Summer habitat selection of female white-tailed deer: can we reduce agricultural field use in Northern Idaho?

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By

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Authorization to Submit Thesis

This thesis of Kayte B. Groth, submitted for the degree of Master of Science with a Major in Natural Resources and titled "Summer habitat selection of female white-tailed deer: can we reduce agricultural field use in Northern Idaho?," has been reviewed in final form. Permission, as indicated by the signatures and dates below, is now granted to submit final copies to the College of Graduate Studies for approval.

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Abstract

Big game species in Northern Idaho provide both ecological and economic benefits to a variety of societal groups. In the Clearwater region, white-tailed deer (*Odocoileus virginianus;* WTD) are one of the main big game species that recreationalists seek, yet are also known to cause significant damage to high-profit crops. Although research is abundant in other parts of WTD range, research on habitat and behavioral ecology of WTD in Northern Idaho is lacking.

The goal of our research was to investigate WTD ecology via fine-scale habitat selection and develop management tools that reduce crop damage through behavioral modifications. Behavioral modifications were intended to reduce the amount of time individuals spent in agricultural fields, and ultimately reduce the amount of damage caused. We used step selection functions to analyze summer home range (May 15 – October 6) habitat selection of 49 adult WTD females in 2017 and 2018, and analyzed data during 5 diel time periods: morning/evening, midday, crepuscular, peak, and night. We found that during the midday and nighttime hours WTD selected to be closer to agricultural field edges, shrublands, and forested habitat types. Similarly, WTD selected to be near agricultural field edges and shrublands during morning/evening hours, yet further away from forested habitat types. During peak hours (i.e., highest occurrence of WTD in agricultural fields), WTD selected for gentle slopes, larger distances from forested habitat, and to be closer to agricultural field edges, roads, and all 3 prominent crop types (hay, pulse, and winter wheat). Lastly, during crepuscular hours WTD selected for gentle slopes, larger distances from pulse crop fields, and closer to agricultural field edges, roads, grassland, and forested habitat types. We also investigated large scale movement patterns and seasonal migration timing. We found that approximately half of the GPS-collared individuals migrated each year, but that there were differences in movement behaviors between the 2 sub-populations. Half of the GPS-collared individuals resided on private land, while the other half resided on an Idaho Department of Fish and Game Access Yes land parcel subject to public hunting pressure. We found that 62% of private land individuals were resident, while 35% were migratory. The opposite was true for the Access Yes individuals with 38% remaining residents, while 65% were migratory. Not only did more publically-accessible individuals migrate, but they also migrated on average 2 months earlier than migrants from the other sub-population.

Our behavior modification deterrent treatments consisted of a fear-enhancing deterrent (a combination of 3 components that target auditory, olfactory, and visual cues), a physical exclusion deterrent (4-strand electric partial fence), and a taste-aversion compound (lithium chloride, LiCl). Efficacy of the fear-enhancing deterrent was determined through counts of used GPS locations in agricultural fields, and distance from deterrent metrics. We found that the weekly number of GPS locations within treated fields was reduced by 23% after the treatment had been deployed, and that on average, GPS-collared individuals preferred to be ~35m further away from deterrent systems when they were on compared to when they were off. We used a log linear model to evaluate our physical exclusion deterrent, and found that WTD crossings (entering or exiting an agricultural field) were reduced by 30% when the fence was up and on compared to when it was down and off. Finally, although we were not able to actively deploy LiCl in a field setting or determine its efficacy as a deterrent treatment for WTD, we were able to investigate muscle and organ tissue withdrawal times and toxicity at a low and high dosage of ingested LiCl over a 10-day period in an analogous small ruminant, domestic sheep. Linear regression models were used to determine that peak lithium concentration (7.8µg/g) occurred in muscle tissues 25 hours post-ingestion at a low dosage of 150mg/kg body weight. At a high dosage (450mg/kg body weight), lithium concentration peaked (45µg/g) 73 hours post-ingestion, and resulted in a high mortality rate, raising concerns over the use of LiCl in a field setting except at low dosages. Overall, this research provides insight to WTD ecology and space-use patterns in Northern Idaho, which can help guide management strategies and actions to reduce WTD crop depredations while aiding in keeping a positive working relationship between agricultural producers, wildlife enthusiasts, and wildlife agencies.

Acknowledgments

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Dedication

To my late grandfather William “Papa Bill” Munson, for always expressing a keen interest in my wildlife career, and especially this research project. Papa Bill is one of the main reasons I chose to pursue this profession as he instilled a fascination of the “wild outdoors” to the Munson brood at a young age, and was always the first to ask me about my latest adventures. His legacy lives on.

