.001		<0.001			0.006	0.46	
2.4-m	<0.001		<0.001		<0.001		0.006			
Outrigger Towards	<0.001						0.46			0.012
Outrigger Away	<0.001								0.012	

Figure 2.4. Odds ratio for the likelihood of captive white-tailed deer not crossing a fence type when compared to the likelihood of not crossing a 1.2-m woven-wire fence.


Odds Deer Will Not Cross
0
0.4
0.8
1.2
1.6
2
2.4
2.8
3.2
Opaque 1.2-m
1.5-m
Opaque 1.5-m
1.8-m
Opaque 1.8-m
2.1-m
2.4-m
Outrigger Towards
Outrigger Away
Fence Type

CHAPTER 3

SUMMARY AND CONCLUSIONS

As the number of deer-vehicle collisions continually increases across the country, state and federal transportation departments look for ways of effectively keeping deer out of roadways. Existing strategies, such as deer visual and auditory deterrents, have been shown to be ineffective as have attempts to alter motorist behavior through roadway signage. Many states have begun incorporating fencing along roadways as a barrier to exclude deer from roads. Height of these fences varies by location and year of construction. Therefore, we evaluated the ability of untamed, captive deer to cross fences of various heights and evaluated design modifications that could be retrofitted to preexisting fences.

From the University of Georgia captive deer herd, we selected adult females (i.e., does ≥1.5 years-old) that appeared to be the least habituated to humans and most likely to act like wild deer. These deer were placed into two-deer groups and then subjected to a series of fencing trials. We first tested their interactions with a 1.2-m woven-wire fence and increased fence heights by 0.3-m increments for each subsequent trial to a maximum of 2.4-m. A trial was completed, and fence height was raised, when each two-deer group had interacted with that particular fence height in each of three treatment areas. Frequency of woven-wire fence crossing by deer decreased as fence height increased. No deer successfully crossed a 2.4-m woven-wire fence.

After the woven-wire fence trials were concluded, we tested efficacy of woven-wire fences retrofitted with an opaque covering. We began these trials with 1.2-m fences and increased the height of fences by 0.3-m increments to a maximum of 1.8-m. There was no decrease in successful crossings when we added the opaque covering to fences.

After the opaque fence trials were concluded, we tested the efficacy of 1.2-m woven-wire fences retrofitted with a 50% opaque, 0.6-m wide, 45° outrigger fence. This outrigger fence was attached to the top strand of each woven-wire fence and secured to each support post. We tested the ability of deer to cross these fences with the outrigger fence facing towards them and away from them. When outrigger fences faced away from the deer, frequency of successful crossings was greater ($P = 0.012$) We then included naïve deer in the experiment to determine if fence-crossing experiences during previous trials influenced a deer's ability to cross a 1.2-m fence with the outrigger modification. In these trials, none (0 of 6) of the naïve deer crossed the fence when the outrigger fence faced towards them. Only one naïve deer crossed the fence when the outrigger fence faced away from them.

In our experiments, no deer crossed the 2.4-m woven-wire fence. The woven-wire fences with opaque coverings had similar efficacy as the same height woven-wire fence without the covering (1.2-m: $P = 0.2$, 1.5-m: $P = 0.5$, 1.8-m: $P = 0.8$). We believed the opaque covering provided deer with a better visual reference, and enhanced their ability to cross. The 2.1-m woven-wire fence and the 1.2-m woven-wire fence with an outrigger fence facing towards the deer had similar efficacy ($P = 0.46$). It may be beneficial to retrofit existing 1.2-m roadway exclusion fences with a top-mounted outrigger fence facing away from the road. This design would decrease successful crossings into the road, and allow deer trapped between two exclusion fences to escape, without the added cost of building earthen ramps or one-way gates. Field trials of the outrigger-style fence should be tested along segments of roadways to evaluate its effectiveness in a real world application before being considered further.

APPENDIX A

EFFICACY OF TACTILE BARRIER AT PROHIBITING DEER MOVEMENT

INTRODUCTION

White-tailed deer (*Odocoileus virginianus*)-vehicle collisions present a significant hazard to motorists in the United States. Dense deer populations, coupled with a growing human population and concurrent expansion of the nation's roadway system have increased the risk of deer-vehicle collisions. Recently published statistical accounts reported 1.5 million deer-vehicle collisions each year, causing approximately 29,000 injuries, 150-200 human deaths, $1.1 billion in property damage, and the deaths of 92% of involved deer (Allen and McCullough 1976, Conover et al. 1995, State Farm Insurance Company 2009). Although the total number of all vehicle crashes throughout the United States has remained relatively unchanged since 1990, the proportion of wildlife vehicle collisions has increased steadily by 6,769 each year with deer-vehicle collisions constituting 77% (5,212/yr) of the collisions with wildlife (Huijser et al. 2007).

Barriers that attempt to exploit "weaknesses" in the hoof function of the white-tailed deer, hereafter called tactile barriers, have shown promise in preventing crossings. Cattle guards and other grates of varying materials and patterns have been used in urban areas to successfully prohibit deer access by creating a surface that is uncomfortable under the hoof (Belant et al. 1998, Peterson et al. 2003, Sebesta et al. 2003). However, cattle guards can be breached if they are not spaced correctly or if the animal's hooves can reach the ground beneath the grate (Reed et al., 1974, Sebesta et al. 2003). Other tactile designs, such as the "slippery fence" design, which uses lubricated sheets of metal angled at 10°, also serve as effective tactile barriers by reducing friction under the hoof of the animal, hindering crossing (Gallagher et al. 2005). Although long expanses of cattle guards and the "slippery fence" are likely infeasible, alternative tactile barriers such as rip-rap (i.e., large pieces of crushed rock) have not been evaluated for effectiveness.

Rip-rap has not been tested specifically as a tactile barrier for deer crossings, although Austin and Garland (2001) and Cramer and Bissonette (2006) discussed how rip-rap was removed from wildlife underpasses and other passageways because it prohibited deer movement. Additionally, in 2004 a swath of rip-rap was used along the Christopher Creek Section of Arizona's State Route 260 as an alternative to ungulate fencing (Dodd et al. 2005). Our objective was to evaluate the effectiveness of rip-rap as a tactile barrier to prohibit movement by captive white-tailed deer.

STUDY AREA

We conducted our study at the Daniel B. Warnell School of Forestry and Natural Resources, Whitehall Deer Research Facility at the University of Georgia, Athens, Georgia, USA. This facility spans 2.4-ha and is bordered by 3-m high, woven-wire fence. The facility has 5 outdoor paddocks (0.4-0.8 ha), 3 sorting pens (15 x20-m), a barn containing of 19 roofed stalls (3 x 6 m), and a rotunda with movable walls to direct deer movement. The outdoor paddock used in this study was dominated by grasses (*Festuca arundinacea* and *Cynodon dactylon*). Experiments were conducted in a smaller pen (0.2 ha) built within the paddock.

METHODS

Animal use and handling procedures were approved by the Institutional Animal Care and Use Committees of the University of Georgia (AUP# A2007-10127-0) at the Whitehall Deer Research Facility. We selected 10 adult females (≥1.5 year-old does) based on their reaction to human interaction, age, and physical condition. We selected does to eliminate extraneous variables, such as the effects of rut, and to ease the process of moving deer between indoor stalls and outdoor paddocks. All deer were ear-tagged for identification and divided into five, two-deer groups, additionally one deer in each group was fitted with a highly visible rubber collar to distinguish individuals among groups. White-tailed deer are social animals, therefore it is important to account for group dynamics when assessing deer behavior around a tactile barrier. Hence, we used two-deer groups as opposed to individuals as it is more natural.

We constructed a treatment area (i.e., C1) within one of the paddocks. The treatment area was bisected by a 6.1-m swath of a single layer of Type III rip-rap. The treatment area was surrounded by 2.4-m, woven-wire fence covered with 100% opaque shade cloth to limit external disturbances to the deer. Water was available at all times on both sides of the tactile barrier within each treatment area, while food was only available on one side. A gate was constructed to allow deer to pass unimpeded during the habituation period. An equal parts mix of Meadow's Edge Deer Feed (Meadow's Edge, Millen, GA) and Omolene #300 Growth Horse Feed (Land O'Lakes Purina Mills, Gray Summit, MO) was used as the food incentive. Food was rationed to 1.4 kg/deer in the treatment areas to increase motivation, via hunger, to access food during the treatment period.

During each behavioral trial, a two-deer group spent 48 hours in the treatment area with access to both sides of the tactile barrier, via a gate, to become habituated to the pen layout (i.e., habituation period). After 48 hours, the deer were excluded from the side of the treatment area containing food and were required to breach the tactile barrier to access their food (i.e., treatment period). This food restriction lasted for approximately 24 hours. At the end of each 24-hour treatment period, we applied "light pressure" to encourage the deer to breach the tactile barrier if it appeared they had not already crossed. We standardized the characteristics of "light pressure" by progressing through three levels of human activity, applied by the same researchers, each time. If deer did not attempt to cross the tactile barrier during Level 1 pressure, we proceeded to Level 2 pressure, and so on. Level 1 pressure involved a researcher standing at the back of the treatment area with the deer that had not crossed. During Level 2, the researcher remained standing and began antagonizing the deer with noise (i.e., clapping and shouting). If Level 3 was necessary, the researcher moved about the pen while continually making antagonistic noise. We discontinued all "pressure" once both deer had attempted to breach the tactile barrier (i.e., attempt to cross and fail or successfully crossed), it was apparent that the deer would not attempt, or 15 minutes had passed since the researcher had entered the pen. If deer had not successfully crossed the tactile barrier after Level 3 pressure, we considered the tactile barrier effective during that individual trial. The deer groups were moved into barn stalls following the treatment period and had access to water ad libitum and an increased ration of food (1.6 kg/deer).

The two-deer groups were monitored continuously throughout the 72-hour experimental period with an infrared day/night camera (Model No. PC1771R-6; Supercircuits Inc., Austin, TX) recording to an ARCHOS 504 Digital Media Player (160 GB) with a digital video recorder station (Archos Inc., Greenwood Village, CO) housed in a waterproof container. We stored the digital video files on hard drives and transferred to computers for review. Videos were reviewed using Videolan-VLC media player 0.8.6 (videolan.org).

RESULTS AND DISCUSSION

During November-December 2008 we conducted tactile barrier experiments with five 2-deer groups. A single layer of Type III rip-rap substrate did not appear to inhibit white-tailed deer crossings. All deer successfully crossed the tactile barrier with little or no hesitation. Some deer attempted to leap across the gap but were unsuccessful. Deer were able to continue moving across the substrate without faltering after landing.

Although, there have been studies that have referenced the use of rip-rap to direct the movement of deer to a certain location or removal of rip-rap to provide access to deer, none have actually evaluated the effectiveness of rip-rap as a tactile barrier (Austin and Garland 2001, Dodd et al. 2005, and Cramer and Bissonette 2006). The most common and prohibitive type of tactile barriers have gaps large enough for the legs of deer to slip through and are deep enough so they cannot make contact with the ground beneath. Mule deer (*O. hemionus*) reportedly crossed narrow, flat, metal cattle guards by catching their dew claws on the guard to keep from falling through (Reed et al. 1974). If mule deer can cross such obstacles, then white-tailed deer might also. Peterson et al. (2003) discovered that a rectangular grid pattern with the rectangle diagonally dissected by a cross member was the most successful grate for prohibiting Florida Key deer (*O. v. clavium*) access to a corn feeder when compared to two different rectangle grid patterns. If rip-rap mimicked the visual and tactile complexity of the above grate pattern, then we expected it to minimize deer crossings.

Over time, rip-rap settles, collects organic and inorganic debris, and plants become established between the rocks. Multiple layers of rip-rap may be needed to effectively minimize deer crossing attempts, but frequent maintenance of the rip-rap would be necessary. In our experiment, plants grew among the rip-rap rocks within weeks of construction, requiring herbicide control. Without frequent maintenance, this would have created a flat mat of rock and grass and further reduced the unevenness and presumably the efficacy of this tactile barrier.

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David A. Osborn
Warnell School of Forestry and Natural Resources
University of Georgia
Athens, GA 30602
706-542-1378; fax: 706-542-8356; e-mail: Osborn@warnell.uga.edu

Comparison of fencing designs for excluding deer from roadways

Daniel W. Stull, Warnell School of Forestry and Natural Resources, University of Georgia, Athens, GA 30602, USA

William D. Gulsby, Warnell School of Forestry and Natural Resources, University of Georgia, Athens, GA 30602, USA

James A. Martin, Warnell School of Forestry and Natural Resources, University of Georgia, Athens, GA 30602, USA

Gino J. D'Angelo, Warnell School of Forestry and Natural Resources, University of Georgia, Athens, GA 30602, USA

George R. Gallagher, Department of Animal Science, Berry College, Mount Berry, GA 30149, USA

David A. Osborn, Warnell School of Forestry and Natural Resources, University of Georgia, Athens, GA 30602, USA *Osborn@warnell.uga.edu*

Robert J. Warren, Warnell School of Forestry and Natural Resources, University of Georgia, Athens, GA 30602, USA

Karl V. Miller, Warnell School of Forestry and Natural Resources, University of Georgia, Athens, GA 30602, USA

Abstract: We evaluated the efficacy of several fencing designs for restricting movements of 18 captive, female white-tailed deer; including standard woven-wire fencing (1.2-m, 1.5-m, 1.8-m, 2.1-m, and 2.4-m tall), opaque fencing (1.2-m, 1.5-m, and 1.8-m tall), and an outrigger fence (i.e., 0.6-m outriggers attached to a 1.2-m wire fence angled at 45°). We recorded the number of successful fence crossings for each deer and characterized behaviors associated with each failed crossing attempt. When considering woven-wire designs, no deer crossed the 2.4-m fence, whereas all deer crossed the 1.2-m fence. We observed no differences in crossing success between woven-wire and opaque fencing at heights ≤ 1.8 m. The outrigger fence was as effective as the 2.1-m fence when the outrigger was angled towards the deer. Efficacy decreased when the outrigger was angled away from the deer. Therefore, this fencing design may act as a 1-way barrier, discouraging deer from entering the roadway, but allowing them to exit it should they become trapped, unlike standard 2.4-m fencing.

Key words: deer-vehicle collision, fencing, *Odocoileus virginianus*, white-tailed deer

Increasing populations of white-tailed deer (*Odocoileus virginanus*), particularly in urban/suburban areas, combined with expanding human populations and increased vehicular traffic have increased the risk of deer-vehicle collisions (DVCs). For example, from 1990-2004, the number of wildlife-related collisions in the United States increased by 6,769 per year with DVCs accounting for 77% (5,212 per year) of the increase (Huijser et al. 2007). Each year, an estimated 1.5 million DVCs cause 29,000 human injuries, 150-200 human deaths (Conover et al. 1995), and $1.1 billion in personal property damage (State Farm Insurance Company 2009).

Various mitigation devices and strategies have been employed in efforts to reduce the frequency of DVCs including animal-detection systems, deer whistles, roadside reflectors, roadway signage, deer population reduction, underpasses, overpasses, and exclusion fences. Construction of exclusion fences likely is the most effective nonlethal strategy for prohibiting deer access to roadways and reducing the risk of DVCs (Falk et al. 1978, Feldhamer et al. 1986, Clevenger et al. 2001). Fencing ≥ 2.4-m in height, when erected on both sides of a roadway, typically excludes deer from the roadway (Knapp et al. 2004, Huijser et al. 2007). However, if roadside fencing does not extend beyond the home ranges of problem deer, they will likely circumvent the fence ends and become trapped within the roadway, thereby increasing the risk of DVC (Conover 2002, Gulsby 2010). To be most effective, exclusion fences must allow deer to escape when they become trapped between opposing fences.

Sauer (1984) reported that white-tailed deer could jump a 2.1-m fence from a standing start and a 2.4-m fence from a running start. In contrast, other researchers have reported that a 2.4-m fence was sufficient to prevent deer crossings (Fitzwater 1972, VerCauteren et al. 2010). Ludwig and Bremicker (1981) concluded that 2.4-m fencing was effective at keeping deer out of roadways, provided that the fence was extended well beyond high-risk areas. Alternately, Gallagher et al. (2003) reported that a 1.7-m tall visual barrier consisting of 100% opaque hanging burlap effectively excluded deer from a feeding station, suggesting that shorter opaque barriers may be as effective at excluding deer as taller woven-wire barriers. Additionally, it has been shown that solid barriers are more effective than woven-wire fencing when directing movements of excited, wild ungulates, with less risk of animal injury (Grandin 2007).

The lack of consensus among studies that have attempted to discern which fences excluded deer can likely be attributed to the variation in disposition of individual deer, even within the same subspecies and geographical area. Wilson et al. (1994) explained that it is difficult to predict how any individual within a population of animals will react in a given situation because risk-taking behavior is distributed along a shy-bold continuum. Therefore, bold deer might be sufficiently motivated to attempt a crossing when confronted with a low-level threat or food restriction. However, shy deer might not attempt to cross unless a flight response was evoked by a high-level threat, with the deer jumping only when panicked.

Our objective was to test various fence designs for their potential to exclude deer from roadways based on a deer's jumping ability and vision-based perception of barriers. We quantified deer behaviors in relation to exclusion fences and compared the efficacy of each fence design to that of standard 2.4-m woven-wire fencing**.** In addition, we conducted an *a posteriori* trial of 1 promising fence design to evaluate the effect of operant conditioning on the fence-crossing behavior of deer.

Study area

We conducted our study at the Warnell School of Forestry and Natural Resources' Whitehall Deer Research Facility at the University of Georgia, Athens, Georgia. The 2.6-ha facility is composed of 5 outdoor paddocks each 0.4 – 0.8 ha in size, 3 sorting pens (15 x 20 m), and an enclosed 19 stall (3 x 6-m) barn. The entire facility is surrounded by 2.4- to 3.0-m tall woven-wire fencing. We used 2 outdoor paddocks with a dominant cover of pine (*Pinus* spp.) and oak (*Quercus* spp.) of various ages. We constructed 3 (0.1 – 0.2-ha) treatment areas within these outdoor paddocks. Each treatment area was surrounded by 2.4-m woven-wire fencing covered with 100% opaque shade cloth to limit external disturbances to the test deer. For each trial, we bisected the treatment areas with the test fence.

Methods

We selected 12 adult (≥ 1.5 years old), non-pregnant, female white-tailed deer for the trials based on their general appearance of good physical health, display of evoked flight responses when approached by a person, and their willingness to jump a 1.2-m woven-wire fence (positive control fence). We believed the ability and motivation of each test deer to jump obstacles to obtain food or flee from a perceived threat was comparable to those of free-ranging deer. Our positive control fence was typical of that used by state transportation departments, including the Georgia Department of Transportation, to delineate the right-of-way along roadways.

We randomly assigned the deer into 6, 2-deer groups and fitted 1 deer in each group with a brightly colored collar that enabled us to differentiate each deer in digitally recorded videos. We removed 2 deer (1 from each of 2 groups) after the 2.4-m woven-wire fence trials, because 1 was injured and the other became habituated to researchers. The remaining 2 deer from these groups were then paired, resulting in 5, 2-deer groups. Although deer assigned to this experiment had no previous fence-jumping experience, we believed some learned to jump fences during our trials through operant conditioning. Therefore, we included 6 naïve deer (i.e., deer without fence-crossing experience) in 3, 2-deer groups in an *a posteriori* trial to test this possibility.

Our test fence designs included: woven-wire fencing (Solidlock®, Bekaert, Marietta, Ga.) of various heights (1.5-m, 1.8-m, 2.1-m, and 2.4-m tall); woven-wire fencing (1.2-m, 1.5-m, and 1.8-m tall) covered with a 100% opaque landscape fabric (DeWitt Ultra Web 3000 Groundcover, DeWitt, Sikeston, Mo.); and 1.2-m tall woven-wire fencing with a 0.6-m 50% opaque plastic outrigger attached to the top and angled at 45° (outrigger fence). We tested the outrigger fence with the outrigger angled both towards and away from the deer. We attached a 5.1-cm strip of white polytape (LACME Electric Fencing Systems, La Flèche, France) linearly along the top, as a visual reference for the deer.

We provided water ad libitum, on both sides of the test fence, in each treatment area. Food (Meadow's Edge Deer Feed, Meadow's Edge, Millen, Ga. and Omolene 300 Growth Horse

Feed, Land O'Lakes Purina Mills, Gray Summit, Mo.) was available only on 1 side of each test fence. During a 48-hr habituation period, which immediately preceded each trial, a 2.4-m solid wooden gate (pass-through gate) located at the end of each test fence remained open, allowing deer to move freely throughout the treatment area (i.e., both sides of the test fence). During this period, we limited food consumption to $\leq$ 1.4-kg per deer per day. Immediately after the habituation period, deer were restricted to the side of the treatment area with no food by closing the pass-through gate. To control for possible treatment area effects, we exposed each 2-deer group to each test fence design in each treatment area ($n = 3$).

We provided deer with 3 levels of motivation to encourage them to attempt a fence crossing, and recorded behaviors specific to each level. We believed the presence of a researcher in the treatment area during gate closing provided a low-level threat to the deer. Therefore, we defined the first 0.5 hr of each trial as the early-forced-choice period. During the subsequent 24 hr of the trial, we separated deer from their food by placing them on the opposite side of the test fence (i.e., food-restriction period). If a deer had not crossed the test fence during the food-restriction period, we attempted to evoke a flight response. During this late-forced-choice motivation period, an individual researcher quietly entered the treatment area and stood motionless. If each deer did not attempt a crossing, the researcher increased the threat level by clapping, shouting and walking toward it. The trial ended when each deer had attempted to cross the fence, or it was determined that it would not do so.

Following each 25-hr trial (early-forced-choice, food-restriction, and late-forced-choice periods, combined), deer were moved into barn stalls and supplied with water ad libitum and an increased supply of feed (1.6-kg per deer per day). All animal care and handling procedures were approved by the University of Georgia Institutional Animal Care and Use Committee (#A2007-10127-0).

Throughout each 25-hr trial, deer behaviors were continuously recorded by an infrared day/night camera (Model No. PC1771R-6, Supercircuits Inc., Austin, Tex.), attached to a DVR (ARCHOS 504 Digital Media Player) and a digital video recorder (Archos Inc., Greenwood Village, Colo.) housed in a waterproof container. Digital video files were stored on hard drives and transferred to computers for subsequent data retrieval. Videos were viewed using the Videolan-VLC media player 0.8.6 (www.videolan.org). We characterized and quantified deer behavior in relation to each test fence, defining behaviors as a crossing, failed attempt, or a fence interaction. We recorded a behavior as a crossing when a deer jumped completely over the test fence. We recorded a behavior as a failed attempt when all 4 of a deer's hooves left the ground, but it did not gain access to the other side. We recorded a behavior as a fence interaction when a deer raised 1 or both forelegs towards the test fence, exhibited a failed attempt, or exhibited a successful crossing. We recorded the time (i.e., elapsed time since gate closing) and duration of each observed behavior. For deer that crossed a test fence multiple times, we used only their first crossing in our data analysis. Deer that crossed during 1 motivation period were excluded from analysis in subsequent periods. For example, if a deer jumped the fence when the gate was closed, the trial ended for that deer-test fence-treatment area combination. We summed each deer's observed behaviors during each 25-hr trial across the 3 treatment areas (i.e., 75-hr of combined observation). Because each deer had 3 opportunities (i.e., 3 treatment areas) to jump a particular test fence design, the cumulative number of crossings could exceed the number of deer tested.