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CHAPTER 1: Introduction

Public concerns over wildlife management are on the rise as the need to balance anthropogenic desires and sustainable wildlife populations continues to become a larger, more complicated and controversial issue (Gamborg et al. 2012; Hampton et al. 2019; Gamborg et al. 2020). With increases in the human population, wildlife species are learning to adapt to anthropogenic effects. White-tailed deer (*Odocoileus virginianus*; WTD, hereafter) are a wildlife species notorious for their ability to inhabit and thrive in an assortment of areas that range from naturally protected National Parks to densely populated urban areas (Gese and Grothe 1995; Kunkel et al. 1999; Richardson and Weckerly 2007; DeNicola and Williams 2008). Because of this versatility, WTD densities are currently on the rise and consequently, so are human and WTD conflicts (Kimball and Nolte 2006; Monteith et al. 2019; Idaho Department of Fish and Game 2019).

As one of the most popular and widespread big game species in Northern Idaho WTD play an important role in both ecological processes and economic gains. Historically, WTD densities fluctuated from being sparse in the late 1800's to reaching a peak in the 1960's (Idaho Department of Fish and Game 2019). After 1960 habitat degradation and heavy harvest rates reduced populations; however, current data show that WTD densities are once again reaching peak numbers (Idaho Department of Fish and Game 2019). High WTD densities quickly become an issue in agriculturally dominated areas as high productivity of the land provides a reliable source of forage.

Throughout the year WTD consume a variety of plants (Taylor 1956), with fall and winter diets primarily consisting of shrubs and evergreens while spring and summer diets are comprised of grasses, forbs, and agricultural crops (Idaho Department of Fish and Game

2002). Agricultural field use and crop consumption is greatest during spring and summer months (Peek 1984), with a multitude of high-profit crops incurring WTD damage (Idaho Department of Fish and Game 2019). These crops include wheat, barley, oats, rapeseed, organic vegetables, bluegrass, hay, and especially pulse crops (i.e., garbanzo beans, lentils, and peas) (Idaho Department of Fish and Game 2019). Depredation control has thus become an important factor in Idaho Department of Fish and Game's wildlife management program (Idaho Department of Fish and Game 2002). High depredation rates lead to immense economic effects on both agricultural producers, as well as Idaho Department of Fish and Game wildlife managers. As the producer's crop production and yields decrease due to WTD damage, claims for compensation are filed. When significant damage occurs producers are compensated for their losses through Idaho Department of Fish and Game depredation accounts (Idaho Department of Fish and Game 2018). Thus, damage prevention is a high priority, and because it is a shared responsibility between the producer and Idaho Department of Fish and Game wildlife managers, a variety of cost-efficient and effective prevention deterrents are needed.

Historically, a wide range of deterrents have been tested from fear-enhancing, taste-based, and barrier techniques to lethal removal methods. Researchers have received varying results on the effectiveness of each deterrent, but have yet to find a method that is universally effective among depredating ungulates in an agricultural landscape. Currently, Idaho Department of Fish and Game deploys zon guns, pyrotechnics, motion-activated sock men, and as a last resort lethal measures that include depredation hunts and kill permits (Idaho Department of Fish and Game 2018). Because these commonly used deterrents, aside from lethal removal, often result in short-lived effectiveness or quick habituation, this project aimed to develop management tools that reduce agricultural crop damage by testing the efficacy and feasibility of 3 deterrent treatments that had yet to be used in an agricultural landscape.

In Chapter II we examine habitat selection and influential environmental characteristics that motivate WTD space use and movements. Using fine-scale GPS-locations we used a step selection function to determine which environmental characteristics are highly influential on WTD movement patterns during 5 diel time periods: morning/evening, midday, crepuscular, peak, and night. We also included a seasonal time interaction, which allowed selection of environmental covariates to fluctuate throughout the crop-growing season. These models can be used as a guide to inform wildlife managers of when and where to place deterrent treatments on the landscape.

In Chapter III we examined the efficacy of 2 deterrent treatments, a fear-enhancing scare tactic and a physical exclusion electric partial fence. We used GPS-locations from treated individuals to determine if WTD use of agricultural fields was reduced for the fear-enhancing deterrent, and WTD field crossing counts to evaluate the effectiveness of the electric partial fence.

Lastly, in Chapter IV we explored the kinetic effects of a taste-aversion deterrent, lithium chloride (LiCl) at a low dosage (150mg/kg body weight) and high dosage (450mg/kg body weight). However, because LiCl had yet to be implemented as a deterrent treatment in an open field setting, many key issues regarding toxicity and withdrawal times in muscle and organ tissues needed to be addressed before open field implementation. To address these issues we conducted a series of LiCl feeding trials with a surrogate ungulate (domestic sheep) to investigate withdrawal times and toxicity levels at differing dosages of LiCl.