We modeled the probability of a deer jumping the fence types (fixed effects) during any motivation period using logistic regression with the lme4 package (www.cran.r-project.org/web/packages/lme4/) in the R statistical system (version 2.9.2; R Foundation for Statistical Computing, Vienna, Austria). We believed *a priori* that deer within common groups would not be independent samples, thus, we treated each deer group as a random effect in a multilevel model (Gelman and Hill 2006). This allowed us to report the least-biased parameter estimates and estimates of variance. Posterior parameter estimates, variances, and P values for the fixed effects (i.e., fence type) were generated using Markov chain Monte Carlo (MCMC) sampling in the languageR package (http://cran.r-project.org/web/packages/languageR). The fixed effect parameter estimates were transformed into odds ratios to aid in interpretation and are to be interpreted as a measure of effect size. We used cross validation to assess model prediction accuracy. We refit the logistic regression model to a training dataset and then compared it to the test dataset not used to fit the model. This error rate was utilized to determine how well the model fit the data and its predictive accuracy. Given the economic importance and human-life risk associated with DVCs, we believed *a priori* that a misclassification rate ≥ 25% was unacceptable.

Results

During 21 January–4 November, 2008, we recorded 1,210 observations of deer behaviors associated with the various test fence designs during 233, 25-hr trials. When compared to 12 (100%) deer that crossed the 1.2-m woven-wire control fence, fewer deer crossed each subsequently taller woven-wire fence [1.5-m = 11 (92%), 1.8-m = 9 (75%), 2.1-m = 5 (42%), and 2.4-m = 0 (0%)]. When pooled across treatment areas, number of fence interactions and successful crossings trended downward as height of woven-wire fences increased (Table 1).

Number of failed attempts trended upward as woven-wire fence height increased from 1.5 m to 2.1 m, then dropped when fence height was raised to 2.4 m. Most deer crossed the 1.5-m woven-wire fences during the early-forced-choice and food-restriction periods (Table 2). When height of woven-wire fence was raised to 1.8-m and 2.1-m, most deer crossed during the late-forced-choice period. The 2.4-m woven-wire fence prevented all deer from crossing.

Of deer in the opaque fence trails, 9 (90%) crossed the 1.2- and 1.5-m fences, and 5 (50%) crossed the 1.8-m fence. When considering opaque fences, number of fence interactions and crossings trended downward as fence height increased. Number of failed attempts was relatively low during all opaque fence trials, but relatively more deer failed when fence height reached 1.8 m (Table 1). Most deer crossed opaque fences during the early-forced-choice and food-restriction periods (Table 2).

Deer with previous experience crossing fences (in our trials) crossed the outrigger fence more when it was angled away from them (9, 90%) than towards them (6, 60%). However, deer interacted with fences less and failed to cross them less when the outriggers were angled away (Table 1). When outriggers were angled away, most crossings occurred during the early-forced-choice and food-restriction periods (Table 2). When outriggers were angled towards the deer, a majority of crossings occurred during the late-forced-choice period. In comparison, deer without previous experience crossing fences (i.e., naïve deer) rarely interacted with either outrigger fence design, or successfully crossed (Table 1). The only fence crossing by naïve deer (2, 33%) occurred when the outrigger was angled away, during the late-forced-choice period.

The logistic regression model predicted 83% (17% misclassification rate) of the fence crossings for the subsample of the dataset used to test model predictive accuracy (Table 3). This error rate fell within our *a priori* rate of acceptability. The fixed effects within the model indicated that the probability of an individual crossing a fence is affected by height and/or design (Fig. 1). Generally, as fence height increased, the odds ratios decreased. The 2.4-m fence had the lowest odds ratio (0.32), suggesting deer were 3.08 (1/0.324 = 3.08) times less likely to cross this fence than the 1.2-m fence. The 2.1-m fence was the second most effective and deer were 2.07 times less likely to cross it than the 1.2-m fence. Deer were 2.07 and 1.64 times less likely to cross the outrigger fence than the 1.2-m fence when angled towards versus away from them, respectively. Among the opaque fences, only the 1.8-m tall fence reduced the likelihood of a successful jump.

Discussion

Because of their effectiveness, fences have been used throughout history to alter wildlife movements and reduce wildlife-related damage (VerCauteren et al. 2006). However, efficacy, cost, and longevity of service vary considerably among fence designs. The efficacy of a particular fence is determined by a deer's physical abilities, motivation to cross, and the ability of that fence to modify deer behavior in response to operant conditioning (VerCauteren et al. 2006). Operant conditioning is the process of learning based on positive and negative reinforcement of behavior over time. To affect the road-crossing behavior of deer, the negative reinforcement associated with going over or under an exclusion fence must exceed the positive reinforcement associated with successfully crossing it. In addition, the level of negative reinforcement must be sustainable or fence efficacy will decline as deer change the balance between negative and positive reinforcement through learning and subsequent behavior modification. It is generally accepted that deer behavior in relation to exclusion fences is influenced by the consequences of their own actions and by observations of the actions of other deer (VerCauteren et al. 2006).

Matthews (2007) reported that the actions of herding animals are often influenced by the behavior of a lead animal. Although we viewed the group dynamic as positive (i.e., 1 deer crossing might encourage the other deer to cross) in regards to our trials, we did not analyze our data for group effect. However, we believed that group dynamics, use of multiple treatment areas (*n* = 3), and use of multiple levels of motivation best simulated real-world interactions between deer and roadside fences. Our measures of deer behavior in relation to each fence design and at each level of motivation provided insight into how deer might have perceived fences, and why some designs were more effective than others. Because our experimental treatments (i.e., fence heights and designs) were not independent of each other, we did not statistically test for treatment-related differences in deer behavior. However, we considered general patterns in deer behavior among treatments, and subjectively evaluated those patterns as related to fence efficacy. Although our treatment areas were not large, deer frequently attempted to jump fences from a running start and from various angles. Therefore, we believed our experimental design was appropriate for the scope of our research, and the results were applicable to typical roadway conditions.

When considering woven-wire fences, it is our opinion that deer perceived taller fences as more difficult to jump. This hypothesis is substantiated by the inverse relationship between deer interactions and fence height. Furthermore, it appeared that either a low-level threat (i.e., early-forced-choice) or food restriction provided adequate motivation for deer to jump fences they perceived as less challenging. A high-level threat, designed to elicit a flight response (i.e., late-forced-choice), was necessary to motivate deer to jump fences they perceived as more challenging. It was unclear if deer learned that 2.4-m woven-wire fences were difficult to jump because of failed attempts at lower heights, or if they simply perceived them as impenetrable barriers. We believed the increasing trend in number of failed attempts as fence height increased from 1.5 m to 2.1 m, followed by a sharp decline when the fence was raised to 2.4 m suggested that deer learned that their efforts to cross would likely result in failure. Although running deer, stressed deer, and deer on uneven terrain might sometimes jump 2.4-m woven-wire fences (VerCauteren et al. 2006), none did so in a 2.4 ha experimental pen in Wisconsin (VerCauteren et al. 2010), and few (<6) are known to have done so at the Whitehall Deer Research Facility during the past 17 years of routine operation (D. A. Osborn, University of Georgia, unpublished data).

The percentage of deer that crossed opaque fences in our study remained high (50-90%), regardless of height. In addition, most deer crossed them during the early-forced-choice and food-restriction periods, suggesting that they perceived them as a relatively low-level challenge. Gallagher et al. (2003) reported that free-ranging deer crossed a burlap fence to access a corn feeder, until the fence reached 1.6 m in height. Our results might have differed from this earlier report because we used multiple levels of motivation. Our finding that only the tallest (1.8-m) opaque fence tested was more effective than the 1.2-m woven-wire fence suggests that opaque fences offer no increase in efficacy over woven-wire fences of similar heights.

Although the percentage of deer that crossed the outrigger fence in each direction was high (60–90%), the relative odds (compared to 1.2-m woven-wire) of the deer crossing when the outrigger was angled towards them was similar to the odds they would cross the 2.1-m and 2.4-m woven-wire fences. Also, the behavioral data suggest that deer perceived the outrigger fence as more challenging to jump when the outrigger was angled towards them. When the outrigger was angled away from them, the majority (60%) of deer crossed during the early-forced-choice and food-restriction periods. In comparison, the majority (88%) of deer crossed during the late-forced-choice period when the outrigger was angled towards them, suggesting that they only attempted to jump it after they had become panicked. Furthermore, the relative number of failed attempts was highest when the outrigger was angled towards the deer. Although the total number of interactions between the deer and the outrigger fence was high, it appeared that deer were less likely to fail at a crossing attempt when the outrigger was angled away from them. Finally, the 3 deer that did not cross when the outrigger was angled towards them, crossed when it was angled away from them.

In our trials using 6 naïve deer, none crossed the outrigger fence when the outrigger was angled toward them, and only 1 crossed when the outrigger was angled away from them. Therefore, we believed that deer with previous fence-crossing experience learned to jump fences through operant conditioning and habituation. The naïve deer that crossed the fence with the outrigger angled away did so only after becoming panicked during the late-forced-choice period of motivation. In our opinion, naïve deer perceived the outrigger fence, in both directions, as difficult to jump. Falk et al. (1978) tested a slightly different outrigger fence design and found that it reduced deer crossings on a major roadway when the outrigger was angled towards the deer. Also, Jones and Longhurst (1958) tested a 0.6-m tall fence with a 1.8-m 25º outrigger and a 1.2-m tall fence with a 45º outrigger and found that deer preferred to cross under the fence when the outrigger was angled towards them, rather than jumping over it.

Although operant conditioning likely affects deer behavior towards fences over time in field situations, we believed that the relative rate of learning in our trials was accelerated by each deer’s frequent exposure to a high level of motivation when a researcher approached close enough to them to evoke a flight response. The rate at which free-ranging deer learn will depend on the relative number of negative and positive reinforcements that each deer receives. This number is determined by the spatial and temporal distribution of deer, level of motivation to cross, and the frequency of their interactions with the fence. However, our research suggested that 2.1 and 2.4-m woven-wire fences and 1.2-m outrigger fences with the outrigger angled towards approaching deer had the highest probability of preventing deer crossings. VerCauteren et al. (2010) reported a similar decrease in the number of successful fence crossings once height of woven-wire fence reached 2.1 m. Because deer in our study were more likely to jump an outrigger fence when the outrigger angled away from them, a 1.2-m fence erected on both sides of a roadway with the outrigger angled away from the road might allow trapped deer to exit the roadway when they become panicked.

Management implications

Our findings suggest that woven-wire fences < 2.1 m in height are mostly ineffective for preventing deer crossings and any cost of retrofitting existing fences with an opaque covering is unjustified. Efficacy of 1.8-m to 2.4-m woven-wire fences might be acceptable depending on the level of exclusion required along a particular roadway. However, the potential gains in efficacy and increased cost associated with each increase in fence height should be taken into consideration when constructing DVC-mitigation fencing. Where exclusion fences of ineffective heights already exist along roadways, their efficacy might be improved by adding height with more woven-wire, or outriggers, to their tops. However, 1.8-m to 2.4-m woven-wire fences could trap deer in the roadway, if they circumvent the fence ends. Shorter woven-wire fences with an outrigger angled away from the road might allow 1-way travel of deer from the roadway, minimizing the potential of DVCs.

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Table 1. Number of behaviors recorded for captive, adult, female white-tailed deer motivated to jump fences during 75-hr observation period (25 hr per treatment area) when pooled across 3 (0.1-0.2 ha) treatment areas, Athens, Georgia, 21 January-4 November, 2008.

	Number of behaviors		
Fence design (number of deer tested)	Fence interaction[a]	Failed attempt[b]	Crossing[c]
1.5-m woven (12)	302	4	27
1.8-m woven (12)	117	14	23
2.1-m woven (12)	109	31	7
2.4-m woven (12)	16	6	0
1.2-m opaque (10)	153	1	27
1.5-m opaque (10)	119	1	25
1.8-m opaque (10)	94	6	18
1.2-m outrigger towards (10)	177	20	8
1.2-m outrigger away (10)	79	2	15
1.2-m outrigger towards, naive[d] (6)	21	2	0
1.2-m outrigger away, naive[d] (6)	17	0	2

[a] Fence interaction = 1 or 2 forelegs raised towards fence, failed attempt, or successful crossing.
[b] Failed attempt = all 4 legs off the ground, but deer remained on same side of fence.
[c] Crossing = deer jumped the fence.
[d] Deer without previous fence-crossing experience.

Table 2. Number and percentage of fence crossings by captive, adult, female white-tailed deer when pooled across 3 treatment areas (0.1-0.2 ha) during 3 periods of motivation; as recorded during 75-hr observation period (25 hr per treatment area) at Athens, Georgia, 21 January–4 November, 2008.

	Number (%) of crossings by period of motivation		
Fence design (number of deer tested)	Early-forced-choice	Food restriction	Late-forced-choice
1.5-m woven-wire (12)	9 (33.3)	7 (25.9)	11 (40.8)
1.8-m woven-wire (12)	5 (21.7)	1 (4.3)	17 (74.0)
2.1-m woven-wire (12)	1 (14.3)	0 (0.0)	6 (85.7)
2.4-m woven-wire (12)	0 (0.0)	0 (0.0)	0 (0.0)
1.2-m opaque (10)	8 (29.6)	11 (40.8)	8 (29.6)
1.5-m opaque (10)	4 (16.0)	10 (40.0)	11 (44.0)
1.8-m opaque (10)	4 (22.2)	7 (38.9)	7 (38.9)
1.2-m outrigger towards (10)	0 (0.0)	1 (12.5)	7 (87.5)
1.2-m outrigger away (10)	3 (20.0)	6 (40.0)	6 (40.0)
1.2-m outrigger towards, naïve deer[a] (6)	0 (0.0)	0 (0.0)	0 (0.0)
1.2-m outrigger away, naïve deer[a] (6)	0 (0.0)	0 (0.0)	2 (100.0)

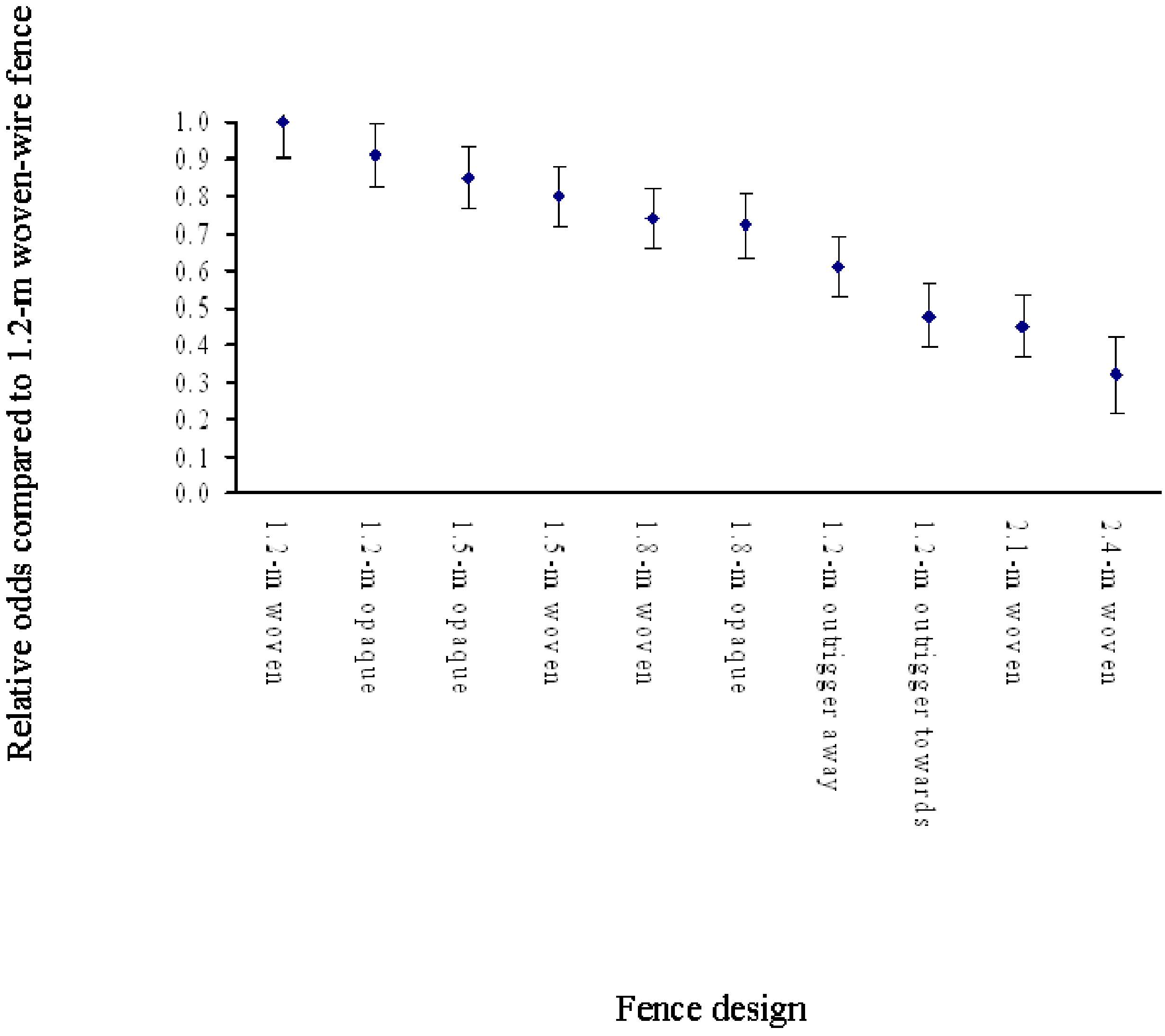
[a] Deer without previous fence-crossing experience.

Table 3. Parameter estimates, odds ratios, P values, and confidence limits for each fence type (fixed effects) estimated by a logistic regression model† using fence crossing data for captive, adult, female white-tailed deer during a 75-hr observation period (25 hr per treatment area) at Athens, Georgia, 21 January-4 November, 2008.

	Model coefficient				Odds ratio		
Parameter	Estimate	LCL	UCL	P-value‡	Estimate	LCL	UCL
(Intercept) 1.2 m contained in intercept	1.001	0.812	1.191	0.0001			
1.2 m opaque	-0.099	-0.265	0.066	0.2452	0.906	0.768	0.905
1.5 m	-0.219	-0.378	-0.065	0.0074	0.803	0.685	0.803
1.5 m opaque	-0.165	-0.333	-0.002	0.0510	0.848	0.719	0.845
1.8 m	-0.303	-0.456	-0.142	0.0001	0.739	0.631	0.743
1.8 m opaque	-0.332	-0.497	-0.167	0.0002	0.717	0.608	0.718
2.1	-0.803	-0.960	-0.642	0.0001	0.448	0.382	0.449
2.4	-1.127	-1.325	-0.924	0.0001	0.324	0.266	0.324
1.2 Outrigger towards	-0.732	-0.898	-0.564	0.0001	0.481	0.408	0.481
1.2 Outrigger away	-0.499	-0.664	-0.331	0.0001	0.607	0.515	0.607

† AIC = 276.9; Unexplained within-deer group variation, $\sigma = 0.33$; MR=17%
‡P-value based on t-distribution; alpa=0.05

Figure 1. Relative odds (bars represent 95% confidence levels) that captive, adult, female white-tailed deer would cross each of various exclusion fence designs during a 75-hr observation period (25 hr per treatment area) compared to a 1.2-m woven-wire fence, Athens, Georgia, 21 January-4 November, 2008



EFFECTS OF FENCES ON ROADWAY CROSSINGS AND HOME RANGE DISTRIBUTION OF WHITE-TAILED DEER

by

WILLIAM D. GULSBY

(Under the Direction of Karl V. Miller and Robert J. Warren)

ABSTRACT

Although many deer-vehicle collision (DVC) mitigation devices have been developed and tested, only fencing has proven effective. Because a 2.4-m woven-wire fence and a prototype outrigger fence (i.e., 0.6-m outriggers attached to a 1.2-m wire fence angled at 45º) were 100% effective at preventing crossings by captive white-tailed deer (*Odocoileus virginianus*), we evaluated the efficacy of these designs at preventing crossings by free-ranging deer. From January to April 2009, we fitted 14 adult does with GPS collars, programmed to collect ≥ 24 locations/day. In June 2009, we constructed a 3.2-km fence treatment that included a 1.6-km section of 2.4-m vertical-wire fence and a 1.6-km section of the outrigger fence. We retrieved collars between January and March 2010. We compared home ranges, core areas, fence crossings, and fence circumventions among deer that encountered the outrigger and 2.4-m fences as well as for deer that did not encounter the fence (i.e., controls), before and after fence construction. Although home ranges and core areas changed among seasons, we found no effect of fencing. Deer with pre-treatment home ranges that approached or encompassed the end of the fence maintained a high degree of site fidelity by circumventing the fences. Fence crossings, however, were reduced by 98% and 90% for the 2.4-m and outrigger treatment groups, respectively. Although we recorded fewer crossings of the 2.4-m fence, the prototype outrigger fence may be a viable option for reducing DVCs because of its affordability and potential as a one-way barrier. More importantly, we believe this study highlights the importance of using localized data on deer home range sizes to determine the minimum length of fencing necessary to prevent circumvention in high-risk areas.

INDEX WORDS: deer-vehicle collision, fencing, GPS collars, home range, LoCoH, *Odocoileus virginianus*, outrigger fence, telemetry, white-tailed deer, wildlife-vehicle collision

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WILLIAM D. GULSBY

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Major Professors:	Karl V. Miller Robert J. Warren
Committee:	John P. Carroll Nathan P. Nibbelink

Electronic Version Approved:

Maureen Grasso
Dean of the Graduate School
The University of Georgia
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CHAPTER 1

INTRODUCTION, LITERATURE REVIEW, STUDY AREA, OBJECTIVES, AND THESIS FORMAT

INTRODUCTION

The combination of abundant white-tailed deer (*Odocoileus virginianus*) populations, an expanding roadway system, and increased vehicular traffic have led to an increase in deer-vehicle collisions (DVCs) in many areas of the United States (Romin and Bissonette 1996). An estimated 1.5 million DVCs (Conover et al. 1995) account for $1.1 billion in damages each year in the United States alone (State Farm Insurance Company 2009). According to the Insurance Information Institute (2008), the average insurance claim for damage incurred from a DVC is $2,800. When medical costs for bodily injury are included, the average cost increases to $10,000. The Georgia Department of Natural Resources, Wildlife Resources Division estimates that as many as 51,000 DVCs occur each year in Georgia, accounting for 13.5 % of all collisions in the state (Bowers et al. 2005).

Many transportation departments have attempted to alleviate this problem using roadside fencing. Although it is clear that deer cannot cross certain fences, little is known about how these fences affect their behavior. The attention given to this problem is increasing, but consultation between biologists and transportation departments will be critical to the reduction of DVCs in the future. The purpose of this study was to evaluate the efficacy of two types of roadside fencing when deployed in the field and their effects on home ranges and movements of free-ranging deer.

LITERATURE REVIEW

Animal-detection systems, roadway signage, intercept feeding, deer whistles, roadside reflectors, and exclusion fences with or without wildlife crossing structures incorporated into them have all been implemented in an attempt to mitigate DVCs (Huijser et al. 2007). Despite the variety of these mitigation strategies, most fall into three main categories: alteration of driver behavior, alteration of deer behavior, or exclusion of deer from the road. Devices designed to alter driver behavior, such as roadway signage placed in areas with a high frequency of DVCs, initially increase driver awareness but motorists quickly revert to their standard driving practices after becoming habituated to them (Putnam et al. 2004). Devices designed to alter deer behavior, such as roadside reflectors or deer whistles, often do not account for the way deer perceive their environment. Recently, D'Angelo (2007) examined the physiological and morphological characteristics of white-tailed deer visual and auditory systems in an attempt to better understand their perception of deer whistles and roadside reflectors. Then these devices were tested in the field and found to be ineffective at preventing deer from entering roadways (D'Angelo et al. 2007, Valitzski et al. 2009).