Each chapter is formatted as an independent manuscript with the intention of future publication. Chapters will continue to be edited and formatted according to accepting journal requests and specifications. They are currently all formatted to meet the University of Idaho's graduate thesis requirements.

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CHAPTER 2: Fine-scale habitat selection of female white-tailed deer on summer range in Northern Idaho

ABSTRACT

Correctly selecting for quality habitat and beneficial topographical features is vital for white-tailed deer (*Odocoileus virginianus*; WTD) survival. Multiple habitat related variables in heterogeneous landscapes have the potential to influence the fitness and persistence of wildlife species. In this study we used fine-scale GPS data to evaluate seasonal movement patterns and important habitat characteristics for WTD in an agriculturally dominated area of Northern Idaho. We used step selection functions to analyze summer range (May 15 through October 6) habitat selection of 49 WTD females in 2017 and 2018. We analyzed data during 5 diel time periods: morning/evening, midday, crepuscular, peak, and night. We found that during the midday and nighttime hours WTD selected to be close to agricultural field edges, shrublands, and forested habitat types. Similarly, WTD selected to be near agricultural field edges and shrublands during morning/evening hours, yet further away from forested habitat types. During peak time (i.e., highest WTD use of agricultural fields), WTD selected for gentle slopes, greater distances to forested habitat, and close proximity to agricultural field edges, roads, and all 3 prominent crop types (hay, pulse, and winter wheat). Lastly, during crepuscular hours WTD selected for gentle slopes, further distances from pulse crop fields, and close proximity to agricultural field edges, roads, grassland, and forested habitat types.

We also investigated large scale movement patterns and seasonal migration timing. We found that approximately half of the GPS-collared individuals migrated each year, but that there was a significant difference in movement behaviors exhibited between the 2 sub-populations. We found that 62% of private land individuals were resident, while 35% were

migratory. The opposite was true for the public land individuals with 38% remaining residents, while 65% were migratory. Not only did more public land individuals migrate, but they also migrated 2 months earlier (October 1) compared to private land migrants (December 1). Our models and migration data provide valuable information and the necessary tools to make informed habitat related management decisions.

INTRODUCTION

White-tailed deer (*Odocoileus virginianus;* WTD, hereafter) are recognized for their ability to inhabit and thrive in an assortment of habitat types, including those altered by human activities such as agriculture and forestry (Pauley et al. 1993; VerCauteren et al. 2011; Potapov et al. 2014). Within the last 100 years WTD population numbers have greatly increased due to anthropogenic landscape changes, extirpation of large predators, and the ability to rapidly reproduce under favorable conditions (Garrott et al. 1993; Rooney and Miller 2003; Smith et al. 2007). As a consequence of increasing densities, WTD and human interactions have also increased (Kimball and Nolte 2006; Monteith et al. 2019; Idaho Department of Fish and Game 2019), generating a need for a better understanding of WTD behavior and habitat selection in regions of recent expansion to make effective management decisions.

Multiple previous WTD studies have been centered on summer range habitat selection and how environmental factors can cause an array of behaviors and movement patterns (DePerno et al. 2002; Kroeger et al. 2020), but populations in Northern Idaho have largely been unstudied. Due to environmental variability, areas containing high-quality forage do not necessarily coincide with areas considered safe from predators. As a result, individuals are often faced with decisions that affect their fitness, at times having to trade off maximizing high-quality forage intake with minimizing predation risk (Kie 1999; Godvick et al. 2009; Hebblewhite and Merrill 2009). Thus, the quality of habitat (defined as the appropriate environmental conditions supporting individual and population persistence; Hall et al. 1997) can depend on a multitude of local conditions including seasonality, time of day, and landscape characteristics. Local conditions influence how individuals perceive and respond to habitat features at different hierarchical scales (Johnson 1980; McGarigal et al. 2016). Within these hierarchical scales, Johnson (1980) described 4 orders of habitat selection: the physical or geographical range of a species (1st order), the home range (2nd order), patches of resources within the home range (3rd order), and acquisition of food items within the patch (4th order). Due to individuals making decisions across multiple scales, it is important to acknowledge scale dependence (Hobbs 2003; McGarigal et al. 2016), and report results on a scale-by-scale level.

Fine-scale habitat selection occurs when individuals choose distinct micro-habitat characteristics that are associated with certain activities such as foraging (Godbout and Ouellet 2010). In general, previous studies indicate that WTD demonstrate a high degree of ecological plasticity but can be acutely selective at micro-habitat scales. Selection within the home range (3rd order) is a commonality among WTD habitat selection studies (Leach and Edge 1994; Brunjes et al. 2006; Storm et al. 2007; Wiemers et al. 2014), yet our study focused on 4th order selection. This allowed us to define the environmental features that were driving habitat selection in an agricultural dominated landscape, and to understand, at the most restricted level possible, what features are ultimately driving WTD behavior and movement patterns.

Advances in Global Positioning Systems (GPS) technology have allowed researchers to collect large datasets to model and investigate habitat use and selection, often through resource selection functions (RSF) (Thurfjell et al. 2014). Although useful and informative, RSFs do not include movement metrics, in which a similar modeling approach of a step selection function (SSF) does (Fortin et al. 2005; Coulon et al. 2008; Roever at al. 2010; Thurfjell et al. 2014). SSFs focus on the individual's specific movement path as it traverses across a landscape. Using GPS locations that are recorded at regular time intervals, movement between consecutive locations can be interpreted as "steps" (Turchin 1998; Thurfjell et al. 2014), and each used step is then paired with localized available steps drawn at random from a distribution of known movement parameters (Roever et al. 2010; Thurfjell et al. 2014). By using movement metrics to constrain availability, the model is able to quantify selection at a finer spatial scale, and link behavioral and movement choices across the landscape.

We used a SSF to identify habitat variables that influence WTD movements across an agricultural dominated landscape. We examined WTD responses to habitat covariates during the crop-growing season when individuals were on summer range. Our goal was to evaluate WTD summer habitat selection to determine how individuals use agricultural fields, namely pulse crops (garbanzo beans, lentils, and peas), as well as other important environmental variables within seasonal and diel cycles. The predation risk allocation hypothesis describes how the existence of predators, or risk of mortality, influence prey species by altering their behavioral options due to the risk of endangerment (Lima and Bednekoff 1999; Sih and McCarthy 2002). The hypothesis suggests that depending on the associated level of risk, individuals may choose to forgo certain activities, such as foraging, that may lead to increased exposure. Along with this, the optimal foraging theory predicts that individuals attempt to either maximize the amount of energy gained or minimize the amount of time spent acquiring that energy (Schoener 1971; Pyke et al. 1977; Schmitz 1992; Kie 1999), which is often achieved through foraging in high quality forage areas. Therefore, we hypothesized that WTD used agricultural fields greatest during time periods when predation risk was minimized (i.e., when human or predator presence was expected to be low), yet high-quality forage opportunities were maximized (i.e., mature crops).

More specifically, we predicted that WTD selected for high-quality natural forage as long as it was available, then switch to crops. Natural forage consists of a multitude of plant species that can provide numerous benefits including high nutritional content, diverse options within a small foraging area, and close proximity to cover. However, as digestibility and nutrient content of natural forage progressively declines throughout the course of the growing season (Lesage et al. 2000), we predicted that WTD switched to preferring agricultural crops where forage digestibility and nutritional content was enhanced either through multiple cuttings of the crop (e.g., hay) or through the addition of fertilizer (increased nitrogen content). Thus, as natural forage was depleted or became dormant later in the growing season, we predicted that WTD offset the risk of foraging in open agricultural fields to obtain cultivated forage that was more digestible with a higher nutritional content.

Habitat selection may also vary depending on time of day. To avoid increased predation risk or high temperatures during the summer months, deer often prefer to forage during crepuscular hours (Montgomery 1963; Kufeld et al. 1988; Massé and Côté 2013). WTD in our study area were exposed to 3 main predators: humans, coyotes (*Canis latrans*), and mountain lions (*Puma concolor*). The threat of human encounters was greatest during the day and in close proximity to road systems, but was essentially nonexistent at night due to hunting regulations and low visibility. Moreover, hunting season was restricted to the last 3 months of the crop-growing season, while coyotes or mountain lions pose a predation risk year round. To reduce encounters with predators, WTD should generally select for gentle terrain to aid in early detection and quick escape (Lingle and Pellis 2002; Dellinger et al. 2018). Thus, we predicted that WTD selected for areas with a gentle slope, areas further away from roads to reduce human encounters, and areas within close proximity to agricultural field edges that provide both available forage and the opportunity to quickly escape into canyon cover for security purposes.

METHODS

Study area

Our study area was located in Latah County, in Northern Idaho and encompassed ~906 square km of WTD summer range as defined by GPS-collared individuals. Dominant land use consisted of agriculture and timber harvest, with 74% of the county being privately owned (Idaho Department of Fish and Game 2016). We studied 2 sub-populations of GPS-collared individuals at 2 study sites, with the eastern study site being located on Little Bear Ridge and our western site on Middle Potlatch Creek (Figure 2.1). The topography of these sites was characterized by deep forested canyons surrounded by rolling agricultural fields, with elevation ranging from 430m at the canyon bottoms to 830m at the highest field point. The climate was characterized by warm, dry summers (July-September) followed by cool, wet winters (December-February). During our study (2017-2019), the mean temperature during summer months was 26.6°C, and mean total precipitation was 1.6cm (PRISM Climate Group).