Exclusion of deer from the roadway using roadside fencing is perhaps the most frequently utilized and studied DVC mitigation technique. Although the construction costs of deer-proof fencing are high, it is the most economical and effective option when human tolerance of deer damage is low, as is the case in areas with a high incidence of DVCs (Bashore et al. 1985, Bryant et al. 1993, Craven and Hygnstrom 1994, DeNicola et al. 2000, VerCauteren et al. 2006). Huijser et al. (2007) estimated the cost of DVC-mitigation fencing to be \$3,760/km/yr with a benefit (e.g., collisions prevented as a result of the fencing) of \$32,728/km/yr.

Woven-wire fencing ≥ 2.4-m in height is generally regarded as effective for preventing crossings by large ungulates (Fitzwater 1972, Falk et al. 1978, Bashore and Bellis 1982, Ward 1982, Sauer 1984, Bryant et al. 1993, Craven and Hygnstrom 1994, Seamans 2001, Kaneene et al. 2002, VerCauteren et al. 2006), and has been shown to decrease DVCs by 60-93% (Ludwig and Bremicker 1981).

The Georgia Department of Transportation (GDOT) currently uses a “game fence” in DVC-prone areas. This fence is 2.74-m tall with three distinct sections (GDOT, personal communication). The lowest section is 22.9 cm of woven wire with 7.6-cm vertical spacing and a strand of barbed wire running along the ground. The next section, which composes the majority of the fence, is 2.2 m of woven-wire fence with 20.32-cm vertical spacing. The third section is two strands of barbed wire spaced 15.24-cm apart and is located 15.24-cm above the woven wire. Although this fence effectively excludes deer from the roadway, it is quite expensive and no wildlife escape structures are incorporated into its design.

Alternatives to high fences that use less material or less-costly material and provide escape routes for entrapped deer have been proposed and tested. For example, Jones and Longhurst (1958) tested a 0.6-m vertical fence with a 1.8-m outrigger angled at 25º and a 1.2-m vertical fence with a 1.2-m outrigger angled at 45º. In both cases, deer were more likely to attempt to go under the fence when the outrigger was angled towards them. Goddard et al. (2001) found that a 0.9-m vertical fence with a 0.8-m, 90º outrigger effectively prevented crossings by red deer (*Cervus elaphus*). Similarly, Stull (2009) reported that a 1.2-m woven-wire fence with a 0.6-m 50% opaque plastic outrigger angled at 45° may act as a one-way barrier, with a higher degree of efficacy when the outrigger is angled towards the deer.

Knapp et al. (2004) and Huijser et al. (2007) reported that maximum effectiveness of any fence design requires that the fence is properly constructed and maintained, located on both sides of the road, is of sufficient length to extend beyond the home ranges of deer in high-risk areas, and has some way for animals to escape from the right-of-way. Additionally, Ludwig and Bremicker (1981) reported that deer will circumvent roadside fences that are too short, resulting in a reduction in their efficacy. However, barriers are often constructed only at deer crossing "hot-spots" (Utah Department of Transportation 2008). "Hot-spot" treatments have the potential to shift or magnify the number of DVCs in an area by funneling deer to a common crossing point (Owen and Owen 1980, Isleib 1995, Clevenger et al. 2001, VerCauteren et al. 2006, Huijser et al. 2007). For example, one study found that where mitigation fencing was used, wildlife-vehicle collisions were highest within 2 km of the fence ends and tapered off thereafter (Clevenger et al. 2001).

Before DVCs can be effectively reduced, factors influencing deer movements in relation to fencing and highways must be more thoroughly understood (Puglisi et al. 1974). However, researchers often use indirect measures such as carcass counts, track counts, or surveys of deer in the right-of-way to examine these movements and almost no direct evidence currently exists regarding behavioral responses of deer to fences (Puglisi et al. 1974, Carbaugh et al. 1975, Falk et al. 1978, Clevenger et al. 2001). Only Feldhamer et al. (1986) have directly studied deer movements in relation to a highway with mitigation fencing. In this study, deer were captured and radio-collared alongside a roadway where several types of fencing were in place. However, because deer movements were monitored using VHF telemetry, the investigators lacked the fine-scale data needed to quantify individual crossings or circumvention events.

The combination of widespread use of roadside fencing and the lack of knowledge surrounding how deer respond to it could potentially exacerbate deer-vehicle interactions. Therefore, I determined the effects of a prototype outrigger-fence design and a 2.4-m woven-wire fence on home range distribution and movements of free-ranging deer. I also evaluated the efficacy of these fences for preventing deer crossings.

OBJECTIVES

The goals of this project were to determine the efficacy of two types of roadside deer fencing and evaluate their effects on deer home range distribution and movements. My specific objectives were to: (1) determine any changes in deer home ranges that occur as a result of the construction of roadside fences; (2) determine if deer circumvent roadside fences to gain access to portions of their home range from which they are excluded; (3) compare the efficacy of a 2.4-m woven-wire fence to that of a 1.2-m woven-wire fence with an outrigger angled at 45º (Figure 1); (4) determine if the outrigger fence served as a one-way barrier by comparing its efficacy when angled toward versus away from the deer.

STUDY AREA

I conducted my study on the 1,215-ha Berry College Wildlife Refuge (BCWR) within the 11,340-ha Berry College Campus in Floyd County, Georgia (Figure 2). Although the refuge is located in the Ridge and Valley physiographic province (Hodler and Schretter 1986), which has elevations ranging from 172 to 518 m, much of BCWR lies in the Coosa Valley and the elevation is typically ≤ 200 m.

The forested habitat on BCWR consists of tree species common to southern forests, including *Acer rubrum, Diospyros virginiana, Ilex opaca, Liquidambar styraciflua, Liriodendron tulipifera, Pinus taeda, Quercus alba, and Q. nigra*. The refuge is also interspersed with some of the last-remaining stands of mountain longleaf pine (*Pinus palustris*).

Hunting is prohibited on the refuge and deer are abundant with an estimated density of 40 deer/km^2 (J. Beardon, Georgia Department of Natural Resources, personal communication). As a result, between 12 and 24 DVCs are reported annually, although the actual number of collisions is likely higher (Berry College Police Department, unpublished data).

The campus is divided into the main campus and the mountain campus. Both campuses are characterized by buildings and facilities interspersed with pastures, woodlots, and manicured lawns. They are connected by a 4.8-km, straight stretch of road known as Lavender Mountain Road (LMR). LMR is a two-lane blacktop road with a speed limit ranging from 40-64-km/hr. Running parallel to LMR is a power-line right-of-way known as the Viking Trail (VT). The area surrounding LMR and the VT is forested and consists of pine stands (*Pinus taeda* and *Pinus palustris*) and mixed forest dominated by oaks (*Quercus* spp.), hickories (*Carya* spp.), and pines (*Pinus* spp.). LMR and the VT are separated by a strip of mixed forest, of similar composition, that ranges from 30-125 m wide. I selected the VT as the construction site for the DVC-mitigation fencing because of its openness, flatness, linear orientation, and similarity to a common situation where a roadway travels through a wooded area harboring an abundant deer population.

THESIS FORMAT

My thesis is presented in manuscript format. Chapter 1 is an introduction and a literature review of previous studies addressing similar research topics. Chapter 2 is the manuscript chapter that will be submitted to a peer-reviewed scientific journal for publication. It describes the efficacy of two types of roadside fencing for preventing deer crossing and their effects on home ranges and movements of white-tailed deer. Chapter 3 presents conclusions and the management implications of the findings of my study.

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Figure 1.1. The 2.4-m woven-wire fence treatment (left) and outrigger fence treatment (right) constructed on Berry College, Floyd County, Georgia.

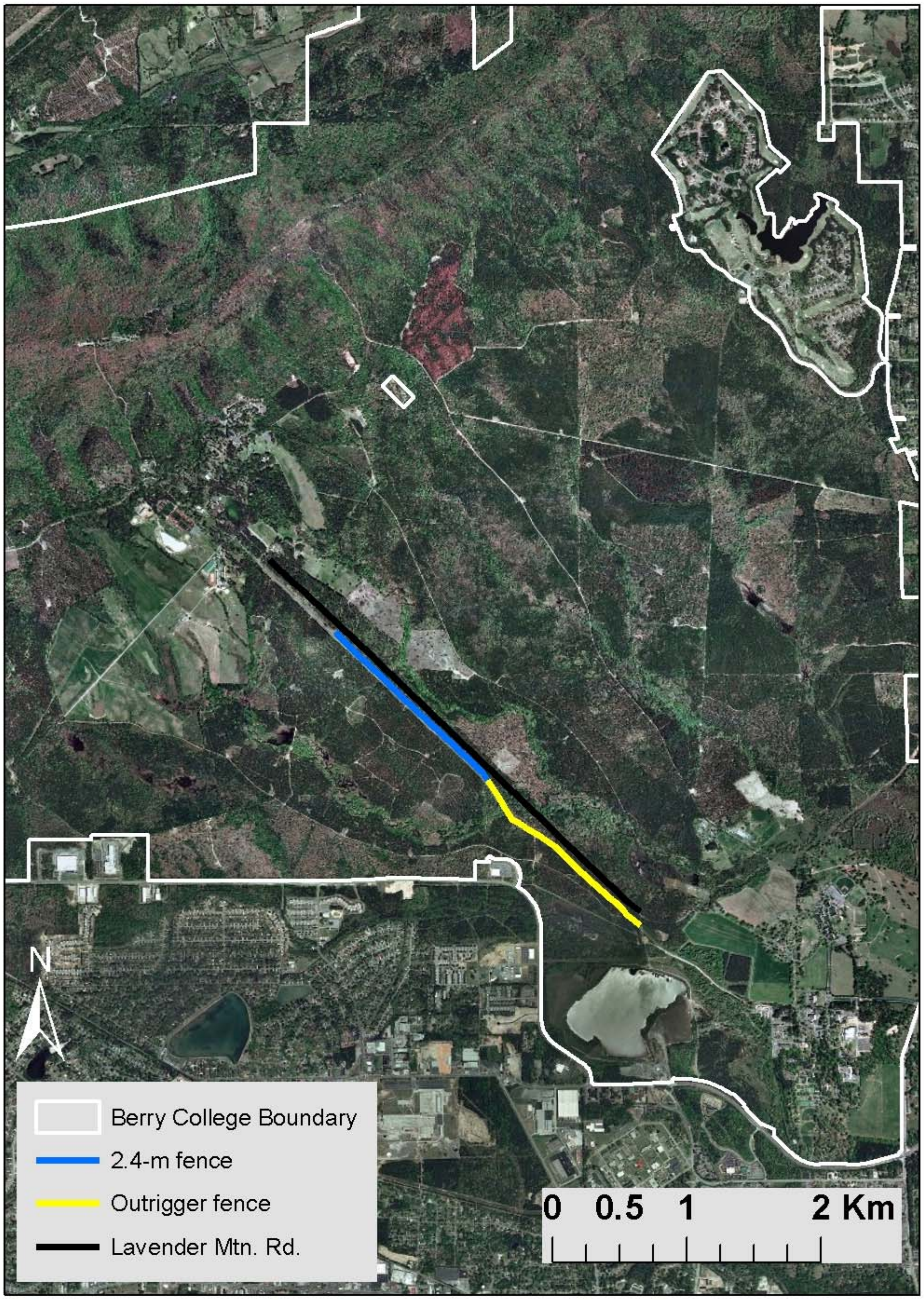

Figure 1.2. A 1-m resolution imagery map from the ArcGIS Resource Center (ArcGIS Online 2010) of Berry College, Floyd County, Georgia and the 1.6-km fence treatments.

CHAPTER 2

EFFECTS OF FENCES ON ROADWAY CROSSINGS AND HOME RANGE DISTRIBUTION OF WHITE-TAILED DEER

ABSTRACT

Although many deer-vehicle collision (DVC) mitigation devices have been developed and tested, only fencing has proven effective. Because a 2.4-m woven-wire fence and a prototype outrigger fence (i.e., 0.6-m outriggers attached to a 1.2-m wire fence angled at 45º) were 100% effective at preventing crossings by captive white-tailed deer (*Odocoileus virginianus*), we evaluated the efficacy of these designs at preventing crossings by free-ranging deer. From January to April 2009, we fitted 14 adult does with GPS collars, programmed to collect ≥ 24 locations/day. In June 2009, we constructed a 3.2-km fence treatment that included a 1.6-km section of 2.4-m vertical-wire fence and a 1.6-km section of the outrigger fence. We retrieved collars between January and March 2010. We compared home ranges, core areas, fence crossings, and fence circumventions among deer that encountered the outrigger and 2.4-m fences as well as for deer that did not encounter the fence (i.e., controls), before and after fence construction. Although home ranges and core areas changed among seasons, we found no effect of fencing. Deer with pre-treatment home ranges that approached or encompassed the end of the fence maintained a high degree of site fidelity by circumventing the fences. Fence crossings, however, were reduced by 98% and 90% for the 2.4-m and outrigger treatment groups, respectively. Although we recorded fewer crossings of the 2.4-m fence, the prototype outrigger fence may be a viable option for reducing DVCs because of its affordability and potential as a one-way barrier. More importantly, we believe this study highlights the importance of using localized data on deer home range sizes to determine the minimum length of fencing necessary to prevent circumvention in high-risk areas.

INDEX WORDS: deer-vehicle collision, fencing, GPS collars, home range, *Odocoileus virginianus*, outrigger, outrigger fence, telemetry, white-tailed deer, wildlife-vehicle collision

INTRODUCTION

The combination of abundant white-tailed deer (*Odocoileus virginianus*) populations, an expanding roadway system, and increased vehicular traffic have led to an increase in deer-vehicle collisions (DVCs) in many areas of the United States (Romin and Bissonette 1996). An estimated 1.5 million DVCs (Conover et al. 1995) account for $1.1 billion in damages each year in the United States alone (State Farm Insurance Company 2009). According to the Insurance Information Institute (2008), the average insurance claim for damage incurred from a DVC is $2,800. When medical costs for bodily injury are included, the average cost increases to $10,000. The Georgia Department of Natural Resources, Wildlife Resources Division estimates that as many as 51,000 DVCs occur each year in Georgia, accounting for 13.5% of all collisions in the state (Bowers et al. 2005).

Most devices designed to mitigate DVCs have failed to account for the way deer perceive their environment (i.e., vision and hearing), or these devices are marketed without data verifying their efficacy. Devices and strategies promoted to reduce DVCs include, but are not limited to animal-detection systems, deer whistles, exclusion fences, herd reduction, intercept feeding, roadway lighting, roadside reflectors, roadway signage, and wildlife underpasses/overpasses. Of these techniques, exclusion fencing is perhaps the most frequently utilized and studied. Although the construction costs of deer-proof fencing are high, it is the most economical and effective option when deer-damage tolerance is low, as is the case in areas with high incidence of DVCs (Bashore et al. 1985, Bryant et al. 1993, Craven and Hygnstrom 1994, DeNicola et al. 2000, VerCauteren et al. 2006). Huijser et al. (2007) estimated the cost of DVC-mitigation fencing to be \$3,760/km/yr with a benefit (e.g., collisions prevented as a result of the fencing) of \$32,728/km/yr.

Woven-wire fencing ≥ 2.4-m in height is generally regarded as effective in preventing deer crossings (Fitzwater 1972, Falk et al. 1978, Bashore and Bellis 1982, Ward 1982, Sauer 1984, Bryant et al. 1993, Craven and Hygnstrom 1994, Seamans 2001, Kaneene et al. 2002, VerCauteren et al. 2006). However, maximum effectiveness of any fence design requires that the fence is properly constructed and maintained, located on both sides of the road, is of sufficient length to extend beyond the home ranges of deer in high-risk areas, and has some way for animals to escape from the right-of-way (Knapp et al. 2004, Huijser et al. 2007).

Successful deer exclusion also can be attained with alternative fencing designs or modifications to a reduced-height, woven-wire fence. For example, Jones and Longhurst (1958) tested a 0.6-m vertical fence with a 1.8-m outrigger angled at 25° and a 1.2-m vertical fence with a 1.2-m outrigger angled at 45°. In both cases, deer were more likely to attempt to go under the fence when the outrigger was angled towards them. Similarly, Stull (2009) found that a 1.2-m woven-wire fence with a 0.6-m 50% opaque plastic outrigger angled at 45° acted as a one-way barrier, with a higher degree of efficacy when the outrigger was angled towards the deer.

Trials conducted on captive deer allow direct observation of crossing events and control of extraneous variables, but fail to account for potential biological and ecological effects on movements of free-ranging deer. For example, a deer that is excluded from a portion of its home range may concentrate its activity in another area or circumvent the barrier, thereby potentially increasing DVCs elsewhere (Owen and Owen 1980, Isleib 1995, Clevenger et al. 2001, VerCauteren et al. 2006). Roadside trials can reveal these responses of deer to barriers, but typically using indirect measures such as carcass counts, track counts, or surveys of deer in the right-of-way (Puglisi et al. 1974, Carbaugh et al. 1975, Falk et al. 1978, Clevenger et al. 2001). To our knowledge, only Feldhamer et al. (1986) have studied deer movements in relation to DVC-mitigation fencing. However, because deer movements in this study were monitored using VHF telemetry, the investigators lacked the fine-scale data needed to quantify individual crossings or circumvention events.

The combination of widespread use of roadside fencing and the lack of knowledge surrounding how deer respond to these fences could potentially exacerbate deer-vehicle interactions. Herein, we report on a study of a prototype fencing design, compare its efficacy to a commonly used fence design, and determine their effects on home range distribution and movements of free-ranging deer.

STUDY AREA

We conducted our study on the Berry College Wildlife Refuge (BCWR) within the 11,340-ha Berry College Campus in northwestern Georgia, USA. The 1,215-ha refuge is located in the Ridge and Valley physiographic province (Hodler and Schretter 1986) with elevations ranging from 172 to 518 m. Hunting is prohibited on the refuge and deer are abundant with an estimated density of 40 deer/km^2 (J. Beardon, Georgia Department of Natural Resources, personal communication). As a result, between 12 and 24 DVCs are reported annually, although the actual number of collisions is likely higher (Berry College Police Department, unpublished data).

The campus is divided into the main campus and the mountain campus. Both campuses are characterized by buildings and facilities interspersed with pastures, woodlots, and manicured lawns. They are connected by a 4.8-km, straight, road known as Lavender Mountain Road (LMR). LMR is a two-lane blacktop road with a speed limit ranging from 40-64-km/hr. Running parallel to LMR is a power-line right-of-way known as the Viking Trail (VT). The area surrounding LMR and the VT is forested and consists of pine stands (*Pinus taeda* and *Pinus palustris*) and mixed forest dominated by oaks (*Quercus* spp.), hickories (*Carya* spp.), and pines (*Pinus* spp.). LMR and the VT are separated by a strip of mixed forest that ranges from 30-125-m wide. We selected the VT as the construction site for the DVC-mitigation fencing because of its openness, flatness, linear orientation, and similarity to a common situation where a roadway travels through a wooded area harboring an abundant deer population.

METHODS

From January to April 2009, we fitted 14 adult female deer (≥ 1.5 years old) with GPS collars. We deployed 10 Televilt Tellus®, 5H1D (Televilt/TVP Positioniong AB, Lindesberg, Sweden) and 4 Lotek 3300L (Lotek Engineering, Ontario, Canada) collars. Deer were captured using a combination of free-darting and rocket nets. When free-darting, we used 2-ml transmitter darts (Pneu-dart Inc., Williamsport, PA) to intramuscularly inject a Telazol® (Fort Dodge Animal Health, Fort Dodge, IA)/xylazine hydrochloride (Congaree Veterinary Pharmacy, Cayce, SC) (300 mg/400 mg) mixture to immobilize deer. We immobilized deer captured in rocket nets with an intramuscular Telazol®/xylazine hydrochloride (100 mg/320 mg) injection. Dosages were calculated assuming an average weight of 45 kg. During immobilization, we monitored vital signs, treated minor injuries, lubricated eyes, and blindfolded each deer. After 90 minutes, we administered a 100-mg injection (50 mg [IV] + 50 mg [IM]) of yohimbine hydrochloride (Antagonil®, Wildlife Laboratories, Fort Collins, CO) to reverse the effects of the immobilization agents. All deer were monitored until ambulatory. Animal handling procedures were approved by the University of Georgia Institutional Animal Care and Use Committee (#A2007-10127-0).

We programmed the GPS collars to collect and store GPS locations, in the form of X, Y coordinates, on their nonvolatile memory. Lotek collars were programmed to collect 48 locations/day at equal intervals throughout the study period. Due to battery-life limitations, we programmed the Televilt collars to collect 48 locations/day at equal intervals from 1 January to 30 June (immediately before and after fence construction) and 24 locations/day at equal intervals from 1 July to 31 December. For all statistical comparisons between collar brands, we filtered data to ensure equal sampling frequencies. Collars were equipped with mortality sensors, programmed to emit a double-pulse VHF beacon after 8 hours of inactivity. We monitored animals once per week using VHF-telemetry equipment to ensure they were alive and that collars were functioning properly. If a mortality signal was detected, the collar was retrieved immediately using radio telemetry. At the end of the study, activation of a remote-release mechanism caused functioning collars to fall from the animal. The release mechanisms failed on 9 collars, so we retrieved these collars via lethal means (gunshot). Upon collar retrieval, we used the Televilt Tellus TPM Project Manager software (Televilt/TVP Positioning AB, Lindesberg, Sweden) and the Lotek GPS 3000 Host Application (Lotek Wireless Inc., Newmarket, Ontario, Canada) to download data. To decrease the probability of erroneous points in the datasets, any points representing non-fixes, impossible locations, and locations with dilution of precision values > 6, were filtered out. After data censoring, we imported GPS fixes for each deer into ArcMap 9.3 (Environmental Systems Research Institute, Inc., Redlands, CA) and projected them in Universal Transverse Mercator (UTM) North American Datum (NAD) 1983 Zone 17 North (meters).

Construction of the 3.2-km fence treatment along the VT began on 18 May 2009 and was completed on 10 June 2009. The fence included a 1.6-km section of 2.4-m Solidlock® Fixed Knot 12.5g Game Fence (Bekaert Corporation, Marietta, GA) to which was attached a 1.6-km section of the outrigger fence. The outrigger fence consisted of 1.2-m Solidlock® Fixed Knot 12.5g Game Fence (Bekaert Corporation, Marietta, GA) with 0.6-m long outriggers (Hearne Steel Company, Hearne, TX) attached to the top, angled at 45° away from the road. Five strands of white Bayco® Finish Line wire (Ag-liner, Inc., Mars, PA) were threaded into pre-cut slots spaced 12.5-cm apart on the outriggers. Total construction costs were $9,356/km ($9.36/m) and $7,370/km ($7.37/m) for the 2.4-m and outrigger fences, respectively.

Deer were assigned to outrigger (n=4) or 2.4-m (n=4) treatment groups according to the fence that their home range overlapped. These groups were independent, as no deer encountered both the outrigger and 2.4-m fences. A control group (n=6) was composed of deer that encountered neither fence. We structured the datasets into 3 time blocks based on when the fence was constructed. The pre-treatment period lasted from the time deer were collared until the day before fence construction was initiated. The first post-treatment period (post-treatment 1), which was designed to assess the immediate effects of the fencing treatments on deer home ranges, lasted from the day after fence construction was completed until 11 September 2009. The second post-treatment period (post-treatment 2) lasted from 12 September 2009 until collar recovery. Sample sizes for the third treatment period were reduced to 3 and 2 for the outrigger and 2.4-m treatments, respectively, due to premature collar failure (n=2) and natural mortality (n=1).