Our study area was comprised of a multitude of vegetative species and habitat types dominated by dryland agriculture and coniferous habitat types, interspersed with shrublands and grasslands (Idaho Department of Fish and Game 2016). Dominant overstory species included ponderosa pine (*Pinus ponderosa*), Douglas fir (*Psuedotsuga mensiezii*), Western larch (*Larix occidentalis*), grand fir (*Abies grandis*), and lodgepole pine (*Pinus contorta*), while the understory species consisted of shrubs, forbs, and grasses. The major agricultural crops planted in our study area were non-irrigated winter and spring wheat, peas, oats, barley, garbanzo beans, lentils, alfalfa, and timothy hay. The growing season for these crops lasted approximately 150 days with fall plantings that occurred in late September and spring plantings that occurred in mid-April. All crops were typically harvested by mid-September. Easy access to available natural vegetation and agricultural crops throughout the summer months allowed for a diverse array of forage opportunities, resulting in a growing season of April through September each year.

Although known to be present, we did not record data for other large-bodied mammalian species co-inhabiting the study area, which included mountain lions (*Puma concolor*), black bears (*Ursus americanus*), coyotes (*Canis latrans*), and elk (*Cervus canadensis*).

Animal capture and handling

We captured 53 yearling and adult (>1 year) female WTD between April 2017 and April 2018. Most individuals were captured by helicopter net-gunning and Clover trapping (Clover 1956). We net-gunned individuals in open agricultural fields while Clover trapped individuals were trapped on ATV routes within the study site canyons. We checked Clover traps daily and baited with a variety of nutritious items including apples, alfalfa, oats, and mineral licks. Captured individuals were restrained and blindfolded to reduce animal stress and ensure safe handling. Once safely restrained, each individual received ear identification tags and fit with a temporary GPS radio collar (Lotek Litetrack420), which was equipped with a drop-off mechanism that was projected to fall off in September of 2019. During the summer months of 2017 we also implemented chemical immobilization through ground-darting as a capture technique. Individuals were darted with either 2mL of BAM (Butorphanol, Azaperone, and Metatomidine) or a mixture of 1.8mL Ketamine and 0.4mL of Xylazine (Idaho Department of Fish and Game 2017). Chemically immobilized individuals were positioned in a sternal recumbent position and vitals were monitored while identification tags and a drug tag were placed in each ear, and a GPS-collar was fit. Individuals were reversed with an intramuscular injection of 0.5mL of Naltrexone and 4.0mL of Atipamezole (BAM reversal) or 1.4mL of Tolazoline (Xylanzine reversal) (Idaho Department of Fish and Game 2017). Following reversal, individuals were monitored until it was determined that appropriate body functions and reactions had fully returned. Capture, animal handling, and monitoring was approved by the Institutional Animal Care and Use Committee at the University of Idaho (IACUC-2017-70).

Preliminary Data Analysis

We recorded locations for GPS-collared individuals every 15 minutes from March through November, and then once a day from December through February. We monitored and extracted location data from GPS-collared individuals on a monthly basis either through aerial telemetry flights or on-ground encounters. Mortalities that occurred within 2 weeks of capture were censored and not used for data analyses.

Seasonal Ranges

We classified individuals as either migrant or resident using net squared displacement (NSD) (Borger and Fryxell 2012). We calculated the distance from the starting location for each individual to each subsequent location within the dataset for that particular individual (Papworth et al. 2012; Singh et al. 2012; Henderson et al. 2018). Due to capture date variation among individuals we chose June 1 as our starting date for subsequent calculations of squared displacement to ensure that all individuals had reached their summer home ranges and that any movements thereafter would represent a deviation from their established summer range. We defined migration as a squared displacement >10km and visually inspected the GPS location data to avoid analyzing exploratory ventures that were not actual migrations. A large proportion of our captured individuals were GPS-collared throughout the entirety of the study, and we thus treated each year for each individual as independent samples as WTD have been known to switch migratory strategies annually (Brinkman et al. 2005, Fieberg et al. 2008). Migratory individuals were used to define the start and end dates of our study seasons, based on arrival/departure dates between summer and winter ranges. Fine-scale, 15-minute location data were only applicable during summer range dates, and thus all analyses hereafter were conducted using summer range data only. To ensure that we only included location data while all individuals were on summer range, we defined our crop-growing season as May 15 through October 6.