We selected only top-hour fixes to estimate home ranges and core areas using the Adehabitat Package (Calenge 2006) for the R software version 2.10.1 (R Development Core Team 2009). We calculated home ranges and core areas, for each deer and treatment period, using 90% and 50% adaptive-local convex hull (*a*-LoCoH) methods, respectively. We used the maximum distance between any 2 points in the data set as the starting point for *a* (Getz et al. 2007), then examined plots of the area covered by a particular utilization distribution against a wide range of values of *a*. When the plot of the estimated area leveled off, we assumed all spurious holes were covered and selected this value of *a* (Getz and Wilmers 2004, Ryan et al. 2006).

We used "Mean Center" in ArcToolbox (Environmental Research Systems Institute, Inc., Redlands, CA) to calculate the mean center of fixes for each deer during each treatment period. We then measured the distance between the mean of center points for each deer from pre-treatment to post-treatment 1 and from post-treatment 1 to post-treatment 2.

To determine barrier efficacy, we quantified crossing events by scrutinizing the daily movement paths of each deer before and after fence construction. We used several criteria to differentiate actual crossing events from spurious (i.e., the result of GPS-location error) ones. When a deer's movement path crossed the fence, we classified the event as a successful crossing as follows: (1) for the 1-hr sampling frequency, ≥ 2 sequential locations had to occur on the opposite side of the fence, farther than 20 m away from the fence; (2) for the 30-min sampling frequency, ≥ 3 sequential locations had to occur on the opposite side of the fence, farther than 20 m away. An event was classified as circumvention only when a distinct movement path going around either end of the fence was observed. We recorded the date and time of each crossing and circumvention event for both fence treatments and recorded the direction of crossing (i.e., outrigger toward vs. away) for the outrigger fence. To account for the unevenness in pre- versus post-construction periods, we calculated the average number of crossing events per sample day (crossings/day) for each deer before and after fence construction by dividing the total number of crossing events by the number of sample days in each treatment period. We used repeated measures ANOVA to compare the efficacies of the outrigger toward, outrigger away and the 2.4-m treatments.

We also analyzed the data to determine the distribution of each deer's point locations around the fences, for each treatment period. We used "Multiple Ring Buffer" in ArcToolbox (Environmental Research Systems Institute, Inc., Redlands, CA) to create linear buffer regions, 50-m in width, starting directly adjacent to each fence treatment and radiating out to 650-m, on either side of the fence. We then joined these buffer polygons to the point layer of each deer for each treatment period, and divided the sum of points occurring in each buffer region by the total number of points contained in the entire multiple-ring buffer to calculate the proportion of points occurring in each buffer region.

RESULTS

Deer encountering the 2.4-m treatment (n=4) crossed the fence area 124 times before fence construction, and only 2 times after fence construction (98% reduction) (Table 1). One deer (#20) was responsible for both of the documented 2.4-m fence crossings. She crossed the barrier, remained on the opposite side for 2-hrs, then crossed again. On average, deer crossed the 2.4-m fence 0.337 times/day (Range 0.09 – 0.51, SE = 0.09) before construction and 0.002 times/day (Range 0 – 0.002, SE = 0.002) after construction (Table 1).

Outrigger efficacy did not differ when angled toward (outrigger toward) versus away (outrigger away) from the deer ($F_{1,6} = 1.46$, $P = 0.27$); therefore, we pooled outrigger crossing data for comparison with the 2.4-m treatment group. Deer encountering the outrigger treatment (n=4) crossed the fence area 228 times before, and 22 times after fence construction (90% reduction) (Table 1). On average, deer crossed the outrigger fence 1.02 times/day (Range 0.54 – 1.50, SE = 0.26) and 0.05 times/day (Range 0.005 – 0.155, SE = 0.035) before versus after construction, respectively (Table 1).

The average number of crossings/day for both treatment groups decreased post-treatment ($F_{1,6} = 20.10$, $P = 0.004$), but the 2.4-m treatment was more effective than the outrigger treatment ($F_{1,6} = 7.96$, $P = 0.03$).

Post-fence construction, we documented 50 and 54 circumvention events for the 2.4-m and outrigger treatments, respectively. One deer (#20), whose home range extended beyond the fence during post-treatment 2 was responsible for all of the 2.4-m circumvention events (Figure 1). Three of 4 deer (#s 1, 10, and 19) were responsible for the 54 recorded outrigger circumvention events. Twenty-six (48%) occurred during post-treatment 1 and 28 (52%) occurred during post-treatment 2. All 3 of these deer had post-treatment home ranges that extended beyond the end of the fence (Figure 2).

The deer whose post-construction home range did not encompass the end of the outrigger fence (#16) accounted for 10 (45%) of the 22 total outrigger crossing events. Eight of these crossings occurred within a 1.5-month period following fence construction, and 2 occurred on 22 October 2009. On 8 December 2009, a flood event downed a 50-m section of the outrigger fence. On 12 December 2009, Deer #16 began breaching the fence through this gap and continued to do so, almost daily, until her collar was recovered on 4 February 2010 (Figure 3).

Home range and core area sizes decreased from pre-treatment to post-treatment 1, and increased again during post-treatment 2. There were no differences in home range or core area sizes among 2.4-m, outrigger, or control groups (Table 2). There was no effect of treatment or treatment period on the mean of center points for each deer (Table 3).

Although deer encountering the 2.4-m fence spent the majority of their time on one side of the fence area, there were a small proportion of points, for each deer, that did occur on the opposite side prior to fence construction (Figure 4). However, post-construction the proportion of points on the opposite side declined to nearly 0 for all deer except #20, which accessed the other side by circumventing the fence during post-treatment 2 (Figure 4). Two deer (#s 12 and 13) encountering the 2.4-m treatment showed an increase in the proportion of points in the 50-m buffer region after fence construction (Figure 4). Relative to the 2.4-m deer, the distributions of deer encountering the outrigger fence were more centered along the fence prior to construction (Figure 5). Although there was a decrease in the proportion of points on one side of the fence after construction, the decline wasn’t notable in 3 (#s 1, 10, and 19) of 4 outrigger deer, because they frequently circumvented the barrier (Figure 5). Three (#s 1, 16, and 19) of 4 deer encountering the outrigger treatment showed an increase in the proportion of points in the 50-m buffer region after fence construction (Figure 5).

DISCUSSION

Our data on the efficacy of the 2.4-m woven-wire fence agree with previous reports that fencing ≥ 2.4-m in height is effective at preventing deer crossings (Fitzwater 1972, Falk et al. 1978, Bashore and Bellis 1982, Ward 1982, Sauer 1984, Bryant et al. 1993, Craven and Hygnstrom 1994, Seamans 2001, Kaneene et al. 2002, VerCauteren et al. 2006).

In addition to the 90% reduction in crossings, we made multiple observations that suggest the outrigger fence was an effective deterrent. We observed multiple instances of deer circumventing to the outrigger-toward side of the fence and repeatedly traveling its length for one to several days, apparently trying to regain access to the other side (Figure 6). Once the deer circumvented back, no similar "pacing" behavior was observed. We also noticed the appearance of a 0.6-m wide deer path along the outrigger-toward side of the fence shortly after its construction, suggesting that many deer exhibited this same behavior. Because no similar path was seen along the 2.4-m fence, we believe that this behavior was elicited only by the outrigger fence. Stull (2009) also observed similar behavior in captive deer when they approached the outrigger-toward side of this fence design. Finally, Deer #16, which was the only deer encountering the outrigger treatment that didn't circumvent, began exploiting the gap left by the December 2009 flood on a daily basis shortly after it was knocked down (Figure 3). Prior to this time, this deer was essentially excluded from the opposite side of the outrigger fence.

Unlike Stull (2009), we found no difference in the efficacy of the outrigger fence in the outrigger-toward versus away direction. Because the outrigger fence was located 30-125 m from the road, and due to the presence of cover between deer and the road, we suspect that deer were not pressured to cross the fence when they were positioned between it and the road. In most situations where DVC-mitigation fencing is used, it is placed on both sides of the road and closer to the roadway. Deer trapped between the road and fences in those situations may be more motivated to cross than in our study.

For those deer whose home ranges did not encompass the fence end, both fence types were effective. However, 3 of 4 deer encountering the outrigger fence, and 1 of 4 deer encountering the 2.4-m fence had home ranges that came close to or encompassed the end of the fence (Figures 1 and 2). As a result, the deer maintained use of their entire home range. Additionally, our finding that 5 of 8 deer showed an increase in the proportion of their point locations just adjacent to the fence highlights the danger of implementing DVC-mitigation fencing without structures that allow safe crossing or escape from the roadway (Figures 4 and 5). This finding is in agreement with those of Ludwig and Bremicker (1981) who reported that barrier efficacy is reduced when fences are of insufficient length, as deer will circumvent the endings. In situations, such as this, where fencing is not of sufficient length to extend beyond home ranges of deer in high-risk areas, crossings are concentrated at the end of the fence, thereby moving or exacerbating existing hot-spots (Knapp et al. 2004, Huijser et al. 2007).

Across groups, mean pre-treatment home range size was 44 ha and the mean long axis of home ranges was 1,164 m in length. However, Rogers (1996) found that home ranges of adult does in northwestern Georgia were, on average, 6 times larger than what we observed. If long axis length increases proportionally to home range size, up to 7 km of fencing would be necessary to prevent circumvention by these deer. Furthermore, because home ranges of adult bucks are typically larger than those of adult does, extension of fences beyond the home ranges of all deer in a high-risk area is difficult, if not impossible. Thus, where DVC-mitigation fencing is used as a hot-spot treatment, fences likely should end at natural barriers to deer movements (i.e., heavy development or bodies of water), or the fence endings must incorporate some means (e.g., wildlife overpasses or underpasses) of facilitating crossings by deer so as to avoid vehicular traffic.

Less substantial fences, such as the outrigger fence, are typically more effective when motivation to cross is low (Goddard et al. 2001). In our study, motivation to cross remained low because deer maintained use of their entire home range via circumvention. The incorporation of devices such as highway overpasses or underpasses into fence designs allows deer full use of their home range while keeping them out of the roadway. This suggests that the outrigger fence design may be effective in situations where crossings structures are in place.

Both fencing designs were of sufficient efficacy to allow examination of their effects on deer home ranges and movements. However, if our fence treatments were of sufficient length to prevent circumvention, more crossings may have occurred. Therefore, we suggest that further testing be done to assess the performance of longer stretches of outrigger fences with and without crossing structures (e.g., wildlife overpasses or underpasses) incorporated into them.

MANAGEMENT IMPLICATIONS

Our results emphasize that deer behavior is equally important as barrier efficacy when attempting to mitigate DVCs. Even fences that are highly effective may relocate, exacerbate, or fail to reduce DVCs if they are of insufficient length. Alternately, less substantial fences may be adequate if they extend beyond deer home ranges and have crossing structures incorporated into their design. Although these structures often are expensive, they may become economically feasible when combined with a less expensive fence such as the outrigger design tested herein. Finally, we recommend the use of localized data on deer home range sizes to determine the minimum length of fencing needed to prevent circumvention in high-risk areas.

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Table 2.1 Total number of fence crossings and average number of fence crossings per day, before and after fence construction, by deer encountering a 2.4-m woven-wire fence (n=4) and an outrigger (n=4) fence on Berry College Wildlife Refuge in northwestern GA.

	Fence crossings			Crossings/day		
Treatment	**Pre**	**Post**	**% Reduction**	**Pre (SE)**	**Post (SE)**	**% Reduction (SE)**
Outrigger toward	110	11	90	0.327 (0.086)	0.037 (0.020)	91 (4)
Outrigger away	118	11	91	0.533 (0.142)	0.045 (0.025)	90 (6)
Outrigger pooled	228	22	90	1.018 (0.257)	0.053 (0.035)	92 (6)
2.4 m	124	2	98	0.337 (0.091)	0.002 (0.002)	98 (2)

Table 2.2 Mean 90% home range and 50% core area size, before and after fence construction, for deer encountering a 2.4-m woven-wire fence (n=4), outrigger fence (n=4), and no fence (controls) (n=6) on Berry College Wildlife Refuge in northwestern GA.

	Pre-treatment		**Post-treatment 1**		**Post-treatment 2**	
	N	**Mean (SE)**	**N**	**Mean (SE)**	**N**	**Mean (SE)**
90% *a*-LoCoH home range (ha)						
2.4 m	4	62 (7)	4	29 (2)	2	82 (62)
Outrigger	4	41 (14)	4	24 (5)	3	46 (7)
Control	6	34 (7)	6	23 (3)	5	51 (9)
50% *a*-LoCoH core area (ha)						
2.4 m	4	17 (1)	4	8 (0.3)	2	28 (21)
Outrigger	4	12 (4)	4	6 (1)	3	13 (2)
Control	6	9 (2)	6	6(0.7)	5	11 (2)

Table 2.3 Mean distance between the mean center of all point locations, from pre-treatment to post-treatment 1 and from post-treatment 1 to post-treatment 2, for deer encountering a 2.4-m woven-wire fence (n=4), outrigger fence (n=4), and no fence (controls) (n=6) on Berry College Wildlife Refuge in northwestern GA.

	Pre- to Post-1		Post-1 to Post-2	
	N	**Mean (SE)**	**N**	**Mean (SE)**
Distance between mean center of points (m)				
2.4-m	4	181.3 (62.1)	2	180.0 (139.0)
Outrigger	4	317.8 (152.0)	3	209.3 (68.7)
Control	6	153.0 (28.1)	5	281.6 (64.2)

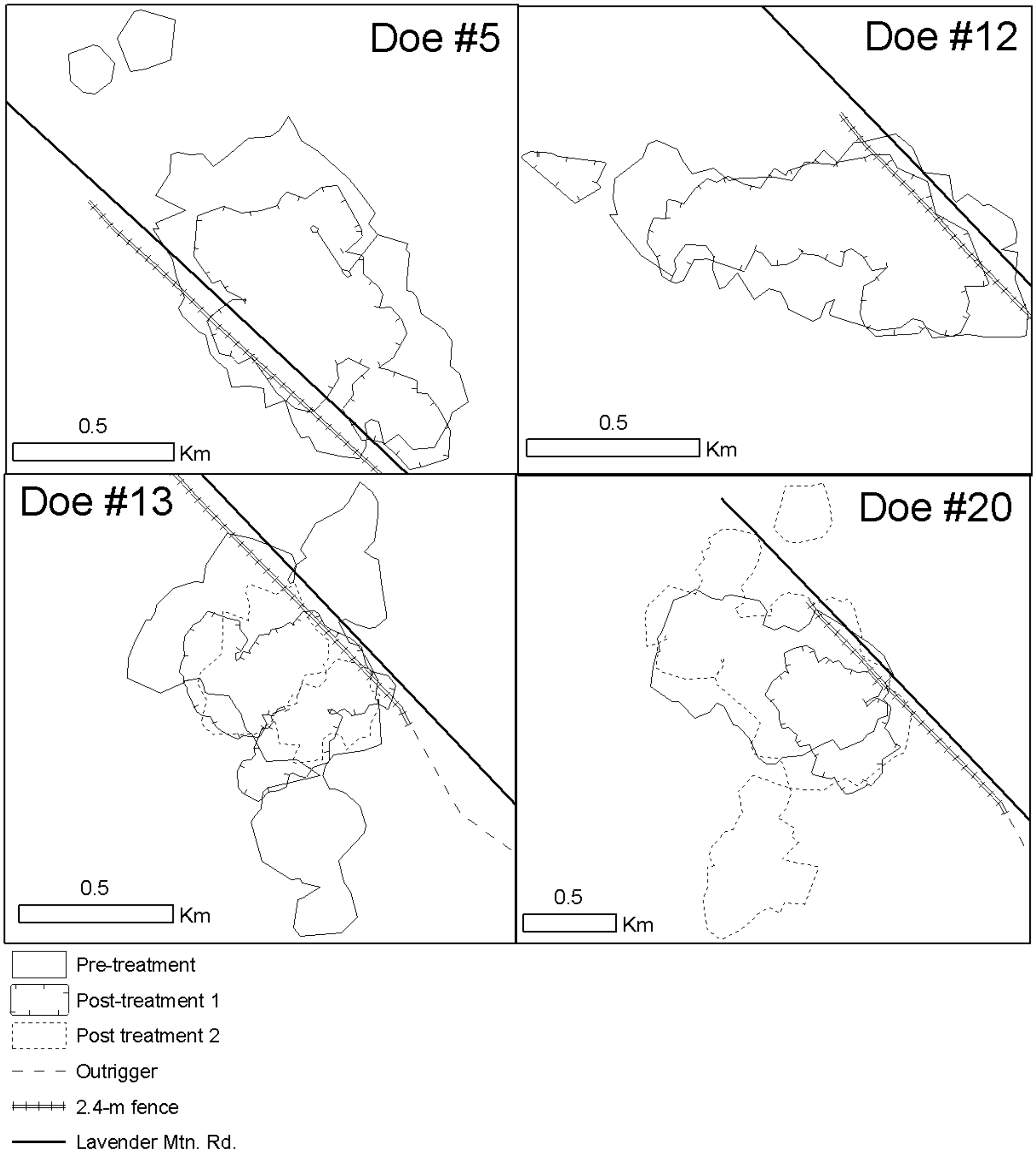

Figure 2.1 90% home ranges and 50% core areas, for deer encountering a 2.4-m woven-wire fence on Berry College Wildlife Refuge in northwestern GA. Pre-treatment was from the time the deer was collared until fence construction began on 17 May 2009, post-treatment 1 was from the time fence construction was completed on 10 June 2009 until 11 September 2009, and post-treatment 2 was from 12 September 2009 until collar recovery in early 2010.

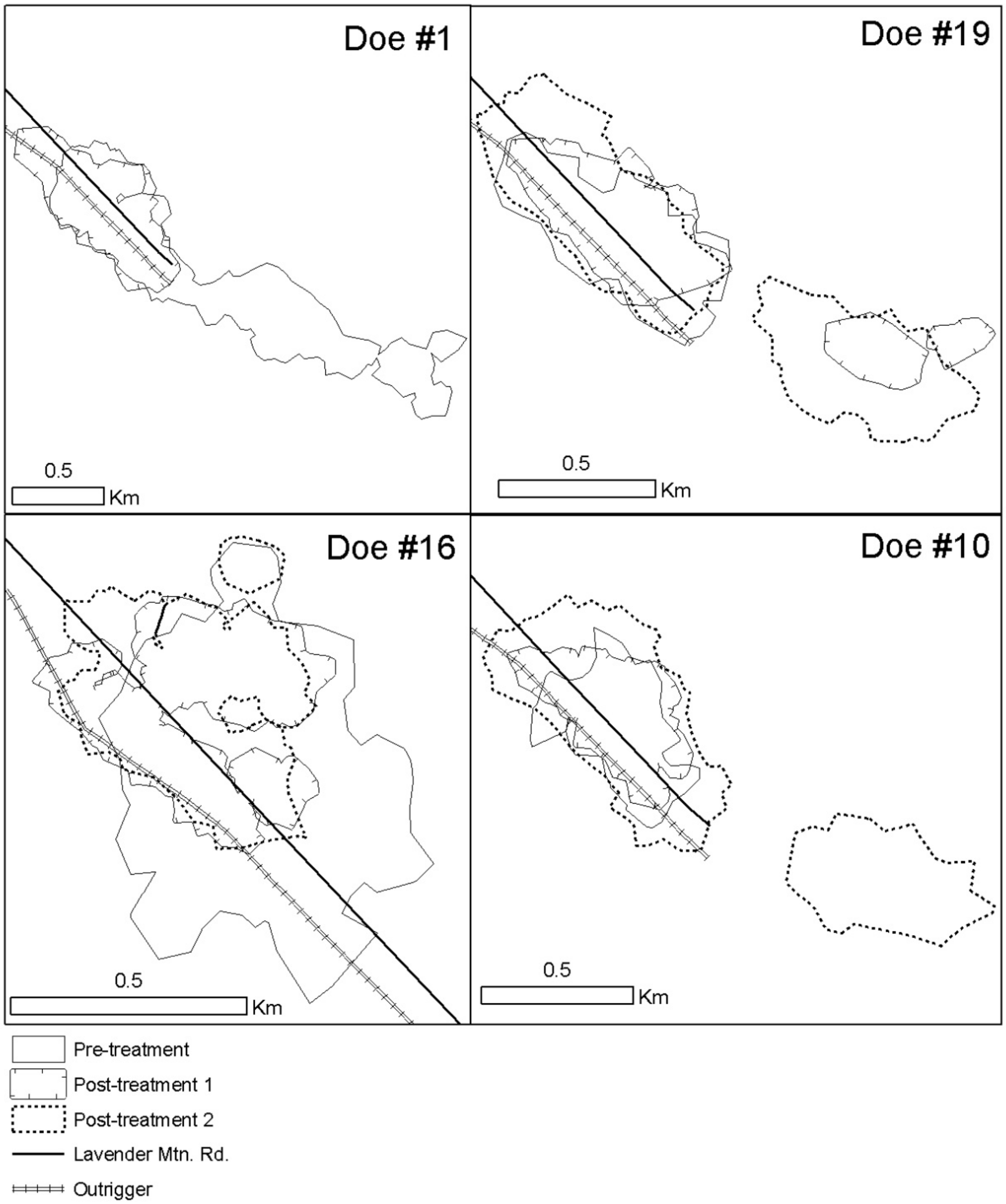

Figure 2.2 90% home ranges and 50% core areas, for deer encountering an outrigger fence on Berry College Wildlife Refuge in northwestern GA. Pre-treatment was from the time the deer was collared until fence construction began on 17 May 2009, post-treatment 1 was from the time fence construction was completed on 10 June 2009 until 11 September 2009, and post-treatment 2 was from 12 September 2009 until collar recovery in early 2010.

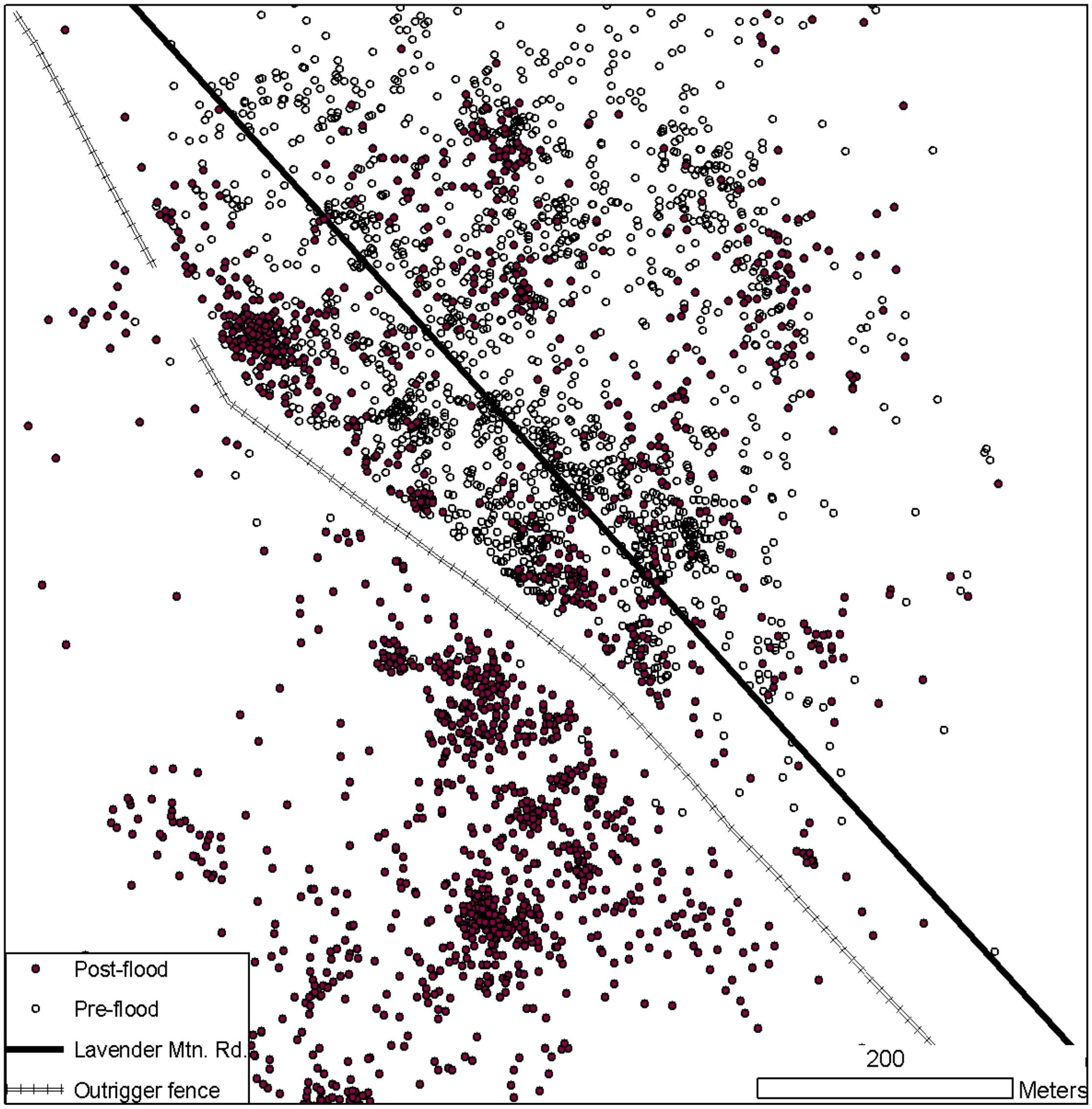

Figure 2.3 GPS point locations for Doe #16 before and after a flood event on 8 December 2009 that left a 50-m gap in an outrigger fence on Berry College Wildlife Refuge in northwestern GA. Points within a 20-m buffer on either side of the fence are not included.

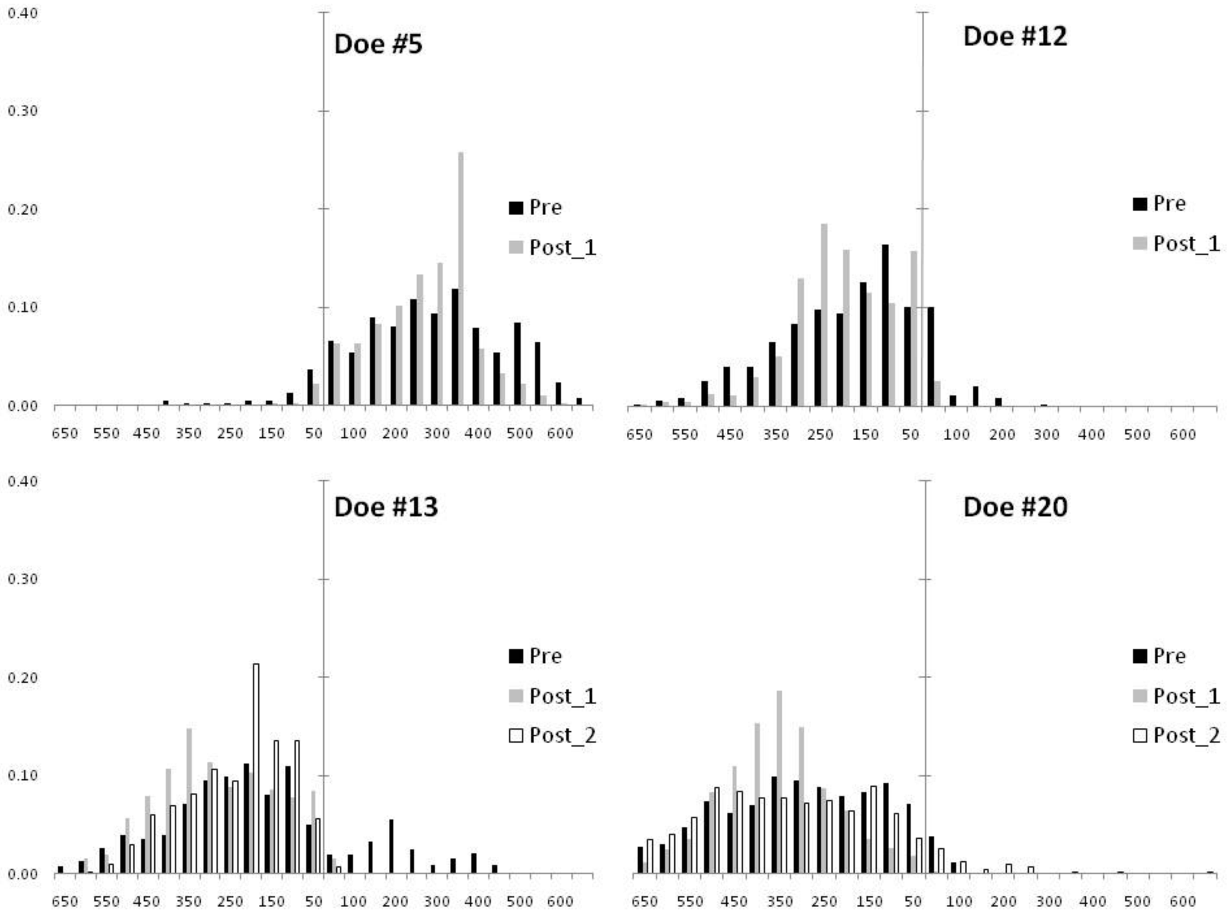

Figure 2.4 Distributions of point locations around a 2.4-m woven-wire fence on Berry College Wildlife Refuge in northwestern GA. Pre-treatment was from the time the deer was collared until fence construction began on 17 May 2009, post-treatment 1 was from the time fence construction was completed on 10 June 2009 until 11 September 2009, and post-treatment 2 was from 12 September 2009 until collar recovery in early 2010. The fence is represented by the vertical axis with the southwestern side to the left of it.

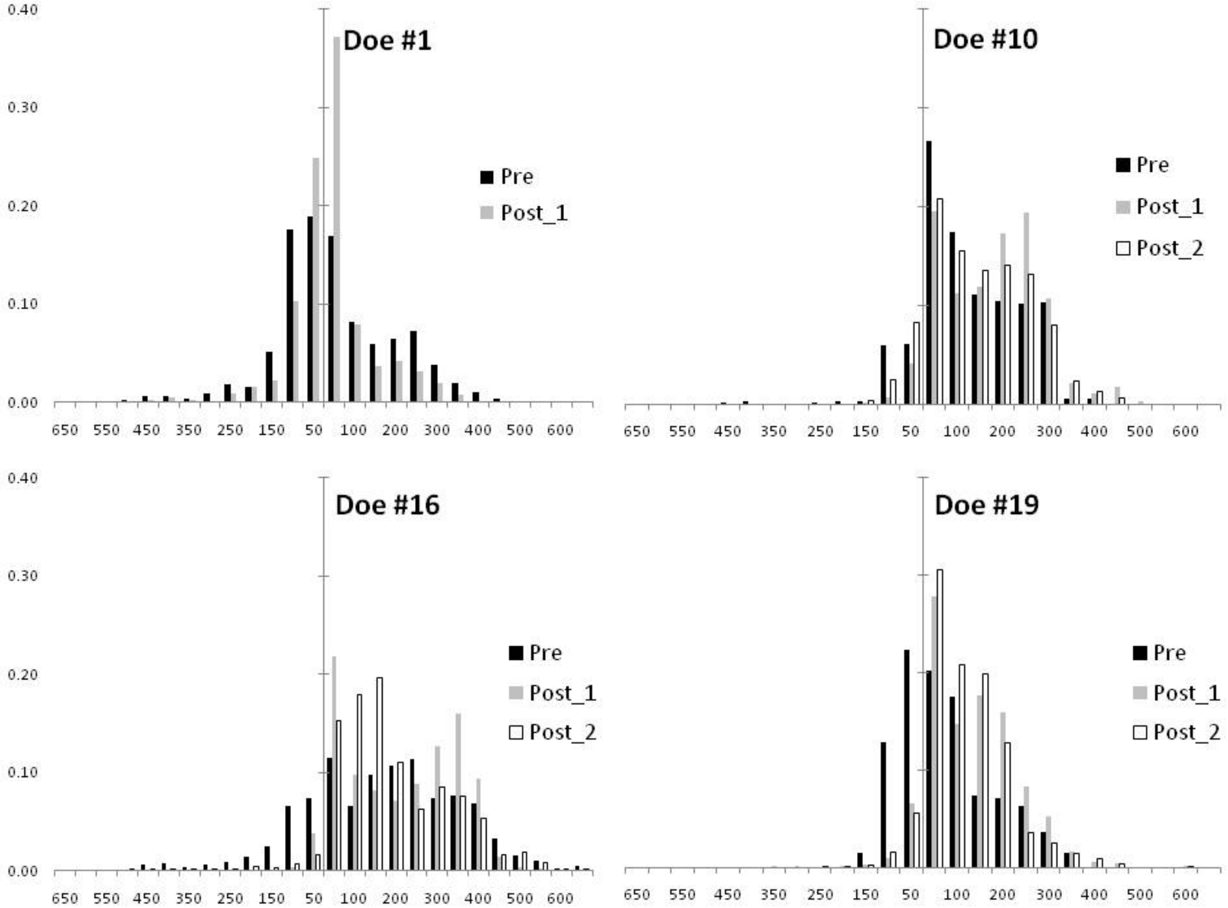

Figure 2.5 Distributions of point locations around an outrigger fence on Berry College Wildlife Refuge in northwestern GA. Pre-treatment was from the time the deer was collared until fence construction began on 17 May 2009, post-treatment 1 was from the time fence construction was completed on 10 June 2009 until 11 September 2009, and post-treatment 2 was from 12 September 2009 until collar recovery in early 2010. The fence is represented by the vertical axis with the southwestern side (outrigger toward) to the left of it.

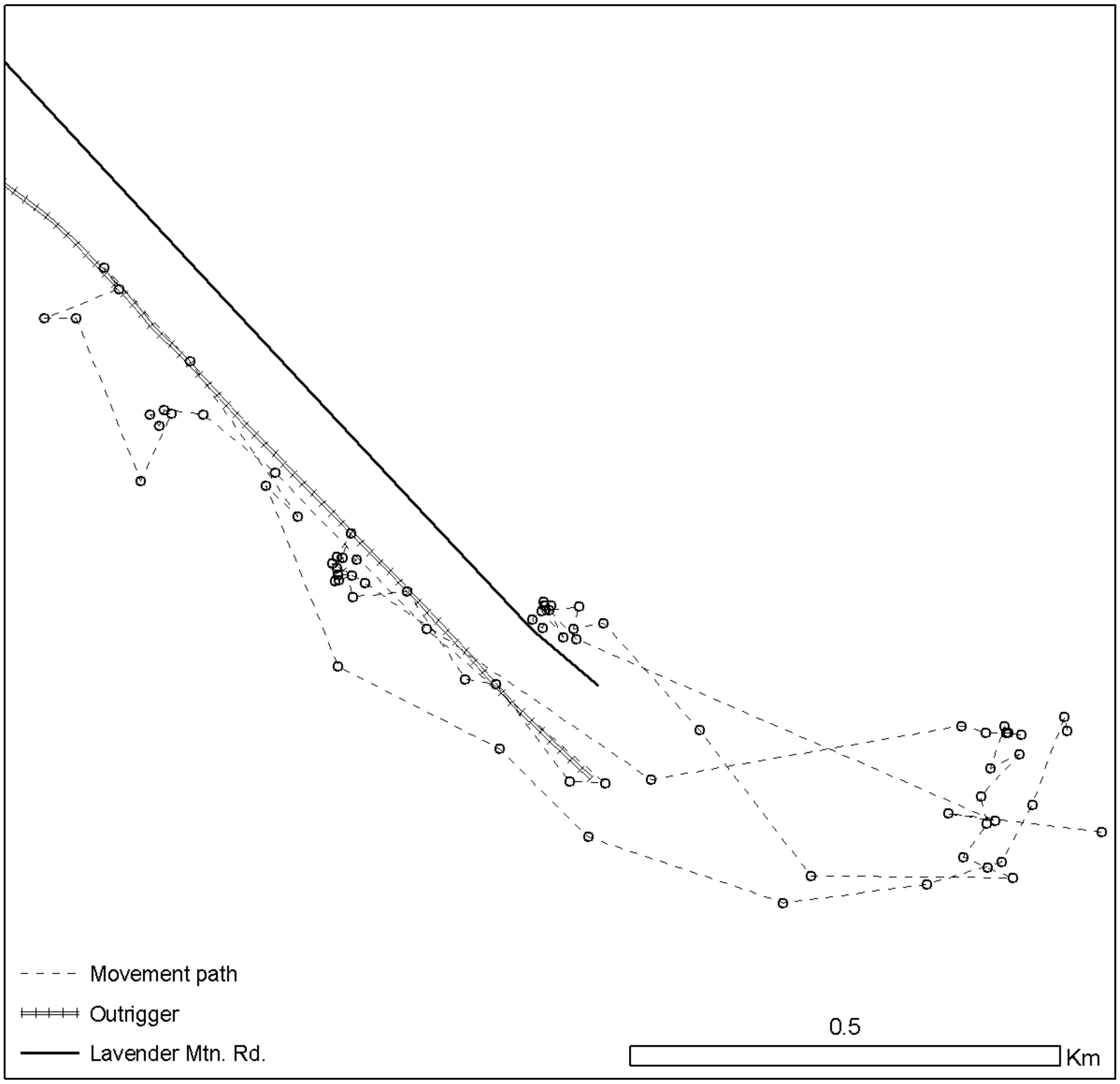

Figure 2.6 A 48-hr movement path showing Doe #19 circumventing an outrigger fence twice on Berry College Wildlife refuge in northwestern GA.

CHAPTER 3

CONCLUSIONS AND MANAGEMENT IMPLICATIONS

Collisions between white-tailed deer and vehicles have been one of the most prevalent and costly types of wildlife-human conflicts for several decades. Despite near extirpation at the turn of the 20th century, deer herds across the United States reached what were likely all-time highs just prior to the turn of the 21st century. Herd sizes in many states are now being brought back to normal levels due to an improved understanding of deer management. However, the concomitant occurrence of increasing human populations and vehicular traffic, increasingly fragmented forests, and decreased hunting access in urban and suburban areas likely means that DVCs will remain problematic.

As a result, state transportation departments are increasingly using deer-proof fencing to exclude deer from roadways. However, traditional deer-proof fencing is often too expensive for use over long distances and these fences can entrap deer in the roadway, thereby exacerbating DVCs. Therefore, I evaluated the efficacy of a traditional deer-proof high fence and a more cost-effective outrigger fence that was previously shown to act as a one-way barrier to deer. In addition, I examined the effects of these fences on deer movements and home range distributions using high-frequency sampling rates with GPS collars.

Interestingly, my results suggest that less-substantial fences, such as the outrigger fence, may be as effective as traditional high fences at preventing deer crossings. However, I found that 3 of 4 deer encountering the outrigger fence continued to access their entire home range after fence construction, via circumventing the end. Because fence-crossing motivation likely is positively correlated with the degree to which roadside fencing excludes deer from their former home range, motivation to cross the fence was probably low for these deer. The only deer that encountered the outrigger fence but did not circumvent it was responsible for the majority of outrigger-fence crossings. These findings suggest that less-substantial, more-economical fences may exclude deer from roadways if they are allowed access to their entire home range by some mechanism. This access can be allowed using wildlife overpasses or underpasses designed to allow deer to cross the roadway safely.

Our results emphasize that deer behavior is equally important as barrier efficacy when attempting to mitigate DVCs. Even fences that are highly effective may relocate, exacerbate, or fail to reduce DVCs if they are of insufficient length. Alternately, less substantial fences may be adequate if they extend beyond deer home ranges and have crossing structures incorporated into their design. Although these structures often are expensive, they may become economically feasible when combined with a less expensive fence such as the outrigger design tested herein. Finally, we recommend the use of localized data on deer home range sizes to determine the minimum length of fencing needed to prevent circumvention in high-risk areas.

Because my study focused on the efficacy and effects of these fencing types on adult does on one study site, extension of my study results to adult bucks or different sites must be done with caution. Home ranges of adult bucks are typically much larger than those of adult does, and extension of fencing beyond the ends of their home ranges would be even more difficult. Likewise, others have reported much larger home ranges for adult does than those of the adult does in my study.

A great number of studies have addressed the problem of DVCs. The authors of these studies have acknowledged the need to understand the effects of roadway fencing on deer, yet my study is the first to examine these interactions using GPS collars. We urge that similar research be done to assess this interaction on different geographic areas and in a variety of situations.

APPENDIX A

HOME RANGES OF TREATMENT AND CONTROL DEER AT BERRY COLLEGE, FLOYD COUNTY, GEORGIA BEFORE AND AFTER FENCE CONSTRUCTION

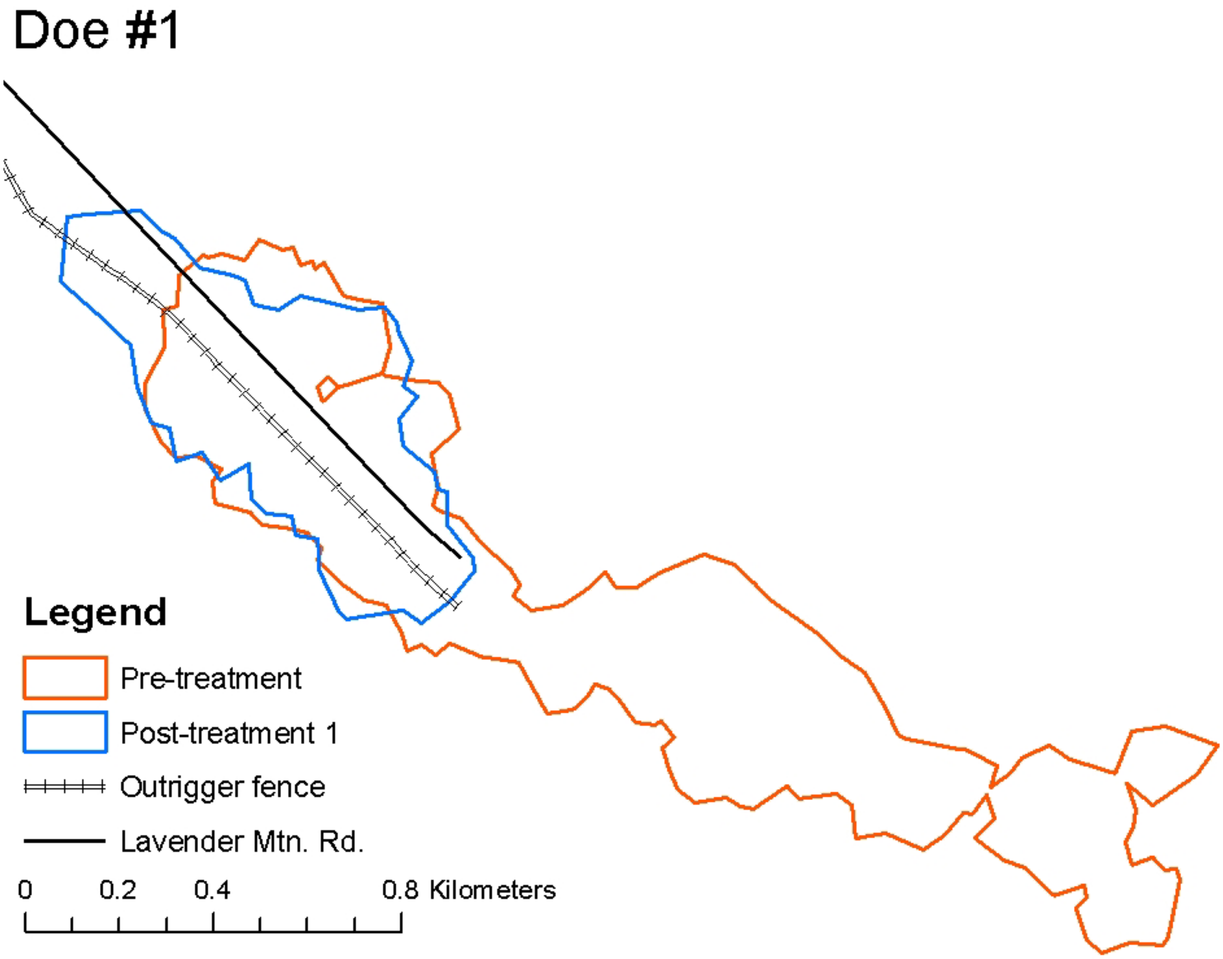

Figure 1. 90% *a*-LoCoH home ranges of outrigger treatment Doe #1 during pre-treatment and post-treatment 1 periods at Berry College Wildlife Refuge.

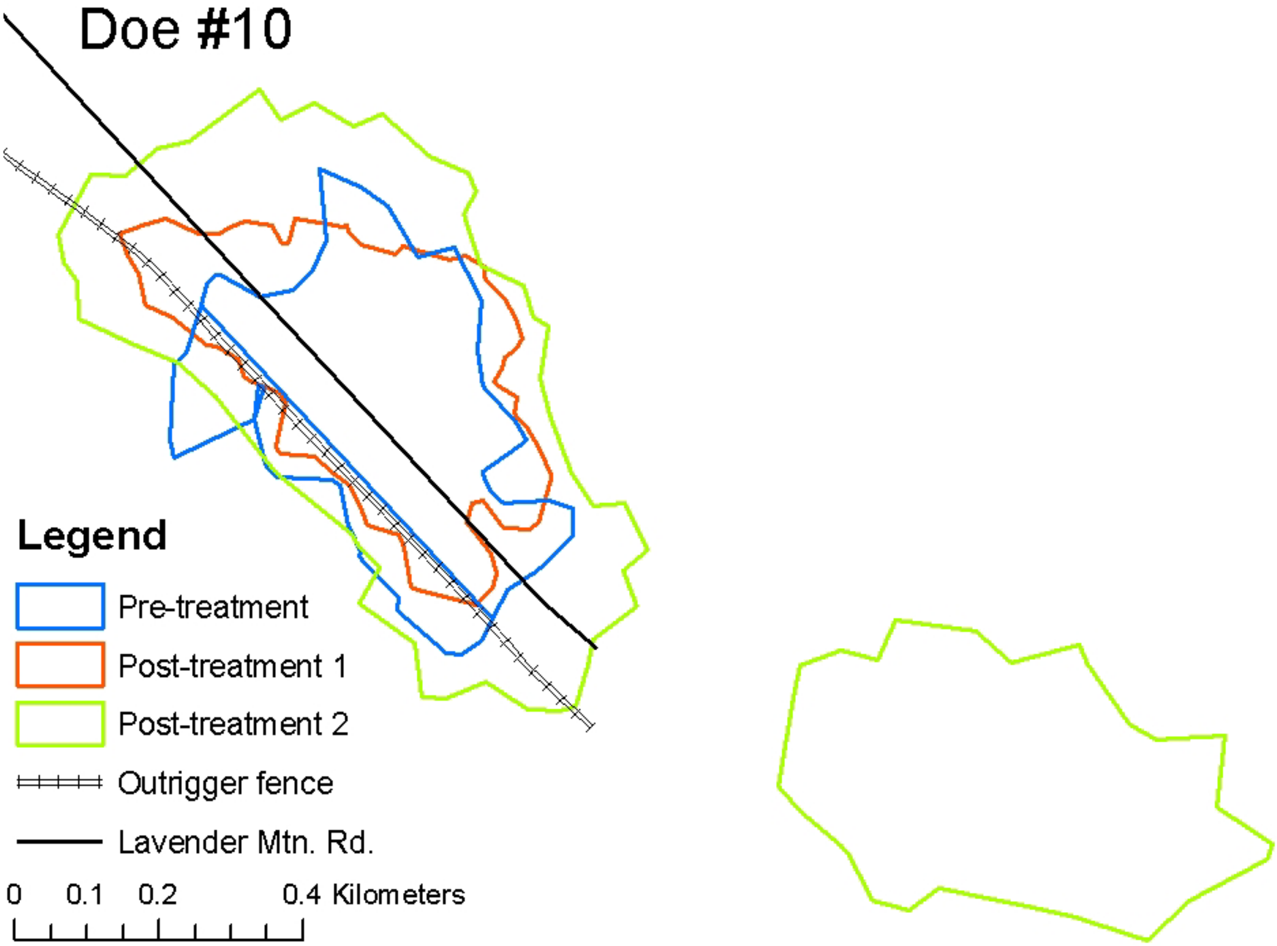

Figure 2. 90% *a*-LoCoH home ranges of outrigger treatment Doe #10 during pre-treatment, post-treatment 1, and post-treatment 2 periods at Berry College Wildlife Refuge.

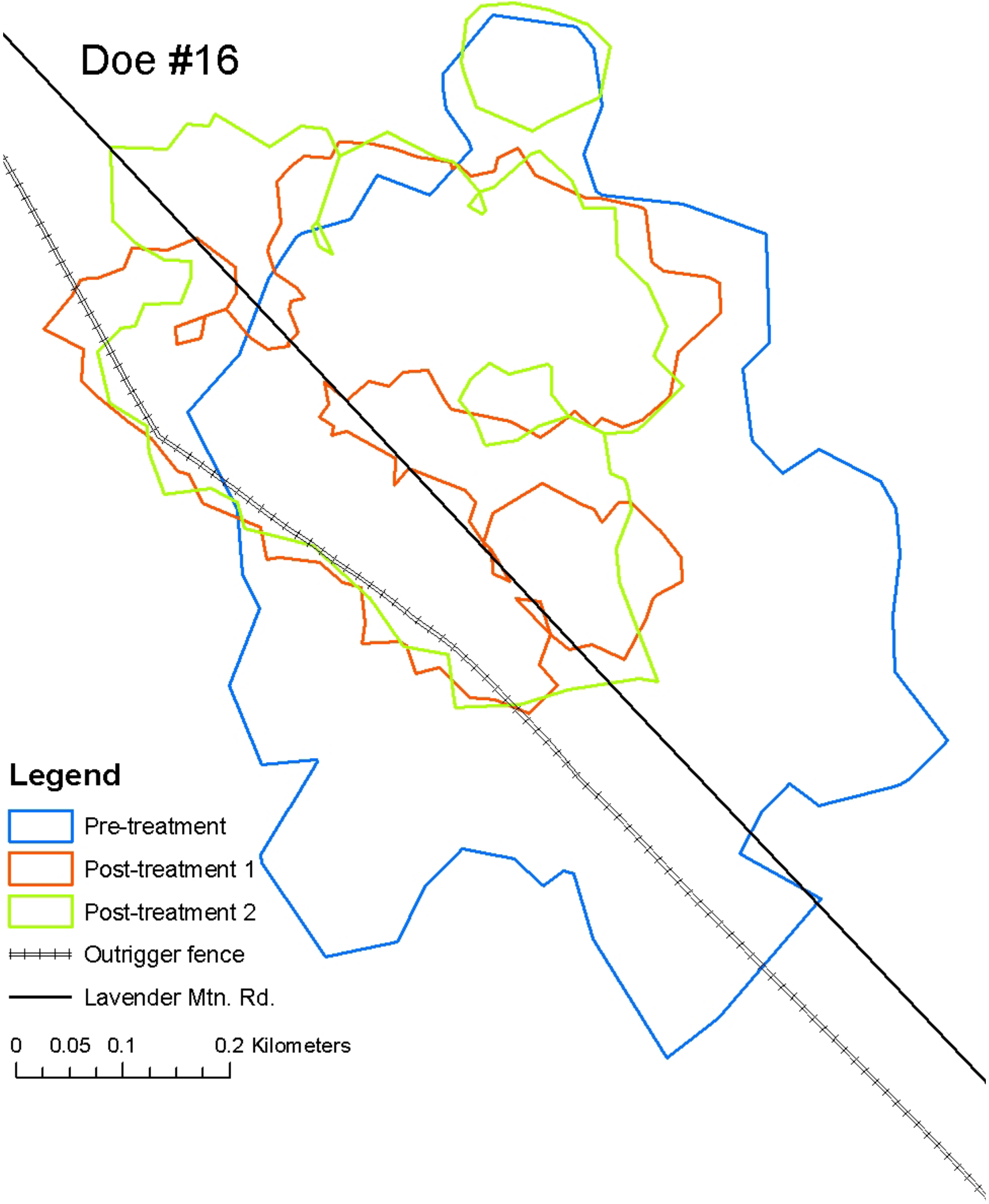

Figure 3. 90% *a*-LoCoH home ranges of outrigger treatment Doe #16 during pre-treatment, post-treatment 1, and post-treatment 2 periods at Berry College Wildlife Refuge.

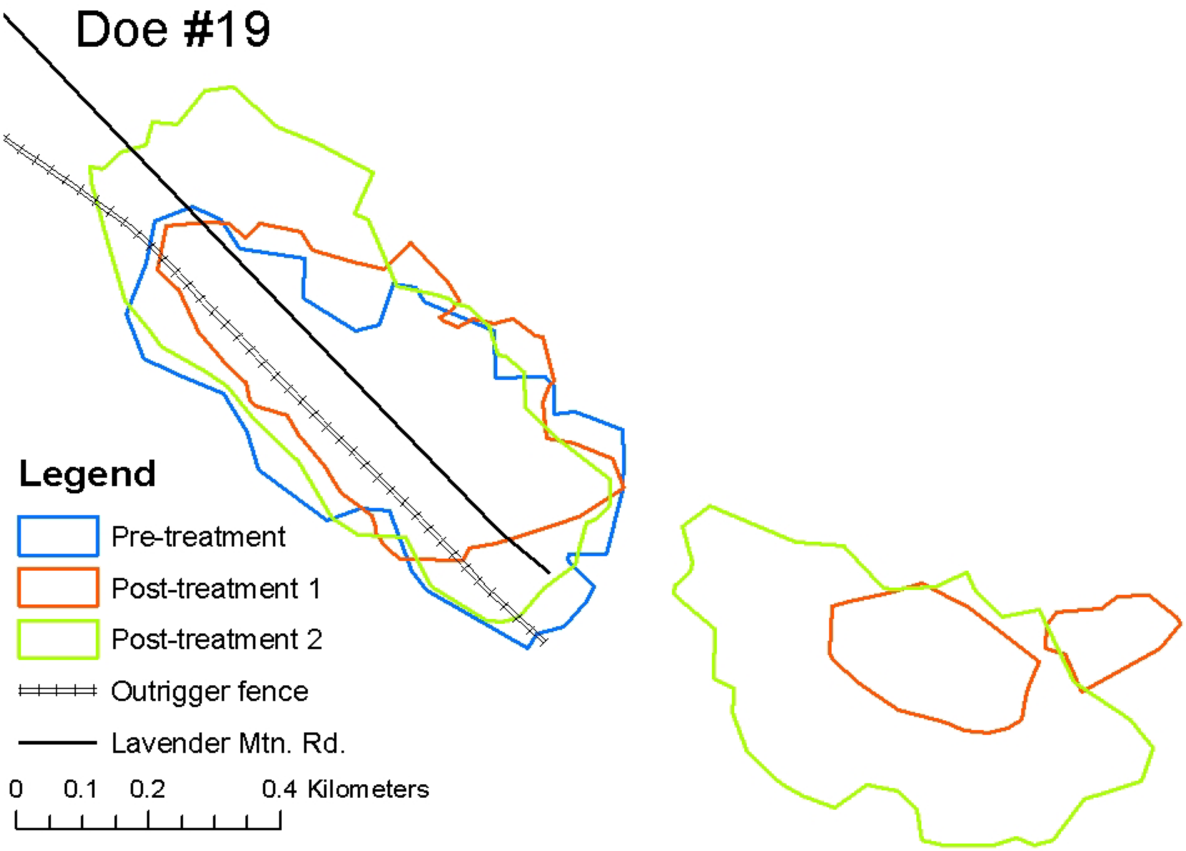

Figure 4. 90% *a*-LoCoH home ranges of outrigger treatment Doe #19 during pre-treatment, post-treatment 1, and post-treatment 2 periods at Berry College Wildlife Refuge.

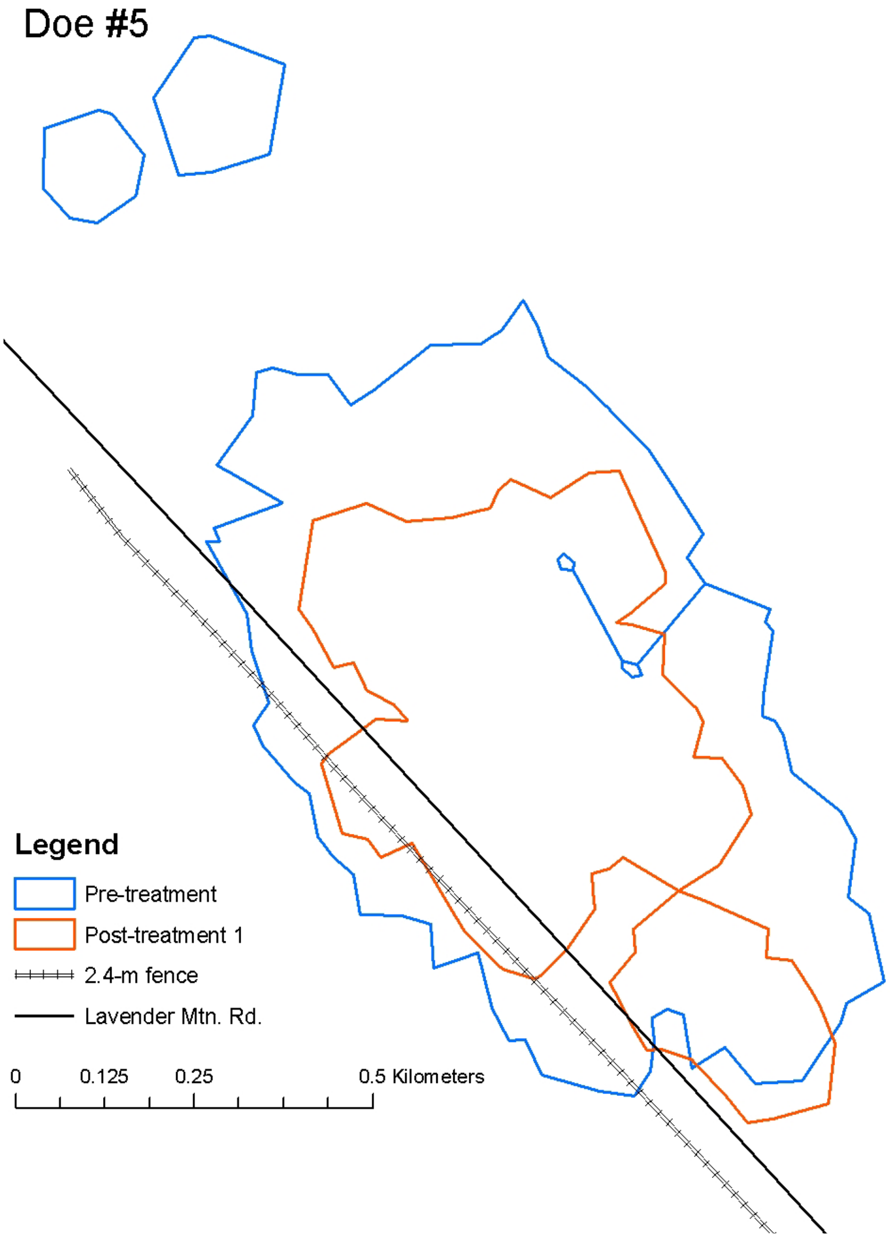

Figure 5. 90% *a*-LoCoH home ranges of 2.4-m treatment Doe #5 during pre-treatment and post-treatment 1 periods at Berry College Wildlife Refuge.

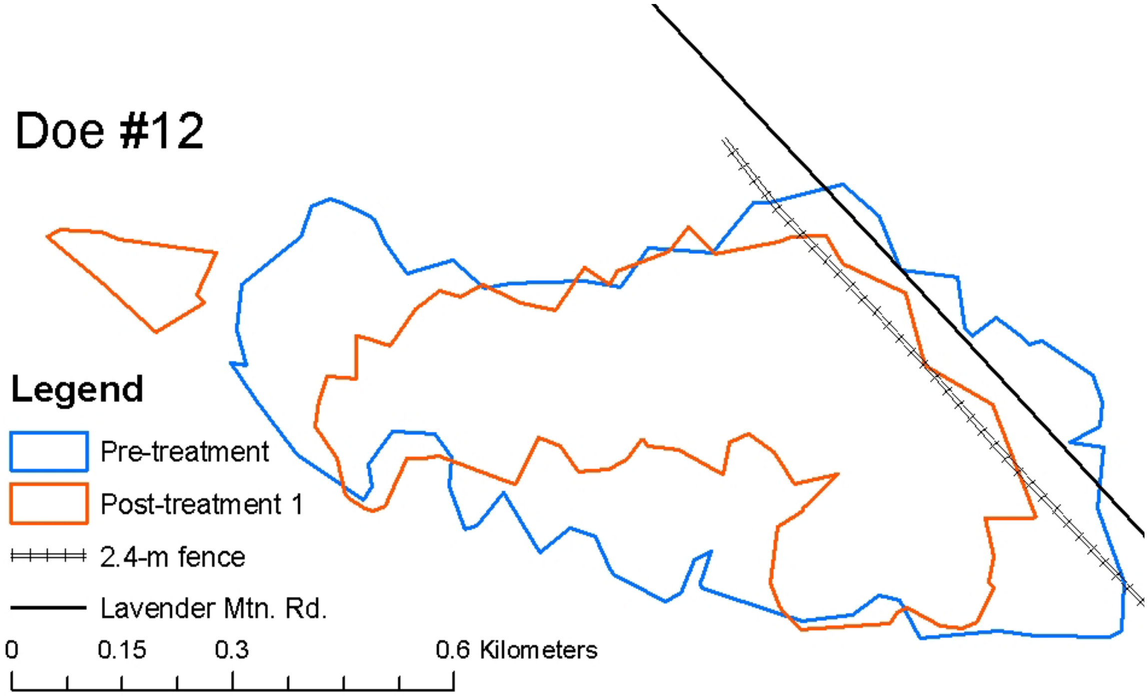

Figure 6. 90% *a*-LoCoH home ranges of 2.4-m treatment Doe #12 during pre-treatment and post-treatment 1 periods at Berry College Wildlife Refuge.

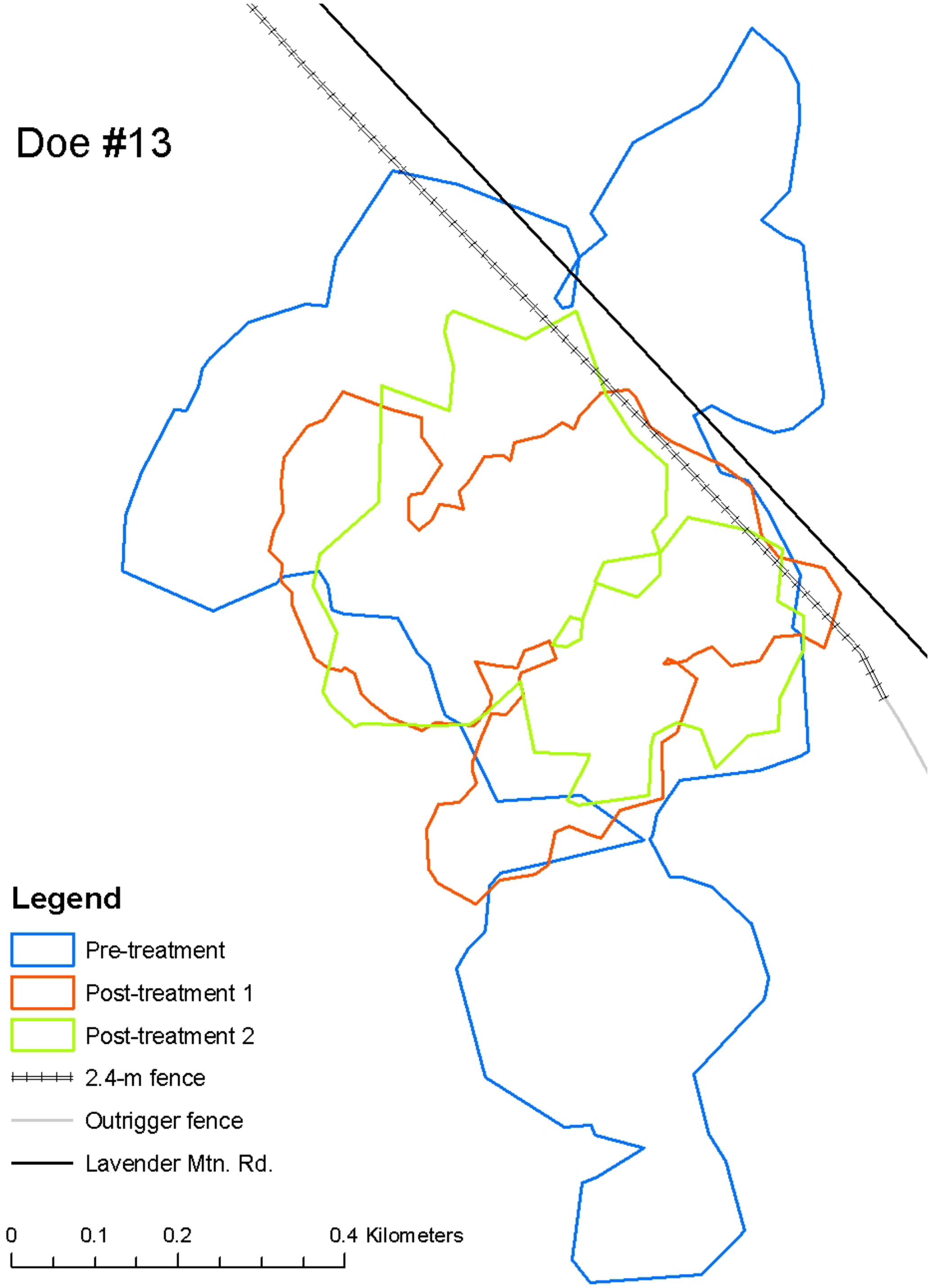

Figure 7. 90% *a*-LoCoH home ranges of 2.4-m treatment Doe #13 during pre-treatment and post-treatment 1 periods at Berry College Wildlife Refuge.

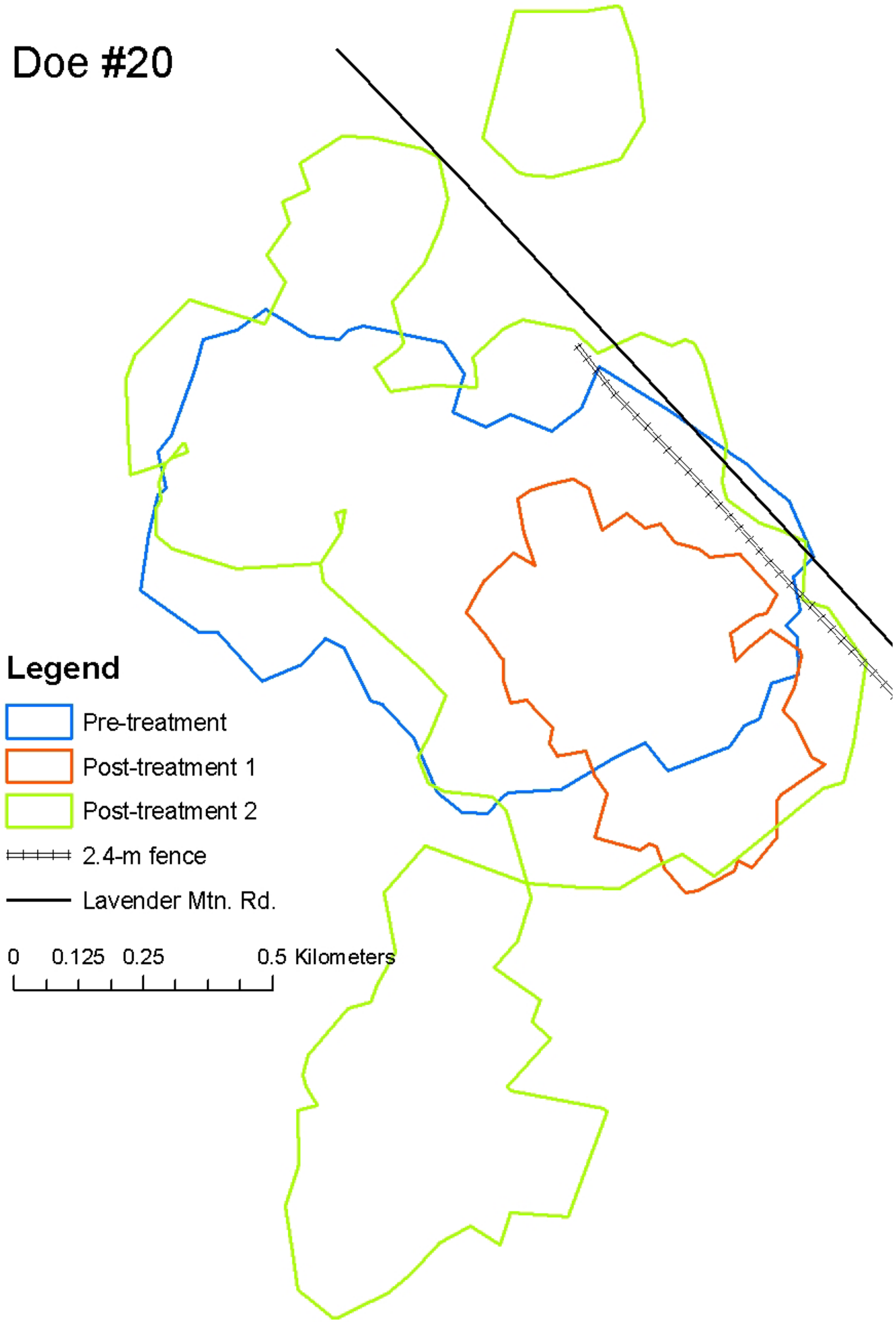

Figure 8. 90% *a*-LoCoH home ranges of 2.4-m treatment Doe #20 during pre-treatment and post-treatment 1 periods at Berry College Wildlife Refuge.

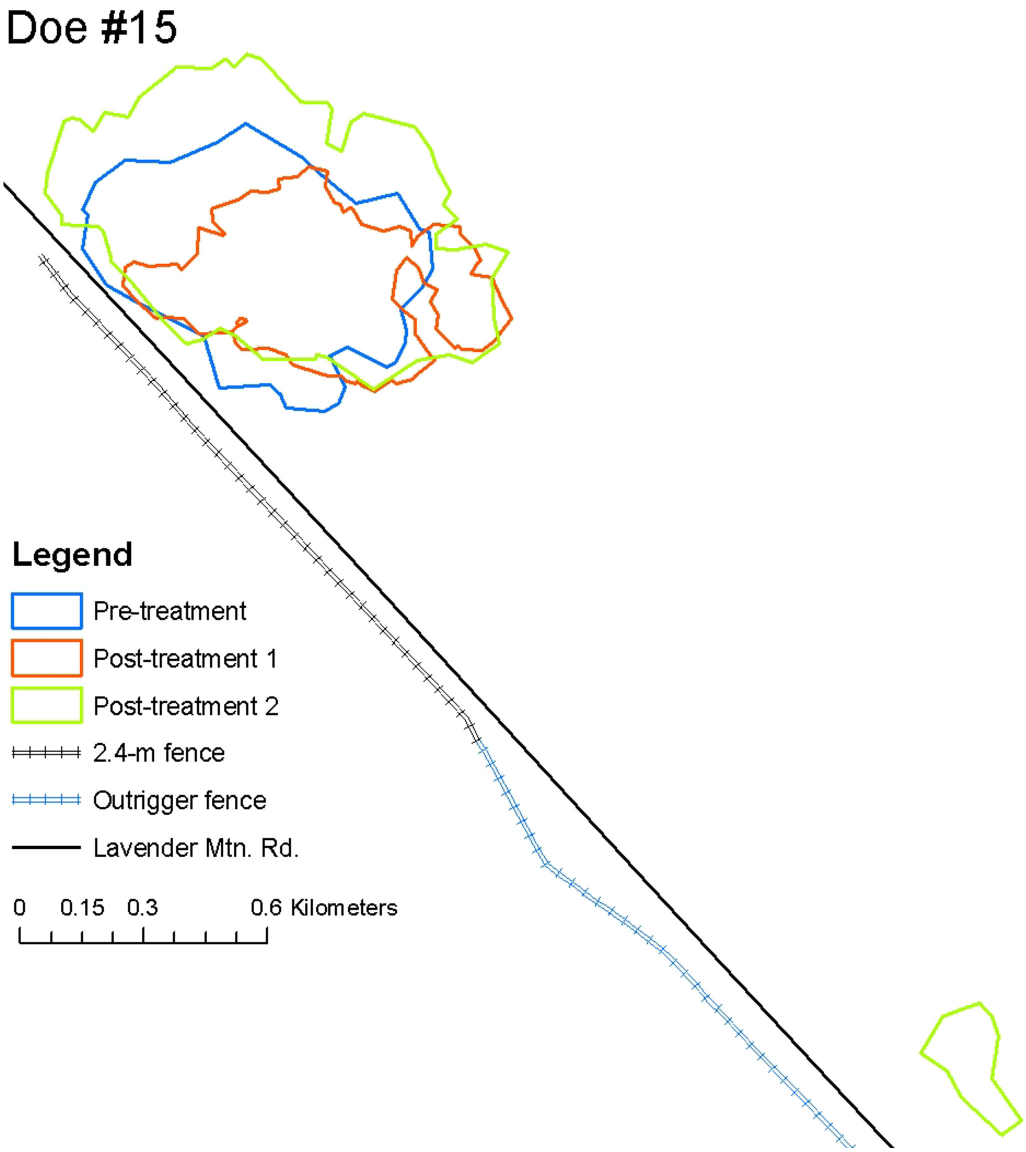

Figure 9. 90% *a*-LoCoH home ranges of control Doe #15 during pre-treatment, post-treatment 1, and post-treatment 2 periods at Berry College Wildlife Refuge.

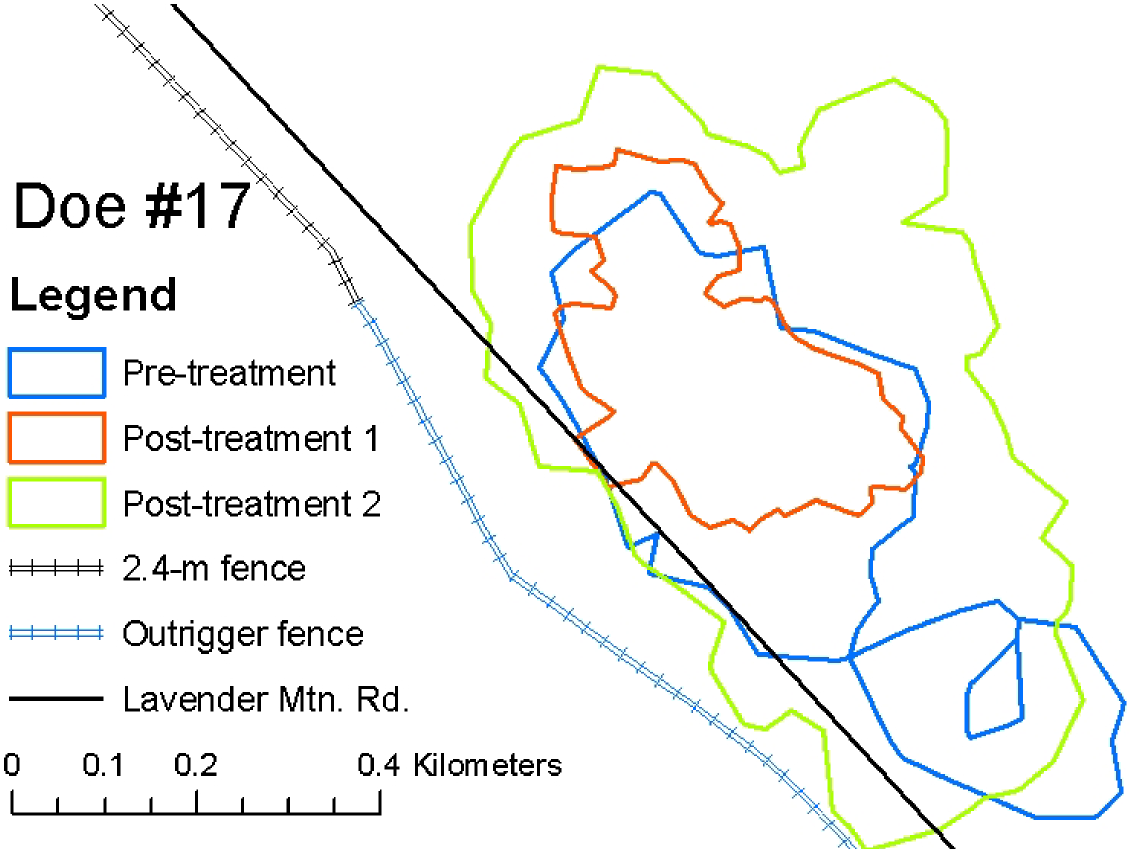

Figure 10. 90% *a*-LoCoH home ranges of control Doe #17 during pre-treatment, post-treatment 1, and post-treatment 2 periods at Berry College Wildlife Refuge.

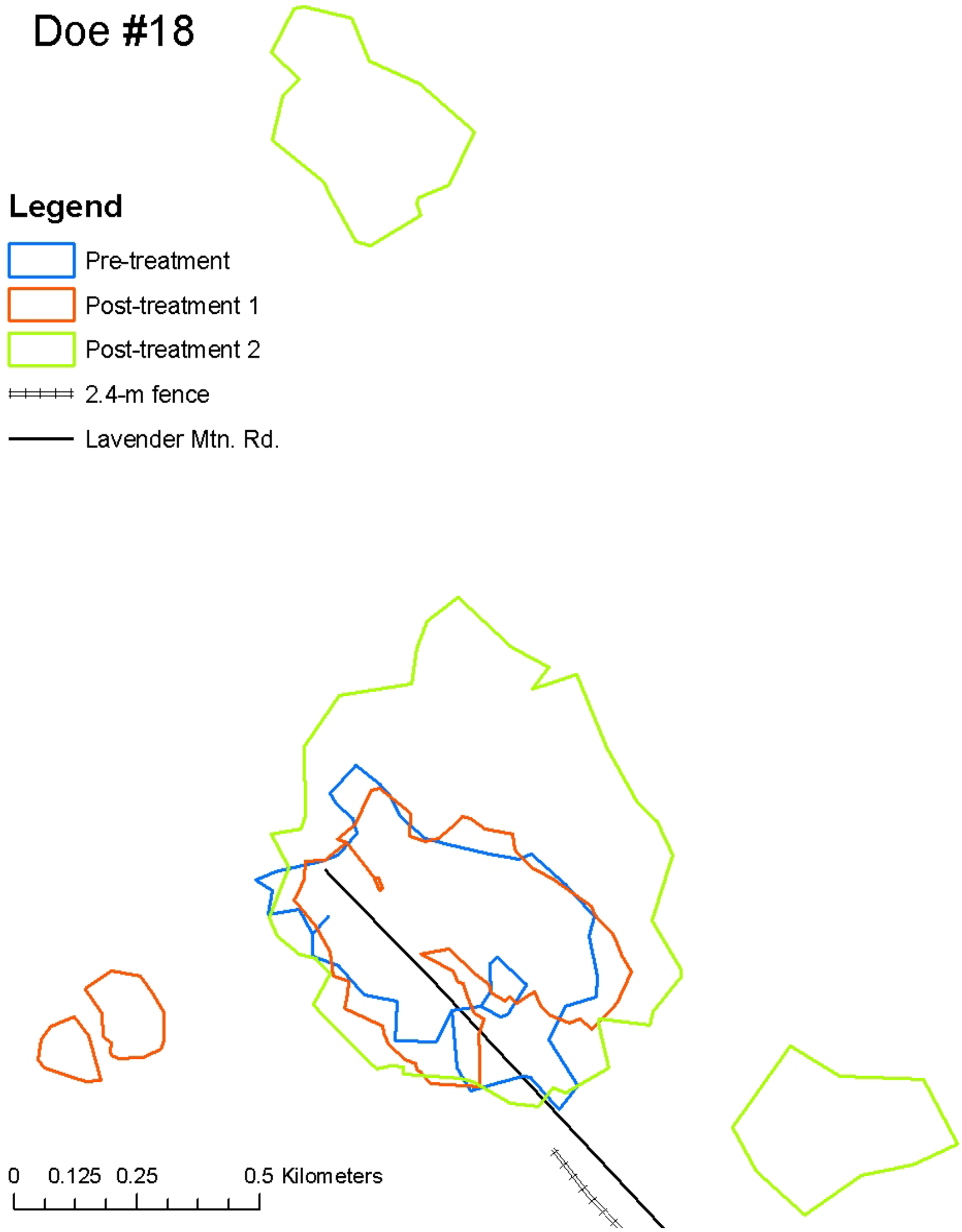

Figure 11. 90% *a*-LoCoH home ranges of control Doe #18 during pre-treatment, post-treatment 1, and post-treatment 2 periods at Berry College Wildlife Refuge.

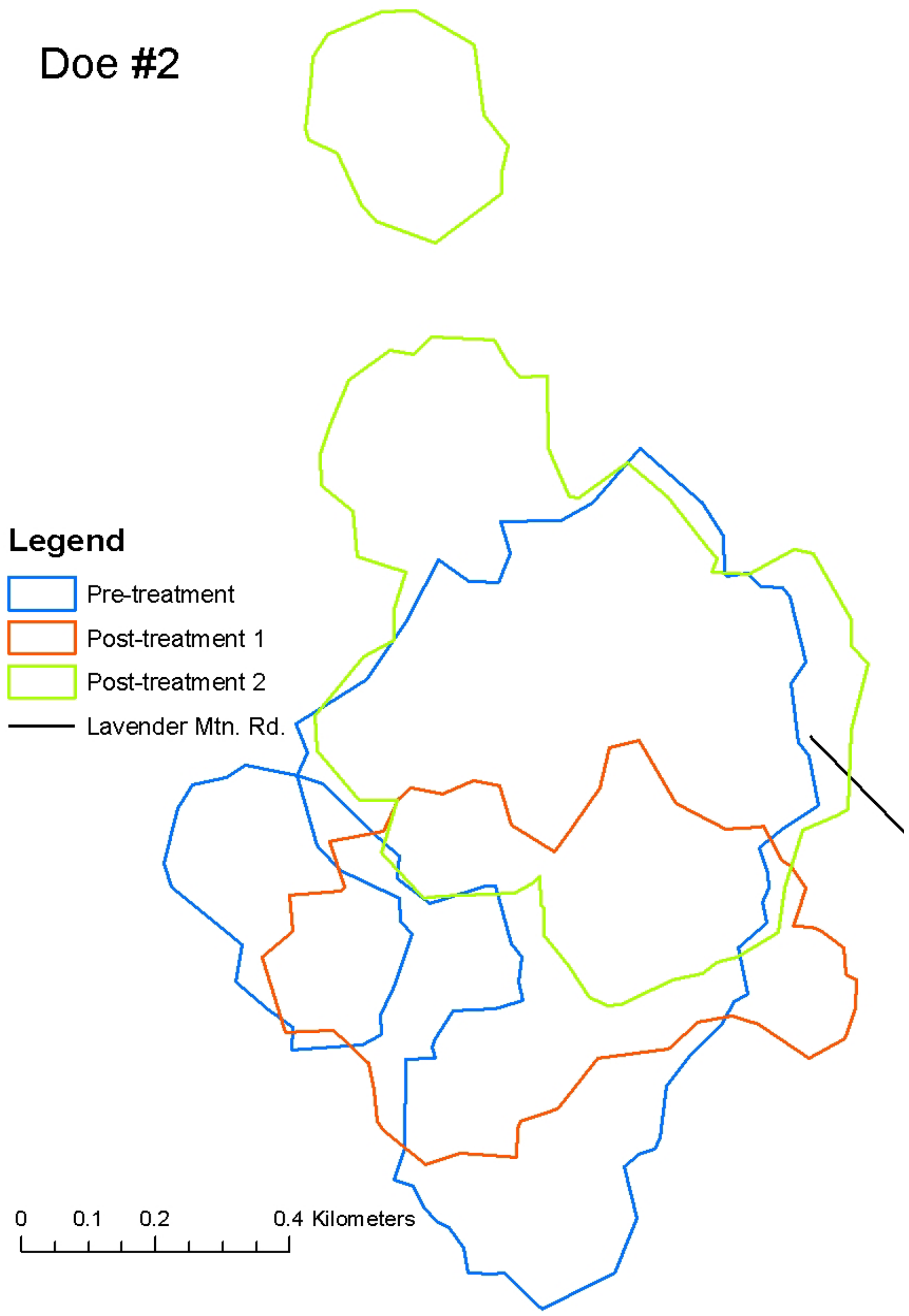

Figure 12. 90% *a*-LoCoH home ranges of control Doe #2 during pre-treatment, post-treatment 1, and post-treatment 2 periods at Berry College Wildlife Refuge.

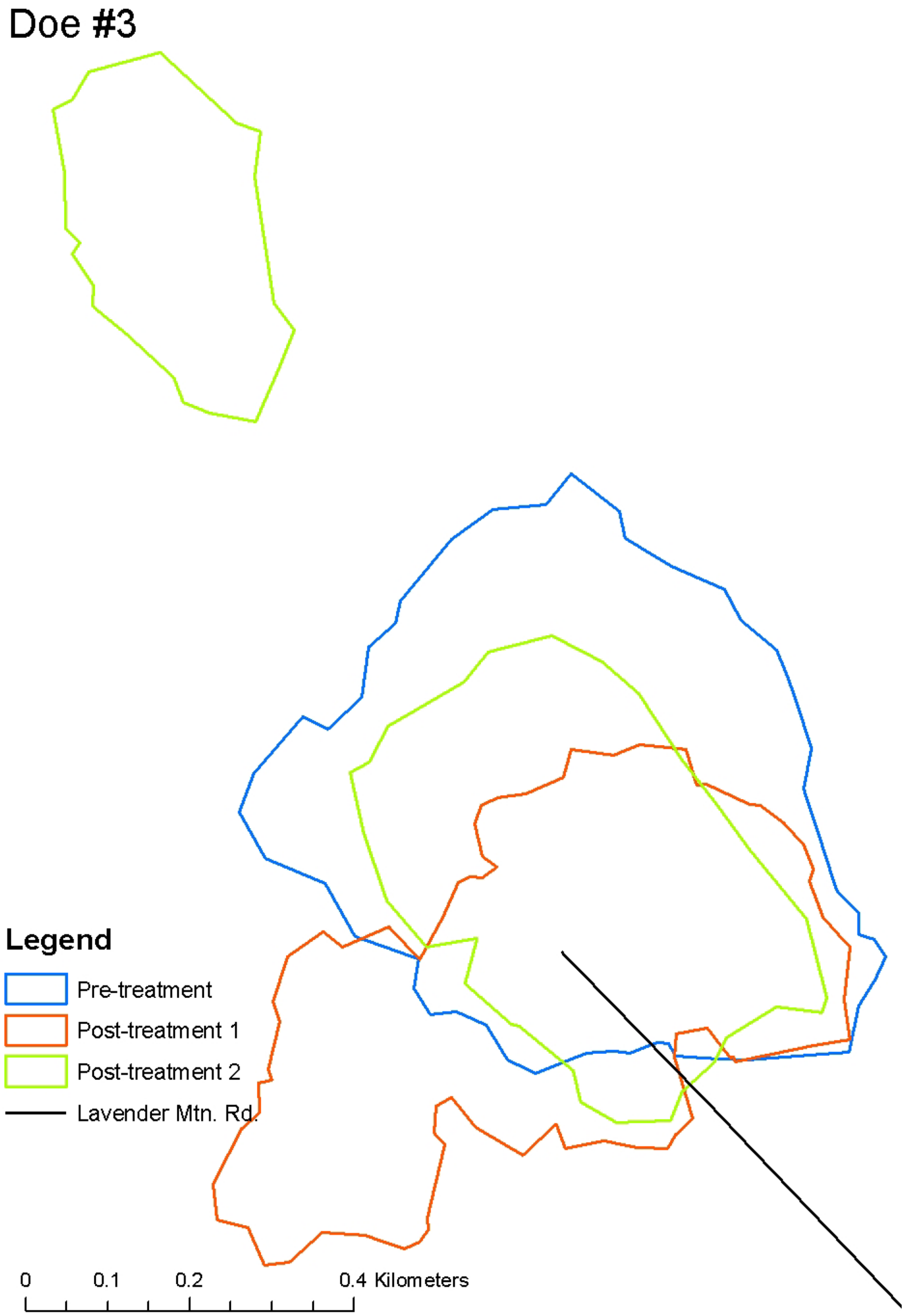

Figure 13. 90% *a*-LoCoH home ranges of control Doe #3 during pre-treatment, post-treatment 1, and post-treatment 2 periods at Berry College Wildlife Refuge.

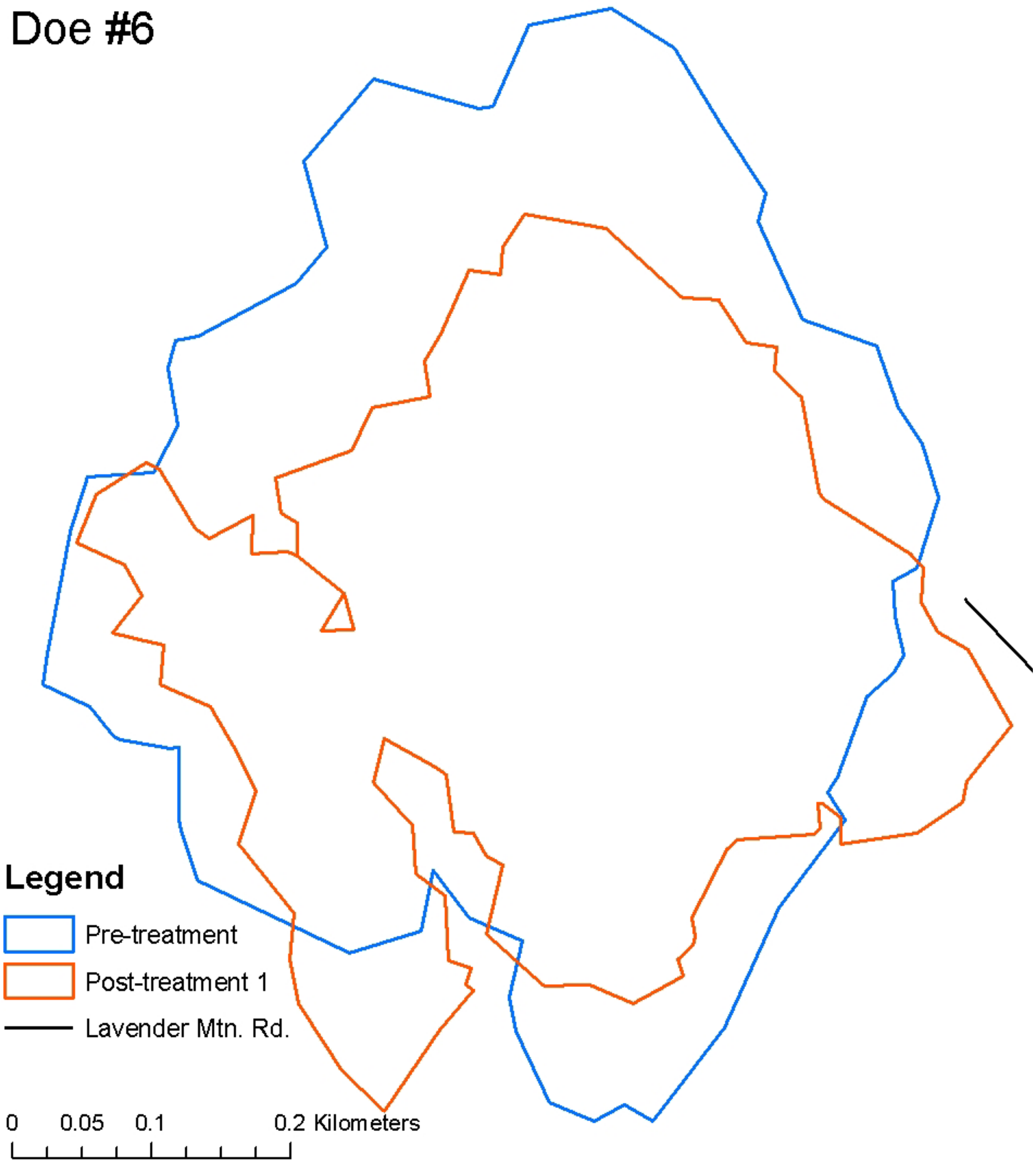

Figure 14. 90% *a*-LoCoH home ranges of control Doe #6 during pre-treatment, post-treatment 1, and post-treatment 2 periods at Berry College Wildlife Refuge.

APPENDIX B

COSTS AND DIAGRAMS OF OUTRIGGER AND 2.4-M WOVEN-WIRE FENCE TREATMENTS CONSTRUCTED AT BERRY COLLEGE, FLOYD COUNTY, GEORGIA

Table 1. Construction cost per meter of outrigger fence and 2.4-m woven-wire fence treatments constructed on Berry College, Floyd County, Georgia.

	Materials	**Labor**	**Total**
Cost of construction ($/m)			
2.4-m	$5.88	$3.48	$9.36
Outrigger	$6.75	$0.62	$7.37

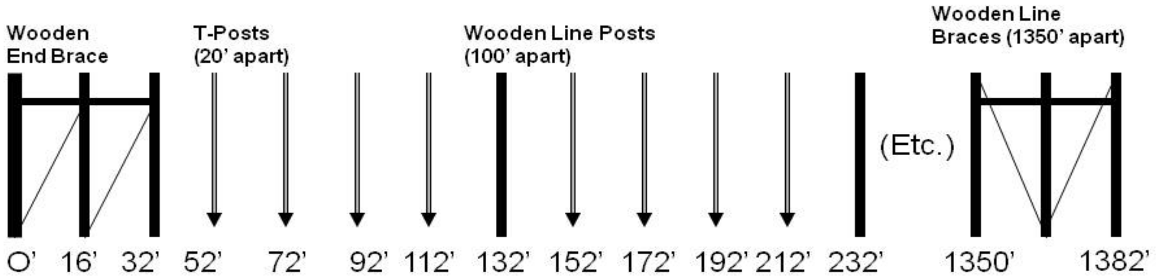

Figure 1. Diagram of 2.4-m and outrigger support post spacing for the 3.2-km fence treatment constructed on Berry College, Floyd County, Georgia. Spacing units are in feet.

VISUAL THRESHOLD IN WHITE-TAILED DEER AS DETERMINED BY BEHAVIORAL ASSAY

submitted to

Graduate Committee
Warnell School of Forestry and Natural Resources
University of Georgia
Athens, Georgia 30602

In Partial Fulfillment of the Masters of Science Degree

by

Bradley Cohen
Warnell School of Forestry and Natural Resources
University of Georgia
Athens, Georgia 30602

May 19, 2010

INTRODUCTION

Abundant white-tailed deer, *Odocoileus virginianus* (Zimmermann, 1780), populations can result in significant societal conflicts when they overlap with dense human populations. Annually on U.S. roadways, deer-vehicle collisions (DVCs) result in $1.1 billion in damages and the loss of 200 human lives (Sullivan and Messmer 2003). Approximately 1.5 million drivers are involved in DVCs each year, many of which go unreported (State Farm Insurance Company 2006). Various techniques have been employed to mitigate DVCs, most of which have proven ineffective and costly (D'Angelo et al. 2004).

Mitigation techniques aimed at reducing DVCs typically fail to consider important aspects of deer physiology, such as hearing and vision. Deterrent devices that rely on deer vision or hearing, such as roadside reflectors and deer whistles, are ineffective at altering deer behavior and reducing DVCs (D'Angelo et al. 2006, Valitzski et al. 2009). Although recent studies have investigated the visual physiology of deer (D'Angelo et al. 2008) and despite a wealth of knowledge about white-tailed deer, little is known about deer vision and its role in deer behavior (VerCauteren and Pipas 2003) which may confound production of effective DVC deterrents.

Wildlife warning reflectors are commonly employed along highways in attempts to reduce DVCs by "provid[ing] an optical warning fence to deer" (Strieter Corp., unpublished instruction manual:3). These reflectors are mounted on posts along roadsides and contain two reflective mirrors with plastic elements that redirect light from car-lights into the roadside corridors. However, these systems are designed without a full understanding of deer visual capabilities and echo a significant problem with DVC deterrent devices – these systems are designed without exploiting the senses of the white-tailed deer (D'Angelo 2004). The color most commonly reflected from these devices is red, a wavelength well above the peak sensitivity of a deer's retinal photoreceptors (Zacks 1985, Jacobs et al. 1994). Therefore, it is not surprising that numerous studies have shown these reflectors and other devices reliant on deer vision are ineffective at reducing DVCs (Boyd 1966, Gilbert 1982, Zacks 1986, Waring et al. 1991, Armstrong 1992, Reeve and Anderson 1993, Sielecki 2001, D'Angelo et al. 2006, Blackwell and Seamans 2008) or altering deer behavior (Waring et al. 1991; Ujvári et al. 1998; VerCauteren et al. 2003, 2006; D'Angelo et al. 2006). A better understanding of the visual capability of white-tailed deer would provide the basis for developing efficient and physiologically relevant strategies to reduce deer-vehicle collisions (D'Angelo et al. 2004, 2006; Blackwell and Seamans 2008).

Most of what is known about deer vision is based on an understanding of the general physiological mechanisms underlying vision, even though similar assumptions have been found to be untrue in other species (Jacobs 1992). Understanding the visual capabilities of any animal requires coupling physiological studies with behavioral observation and substantiation (Jacobs 1992). To date, only three studies have been published that used a behavioral measure to examine the visual capabilities of white-tailed deer (Zacks and Budde 1983, Zacks 1985, Smith et al. 1989). However, each of these studies was confounded by small sample size, as well as brightness, luminance and other variables that influence visual systems (VerCauteren and Pipas 2003).

Previously, D'Angelo (2007) examined morphological characteristics of the white-tailed deer eye. My research will use behavioral measures of deer visual thresholds, to delineate the differences between reported photoreceptic activity (Jacobs et al. 1994) and perceptive sensitivity particularly at the purported extreme ends of the deer's visual spectrum.

BACKGROUND

The eye of the white-tailed deer is typical of mammals in that light travels through the cornea, enters the eye via the pupil opening, and passes through the lens, aqueous humour, and vitreous humour before striking the retina (Walls, 1942). The retina contains photoreceptors responsible for converting the stimulus light into a neurological signal that is sent via the optic nerve to the brain where perception of the light occurs.

Deer eyes are well adapted to low light conditions, containing a tapetum lucidum that acts as a mirror, reflecting incident light that hasn't been absorbed by photoreceptors back to the retina (Duke-Elder 1958). The tapetum lucidum is a half-moon-shaped structure specialized for amplifying visual sensitivity and acuity of darker objects (D'Angelo et al. 2008). The tapetum lucidum of white-tailed deer is specialized to reflect short-wavelength blues and medium wavelength yellows (D'Angelo et al. 2008). Therefore, light that enters the eye of a white-tailed deer has a chance to be absorbed multiple times, and sensitivity to blue-yellowish wavelengths is enhanced. It is the tapetum lucidum that helps make the white-tailed deer's eye light-sensitive, providing an improved interpretation of visual images in low-light conditions (Ali and Klyne 1985).

The anatomical structure of the white-tailed deer eye is well adapted for their crepuscular activity (D'Angelo et al. 2008). Deer also possess a horizontal slit pupil that facilitates efficient eye function in a range of lighting conditions (D'Angelo et al. 2008). The horizontal slit pupil is important for controlling the amount of light entering the eye and is capable of extreme vertical adjustments ranging from a narrow slit in bright light to a broad oval in low light situations (D'Angelo et al. 2008). It allows the highly light-sensitive visual system of the white-tailed deer to function in full daylight without overwhelming the photoreceptors of the retina (Ali and Klyne

1985). At the same time this horizontal slit pupil helps enhance visual acuity by enabling all wavelengths of light to be focused on a strip of retinal cells that contain high densities of photoreceptors (Malmström and Kröger 2006).

Deer retinas contain both rod and cone photoreceptors (Witzel et al. 1978). Rod and cone photoreceptors respond differently to similar wavelengths of light. The photopigment in each type of cell is sensitive to different ranges of wavelengths and responds maximally to a specific wavelength, referred to as its peak sensitivity. Rod photoreceptors take little energy to activate and are responsible for vision in low-light conditions. In white-tailed deer, rod pigments have peak sensitivity at wavelengths of 497nm, which corresponds to blue-green light (Jacobs et al. 1994).

Cone photoreceptors contain highly specialized photopigments that require more energy to activate and are responsible for the perception of colors. Deer are dichromats; their eyes contain two types of cones with different spectral sensitivities (Jacobs et al. 1994, Jacobs et al. 1998). One cone photoreceptor contains a short-wavelength photopigment having peak sensitivity at 450–460 nm (Jacobs et al. 1994). The other cone photoreceptor contains a middle-wavelength photopigment having peak sensitivity at 537 nm (Jacobs et al. 1994). Cone photoreceptors are distributed throughout the deer's retina, but middle-wavelength cones occur at highest densities (~32,000/mm^2) along a horizontal visual streak that aids in expanding the deer's field of view and visual acuity (Jacobs et al. 1994, D'Angelo et al. 2008).

Under low light conditions, rod photoreceptors produce the majority of the electrical signals to the brain, aiding in the production of uncolored vision (Jacobs 1993). Under conditions with ample light, rod photoreceptors are over-stimulated and stop generating signals to the brain. In this situation, cone photoreceptors produce the majority of the signals, leading to the perception of both blue and yellow-green colors (Jacobs et al. 1994). This distinction of two different colors enables deer to perceive the difference between the land and the sky, helping them to better detect objects along the horizon (D'Angelo et al. 2008).

Despite the important role vision plays in a deer's perception of its environment and its consequent behavior (Sauer 1984, Birgersson et al. 2001), there has been little study in this area (Jacobs 1993, D'Angelo et al. 2004). Most of what is assumed about how deer perceive visual stimuli is based on the anatomical structure of the eye and the types of photoreceptors in the retina (VerCauteren and Pipas 2003). Similar inferences in other species, such as the pigeon (*Columba livia*) and the turtle (*Pseudemys scripta elegans*), have not been verified (Kreithen and Eisner 1978, Arnold and Neumeyer 1987). Thus, statements about visual capabilities require direct behavioral substantiation (Jacobs 1992).

Only three behavioral investigations of the visual capabilities of white-tailed deer have been published. Zacks and Budde (1983) used operant conditioning to demonstrate that white-tailed deer could discriminate between a long-wavelength stimulus and an achromatic stimulus. Utilizing a similar operant conditioning paradigm, Zacks (1985) further concluded deer were most sensitive to light at 545 nm. In a forced-choice feeding test, deer learned to discriminate between short-wavelength (500 nm) and long-wavelength (580-620 nm) stimuli, suggesting that deer could discriminate green from yellow and orange (Smith et al. 1989). However, interpretation of these studies is difficult due to small sample size, brightness, hue, luminance and other variables that influence the visual systems of animals (VerCauteren and Pipas 2003).

Birgersson et al. (2001) attempted to address whether brightness was a possible confounding factor in the behavioral visual studies of cervids. They demonstrated that fallow deer (*Dama dama*) chose a color stimulus associated with a positive reward regardless of varied brightness and concluded that fallow deer use color to discriminate between visual stimuli. However, this study utilized a small sample and the colors painted onto stimulus plates expressed wavelengths across a large proportion of the visible light spectrum. Consequently, delineating what specific wavelength elicited the response is impossible. Because animals may solve discrimination problems in multiple ways, interpretation of studies employing complicating variables is open to bias (Jacobs 1981). Thus, a well-designed, operant-conditioning experiment that eliminates confounding variables is necessary to determine the sensitivity of white-tailed deer to various wavelengths.

OBJECTIVE

Delineate the visual threshold of white-tailed deer (i.e., the lowest intensity which can be detected 50% of the time at a specific wavelength) in light and dark conditions for the short and long wavelength ends of their purported visual spectrum.

METHODS AND MATERIALS

The research will be conducted at the Daniel B. Warnell School of Forestry and Natural Resources Whitehall Deer Research Facility at the University of Georgia. The facility spans 2.6 ha (6.5 ac), and includes eight outdoor paddocks, 19 roofed barn stalls, a rotunda for moving deer from the outdoor pens and paddocks to the barn stalls, and a livestock cradle system for safely restraining un-sedated deer. Between 50 and 100 white-tailed deer are housed at the facility annually.

During the study, I will use 21 female white-tailed deer, ranging in age from 1.5 to 5.5 years old. Deer will be housed separately in barn stalls, which have been modified for purposes of this research. Each stall is equipped with an interactive deer-training-device (DTD, see Fig.

1). The DTD contains a programmable relay, two food dispensers, two food troughs with pneumatic lids, and a stimulus light mounted above each trough. The programmable relay functions as a digital timer, enabling the programmer to make a number of timed on/off switches in a step-wise fashion. Through specific sequencing, the DTD opens and closes the trough lids, turns the stimulus lights on or off, dispenses food, and counts the number of correct and incorrect responses by a deer.

Phase 1 (adaptation and pre-training)

In this phase, which will last 2 days, the deer will be habituated to the barn stall and the DTD. During adaptation, the DTD's lids will remain open at all times, food will be dispensed throughout the day and can be consumed *ad libitum*. During pre-training, lids will open for six, 20-minute periods so deer can feed from either trough. During this phase, I will measure amount of food consumed by each deer.

Phase 2 (training)

In Phase 2, I will screen for deer capable of being trained to associate a supra-threshold stimulus white-light with a food reward. This broad spectrum white-light is generated by three light emitting diodes (LEDs), with specific wavelengths chosen because they are easily seen by deer. Six daily training periods (i.e., period during which trials are conducted), each of 20 minutes duration, will occur between 00:00 and 20:00 GMT. The DTD will begin each training period by activating the stimulus white-light over one of the troughs, while the light over the other trough remains off (Fig. 2). After eight seconds, both trough lids will open while the stimulus light remains on. When a deer approaches the DTD to feed, it will choose to eat from one of the two troughs. If it chooses to eat from the trough with the light off, this will register as an incorrect choice by activating an infrared sensor in front of the trough. An incorrect choice will result in the immediate shutting of both lids, and a three-minute pause before the start of another trial. If the deer chooses to eat from the trough with the stimulus light on, this will register as a correct choice by activating an infrared sensor in-front of that trough. A correct choice results in a 60-second window in which the trough lids stay open and the deer is allowed to eat. After 60 seconds, both lids close, 28g of pelleted food are dispensed into each trough, and there is a three-minute pause before the start of another trial. Dispensing food into both troughs ensures that deer do not condition to the aural stimulus.

Ambient light conditions will be controlled using a 12:12 (light:dark) cycle. Three training periods will test performance during lighted conditions and three training periods will test performance during dark conditions. Performance will be measured as the number of correct and incorrect choices where a correct choice is the deer attempting to eat from the trough with the light on. The amount of food consumed will be recorded to ensure that deer are eating sufficient daily rations. Deer will be considered to have met the criteria of being trained when they have completed five sessions with 75% correct choices or more in each session. When deer are considered trained to the white-light stimulus, they will begin Phase 3.

Phase 3 (testing)

In this phase, deer will be trained to associate a stimulus light in the far ends of their purported visible spectrum (360-405 nm, 590-630 nm) with a food reward. During testing, similar procedures to Phase 2 will be used. The only difference in procedures will be the wavelength of the stimulus light. Deer will be trained to stimulus lights expressing specific wavelengths at the highest intensity available. The wavelengths of the stimulus lights will be one of the following: 360 nm, 405 nm, 590 nm, and 630 nm. The deer will be trained first to 405 nm. When deer meet the performance criteria stated in Phase 2 and are considered trained, intensity will be systematically halved every session until the percent correct response is 50%. Deer will then be trained and tested at 360 nm, then to 590 nm and lastly 630 nm. Should the deer be unable to meet the performance criteria after 15 days of training, testing will begin regardless. Measurements will be the same as those taken in Phase 2.

An increment-threshold spectral sensitivity function will be made for both ends of visual spectrum (see Fig.3 for example). Spectral sensitivity functions allow for comparisons of sensitivity across different wavelengths of light. This spectral sensitivity function will be compared to the photoreceptor sensitivity function by Jacobs et al. (1994). Hence, differences between photoreceptic activation and perception will be described. If the two sensitivity functions vary significantly, additional testing at 380 nm, 440 nm, 550 nm and 610 nm will occur. A repeated measures ANOVA and Tukey's HSD will be used to test for statistical differences in sensitivity between different wavelengths.

PERSONNEL

Dr. Robert J. Warren and Dr. Karl V. Miller, Warnell School of Forestry and Natural Resources, and Dr. George Gallagher, Berry College, will serve as principal investigators for the proposed project. David A. Osborn, research coordinator and Whitehall Deer Research Facility manager, will assist with project implementation at the Whitehall Deer Research Facility. Bradley S. Cohen will conduct this research in partial fulfillment of the requirements for a M.S. degree at the University of Georgia.

FUNDING

Funding for this research has been provided by a contract with the Georgia Department of Transportation and the Berryman Institute to Drs. Warren and Miller. All project costs, including Mr. Cohen's graduate assistantship (August 2009 to May 2011), are covered by this agreement.

PERMITS

The University of Georgia Institutional Animal Care and Use Committee has approved the project protocol for animal use and handling (AUP# A2010 1-010) at the Whitehall Deer Research Facility.

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Figures:

Figure 1. Pictures of the "deer-training-device" (DTD) showing the programmable relay and food dispenser (A), the side-by-side orientation of the two trough-boxes (B), and the device from inside the barn stall with trough lids open and lights above the lids (C).

Figure 2. Functional block diagram of the program for “deer-training-device” (DTD) in the training and test phases of the experiment. After recording the data from the previous day’s session, the program is restarted and the light turned on is randomly assigned. Performance, checked by correct (Y) or incorrect (N) decisions, is registered by the computer and verified by observers on randomly chosen intervals.

Figure 3. Example of increment-threshold spectral sensitivity function (taken from Jacobs et al. 2001). The lines above the points represent the standard deviation.

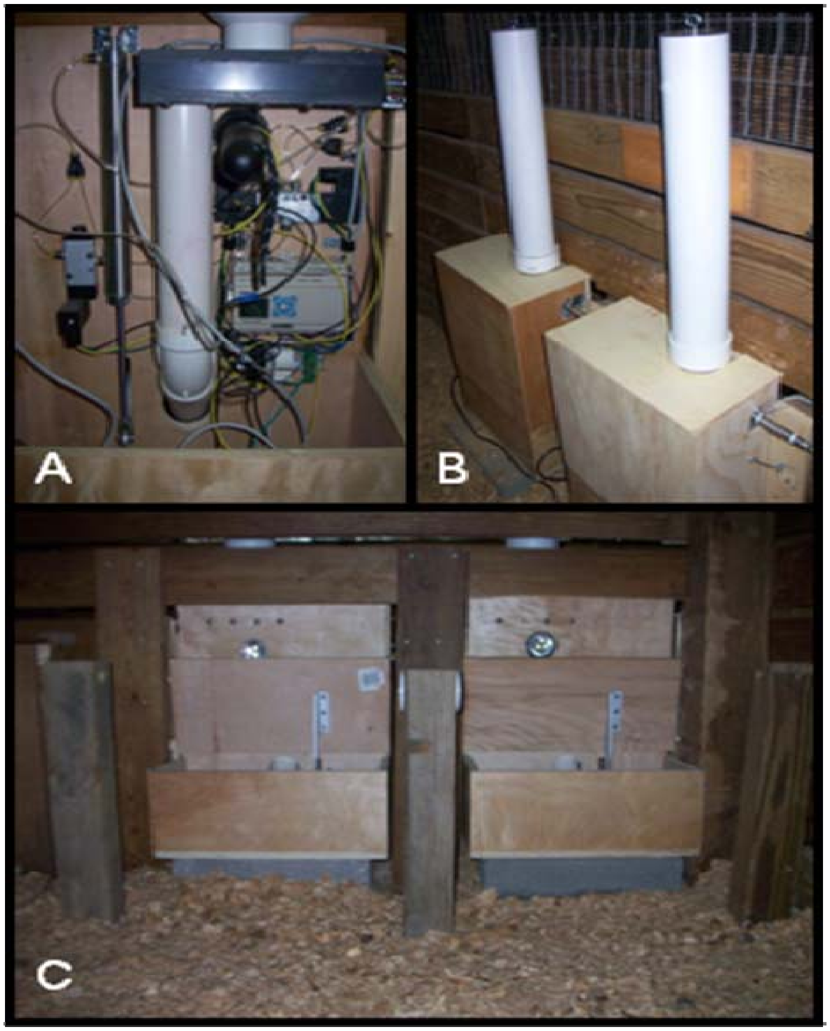

Figure 1.

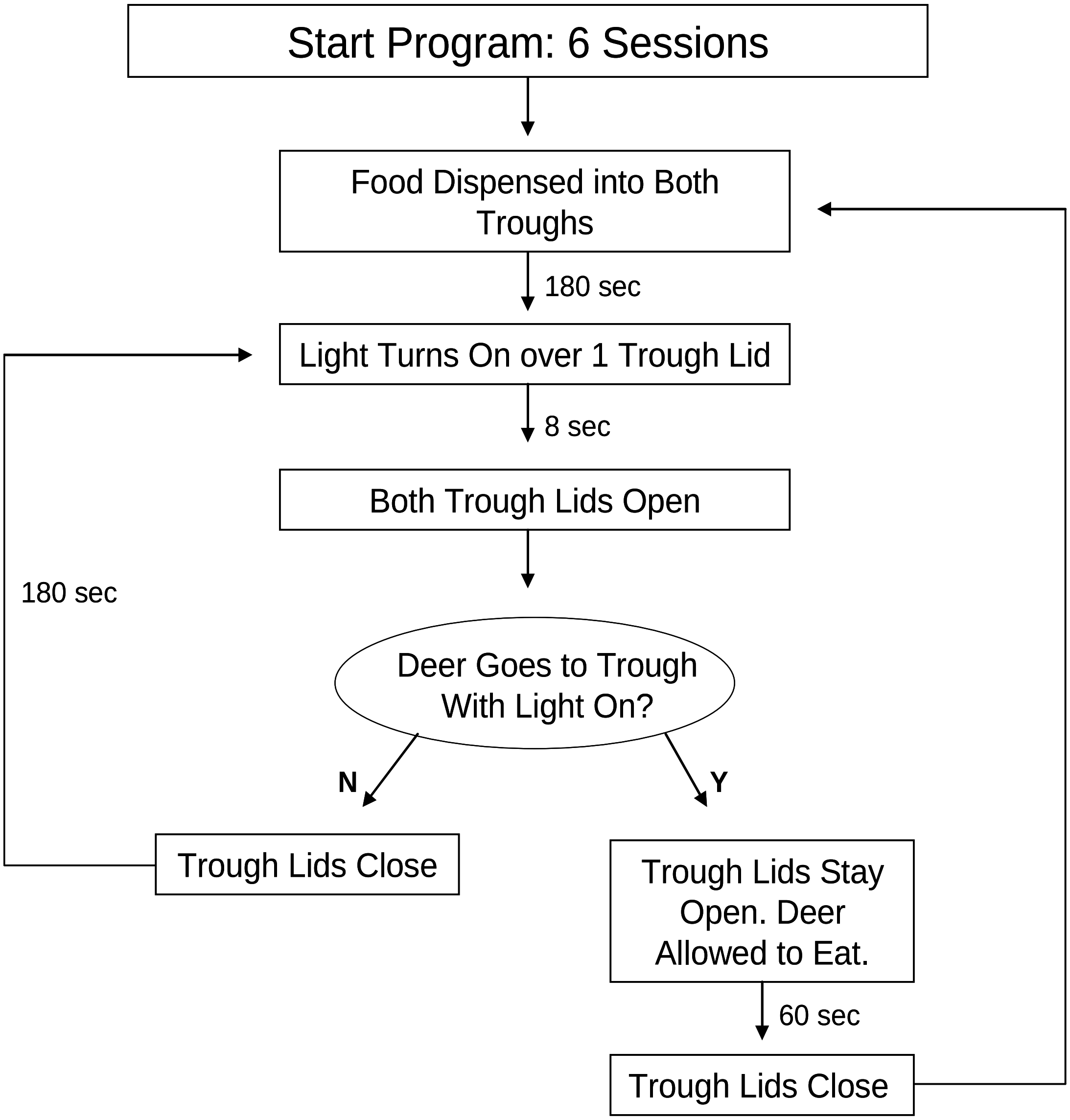
Start Program: 6 Sessions
Food Dispensed into Both Troughs
180 sec
Light Turns On over 1 Trough Lid
8 sec
Both Trough Lids Open
180 sec
Deer Goes to Trough With Light On?
N
Y
Trough Lids Close
Trough Lids Stay Open. Deer Allowed to Eat.
60 sec
Trough Lids Close

Figure 2.