Behavioral Classification

We used a Residence in Space and Time method proposed by Torres et al. (2017) to separate behavioral states using a combination of the amount of time that an individual spent at a particular location, as well as the total distance traveled within a sampling period (15-minute duration periods). We categorized behavioral states as bedding (time intensive, minimal distance covered), foraging (slow, but continuous movement e.g., a deer slowly walking through an agricultural field), and transit (moderate time periods over long distances) (Torres et al. 2017). The residence distance (RD) and residence time (RT) were calculated between consecutive 15-minute location points by constructing a circle around every location point using an average travel speed of 5 miles per hour as a radius distance (i.e., a radius of 1.25 miles or ~2000 meters around each location). If two consecutive points did not have overlapping circles, a zero was given as RD and RT values (Torres et al. 2017). However, if circles did overlap, the RD value was calculated as the path length (in meters) between the location points and the RT value was calculated as the amount of elapsed time (Torres et al. 2017). Subtracting RT from RD resulted in a residual value that was standardized and given a value between -1 and 1 (Torres et al. 2017). Classified behaviors were separated by positive residuals (time and distance intensive location points), residuals with a 0 value, and negative residuals (time intensive, minimal distance) (Torres et al. 2017). WTD use different parts of the landscape to carry out different behaviors, and we focused on examining habitat selection during times of movement and consumption of forage, when crop depredation is likely to occur (i.e., foraging and transit).

Development of Environmental Predictive Variables

We developed a list of 15 environmental variables that were selected to represent potential influential factors affecting habitat selection (Table 2.1). Previous studies (Murphy et. al 1985; Pauley et al. 1993; Kittle et al. 2008; Duquette et al. 2014; Dellinger et al. 2018), along with on-site observations at the study sites, guided covariate selection. For topographical features, we used a 10m-resolution digital elevation (DEM) layer created by the United States Geological Survey (USGS) National Elevation Dataset. We derived a slope layer using ArcMap tools (ESRI 2010). We obtained a Latah County classified road system layer through the Idaho Department of Transportation GIS data services to use for our distance to road covariate (ESRI 2010). We used a 30m-resolution USDA Landfire Existing Vegetation Cover (EVC) layer to classify areas of canopy cover that were either greater than 40% or less than 40% (Landfire 2014). We chose a breaking point of 40% because silviculture activities (commercial thinning or other limited-entry practices) are typically represented in forested areas with <=40% canopy cover (Rowland et al. 2018; Eckrich et al. 2019). We separated all cover categories into 3 groups of canopy cover: low (0-25%), mid (26-50%), and high (51-75%). To describe habitat types, we used a 1m-resolution fine scale landcover layer developed by Idaho Department of Fish and Game (2018). We extracted grassland, forest, and shrubland cover types to include in our analyses. Lastly, we generated a crop type layer by visiting private landowners to delineate and label agricultural crop fields within the study area. We chose to focus on selection among the most profitable crops that WTD are known to damage in our study area. These crop types consisted of hay (alfalfa and timothy), pulse crops (garbanzo beans, lentils, and peas), and winter wheat. We transformed each categorical covariate into a continuous covariate by calculating a “distance to covariate” measurement. For example, instead of using binary values of 0 or 1 to portray use of grassland, we transformed values to be a distance measurement to the nearest grassland classified polygon. Delineated field boundaries also allowed us to calculate the distance from each location point to the nearest agricultural field edge.

Prior to modeling we conducted Pearson's pairwise correlation tests for multi-collinearity among all covariates. If covariates were highly correlated ($|r|>0.6$) (Dormann et al. 2012), the covariate with less management utility or was less biologically interpretable was removed from further analyses (Table 2.1). All covariate values were standardized to range between 0 and 1.

Step Selection Function

To understand how each of our covariates affected WTD habitat selection we used a step selection function (SSF) (Fortin et al. 2005). Straight-line segments were created to connect successive animal locations (i.e., steps) (Turchin 1998; Fortin et al. 2005; Coulon et al. 2008). Thus, steps (i.e., segments of the landscape) become the sampling unit in which actual steps taken by an individual were compared to randomly chosen available steps. Each observed step was paired with 5 random available steps, in which random step had the same starting point but varied in the step length and/or direction of the ending point (Fortin et al. 2005; Coulon et al. 2008). Step lengths and turning angles (i.e., the angle created when a switch in direction between the previous location and a new location occurred) of all GPS-collared individuals were pooled together and random steps were drawn from the distribution of observed step lengths and turning angles (Fortin et al. 2005; Coulon et al. 2008). Based on the model formulation described by Forester et al. (2009) we modeled the probability of an individual being located at a particular location (*b*) given that the animal moved from location *a,* and that the location prior to *a* was a_0:

$$f(b \mid a, a_0, Z) = \frac{\phi(a_0, a, b; \theta)\omega\{Z(b); \beta\}}{\int_{c \in D_a} \phi(a_0, a, c; \theta)\omega\{Z(c); \beta\}\, dc}$$

where D_a represents what is available to an individual during the specified time interval and the numerator is the step selection function. The first half of the numerator, $\phi(a_0,a,b;\theta)$, represents how an individual would move if habitat selection was irrelevant (i.e., randomly if selection did not occur) where θ is a vector of parameters controlling the density ϕ (Forester et al. 2009). The second half of the numerator, $\omega\{Z(b);\beta\}$, represents the selection for habitat covariates at a particular location $Z(b)$, and can also be written as a log-linear function of β:

$$\omega\{Z(b);\beta\} = \exp(\beta_1 Z_1 + \beta_2 Z_2 + \beta_3 Z_3 + \cdots + \beta_n Z_n)$$

where β is the coefficient estimated by conditional logistic regression with its associated habitat covariate(s) of Z at location b with n representing the total number of covariates (Forester et al. 2009).

Time Interactions

WTD use of agricultural fields is highest during spring and summer months (Peek 1984), and because approximately 58% of Latah County is comprised of agricultural land (National Agricultural Statistics Services 2017), we structured our analyses to examine patterns of agricultural field usage. To quantify patterns of deer selection relative to agriculture, we overlaid movement locations from GPS-collared individuals with an agricultural crop map to determine if agricultural field usage fluctuated throughout the growing season and if a temporal interaction would be necessary (see below for details on modeling approach). Because WTD typically forage and move across the landscape more often during specific hours within a 24 hour diel cycle (Webb et al. 2010), we also needed to consider separating our dataset into diel cycles. We separated our location data into 5 periods for analysis: morning/evening (2hrs to 3hrs after sunrise and 2hrs to 3hrs before sunset), midday (7hrs to 9hrs after sunrise), crepuscular (0.5hr before sunrise to .5hr after sunrise and 0.5hr before sunset to 0.5hr after sunset), peak (0.5hr before sunset to 1.5hr after sunset), and night (4.5hrs to 6.5hrs after sunset) (Figure 2.2). Analyses were conducted separately for each of the time periods.

We fit SSF models one covariate at a time to each individual deer within each time period to verify if: 1) selection was evident, but varied throughout the crop-growing season and a seasonal interaction was necessary (Figure 2.3A); 2) selection was evident, but constant throughout the season (Figure 2.3B); 3) no selection was evident among individuals and the covariate was excluded from models that included multiple predictor variables (Figure 2.3C). Models were fit at the level of the individual instead of at the population level due to the high diversity of selection patterns observed among deer. To simplify and describe these diverse selection strategies among deer, we constructed 3 model sets representing competing hypotheses, which described the environment in terms of security from predation risk, forage quality and availability, or a combination of the two (Table 2.2). Environmental covariates included forage-specific covariates (distance to grassland, distance to hay, distance to pulse, distance to winter wheat), security-specific covariates (slope, distance to road, distance to field edge, distance to forest, distance to shrubland), or a mixture of the two (Table 2.2). We ranked model performances using Akaike's Information Criterion (AIC – Symonds and Moussalli 2011), and identified the best performing model for each individual.

Each individual was then categorized as using a behavioral strategy focused on forage, security, or combination of the two. We also used AIC scores to rank each model on a numbered scale (1 being the best ranked and 3 being the worst ranked) for each individual to obtain the average ranking per model across individuals. Lastly, for population-level inference we averaged coefficient estimates for each model (forage, security, or combination behavioral strategy), based on the collection of coefficients for individual deer.

Predictions through Probability Ratios

For each diel cycle period (morning/evening, midday, crepuscular, peak, and night) we calculated the average beta coefficient across all individuals for each model covariate. Although selection patterns of individuals varied considerably, we interpreted average beta coefficients with CI's that did not overlap 0 as signifying significant positive or negative selection, and subsequently calculated relative probability selection ratios from each significant beta coefficient. Selection probability ratios quantify the likelihood of an individual selecting to be at a location with covariate values H(a) in relation to selecting another location with covariate values H(b), which form the following equation:

$$R_{a,b} = \frac{\exp[H(a)'\beta]}{\exp[H(b)'\beta]}$$

where R is the ratio of a/b produced and β is the average beta value for a particular covariate produced by the SSF model (Wilson et al. 2014). Because individuals are limited in how far each can travel within the 15-minute GPS-collar recording time frame, we limited our a/b contrasts of various "distance to" covariates for our selection ratio calculations to a maximum distance of 2.7km (e.g., 2.7km versus 0km, 3.5km versus 0.8km, etc.). Thus, distances were recorded on scale from 0 (location was within a polygon categorized as the covariate, i.e., on a field edge), or as any distance up to 2.7km away from the nearest categorized covariate polygon. Thus, when comparing 2 hypothetical sets of covariate values to calculate selection probability ratios, the numerator in the above equation contained the smaller measured distance and the denominator contained the larger measured distance. For example, to determine how much more likely WTD are to select a location in a pulse field (standardized value of 0) than a location 0.9km away (standardized value of 0.1), using an average β=-10.43, we obtain a ratio of ~3 times greater.

RESULTS

Seasonal Ranges

The majority of migrating individuals (15 out of 21, 71%) returned to their summer home ranges by May 15th the following year, which was our cut-off date for summer range habitat selection (Figure 2.4). However, there was 2 month difference between the two sub-populations in the timing of fall migration from summer range to winter range (on average, Middle Potlatch Creek individuals migrated in October while Little Bear Ridge individuals migrated in December; average time difference between the two sub-populations was 55 days). Not only did the 2 sub-populations differ in the timing of summer to winter migrations, but also in the proportion of migratory versus resident individuals within each study site sub-population. Thirty-eight percent of the Little Bear Ridge sub-population migrated, whereas sixty-two percent of Middle Potlatch Creek individuals migrated.

Behavioral Classification

During 2017 and 2018, we collected 571,154 locations from 49 GPS-collared individuals from May 15 through October 5, including, 224,544 (~39%) bedding locations that were not included in subsequent analysis. Thus, we used 184,092 foraging locations (~32%) and 162,516 transit locations (~29%) in our step selection analysis.

Fine-scale Habitat Selection

Of the 15 initial covariates, 6 were highly correlated with more descriptive covariates and were not included in subsequent analyses. The combination model was the best performing model during midday, crepuscular, and peak hours with an average ranking of 1.15, 1.82, and 1.51 respectively. However, the security model was the best performing model during morning/evening and night hours, with an average ranking of 1.71 and 1.73, respectively.

Our model results for each diel cycle reveal that WTD were influenced by different environmental variables (Table 2.3). During morning/evening hours WTD strongly selected to be near agricultural field edges and shrubland, but avoided forested habitats (Table 2.3). During midday hours, WTD selected for areas that were near agricultural field edges, and more specifically near pulse (garbanzo beans, lentils, and peas) crop fields (Table 2.3). They also selected to be near shrubland areas and forested areas. However, WTD avoided being in close proximity to grassland areas and hay fields during midday hours.

During crepuscular hours, WTD strongly selected to be close to field edges and roads (Table 2.3). They also selected for gentler slopes and to be closer to grassland and shrubland areas, yet avoided pulse crop fields. During night hours, WTD strongly selected to be near field edges, and to a lesser degree, also selected to be near shrubland and forested areas

(Table 2.3). Lastly, during peak hours, WTD strongly selected for gentle slopes, to be closer to field edges (particularly that of pulse fields), but strongly avoided forested areas (Table 2.3). They also selected to be near roads, hay fields, and winter wheat fields.

To determine statistically significant covariates we plotted average beta values across individuals for each diel period. For example, distance to agricultural field edge, distance to forest, distance to a pulse field, and slope were all statistically significant covariates effecting WTD selection during peak hours (Figure 2.5). WTD were ~3 times less likely to be 0.9km away than inside the field (Figure 2.6). Distance to field edge, which included all agricultural crop fields, was statistically significant across all diel cycles, and WTD were more likely to be found on the field edge than at any other distance. When compared to 2.7km away from a field edge, WTD were ~2.7 times more likely to be located within a field edge during morning/evening, midday, and crepuscular hours (Figure 2.7 A, B, and C). WTD were also ~6.4 and ~6.8 times more likely to be within a field edge than 2.7km away during peak and night hours, respectively (Figure 2.7 D and E).

DISCUSSION

Our study indicates that a combination of anthropogenic effects, predation risk, and nutritional resource availability drive WTD movement patterns in an agriculturally dominated area of Northern Idaho. WTD behavioral responses and selection varied substantially throughout the crop-growing season, and also within diel cycles. We found that although only roughly 16 km separated our 2 study sites and all on-coming winter environmental characteristics such as forage deterioration, lower temperatures, and snowfall occurred simultaneously between the two sites, our 2 sub-populations exhibited different migratory behaviors. More Middle Potlatch Creek individuals were migratory, and these individuals migrated 2 months earlier than Little Bear Ridge individuals. While it was beyond the scope of this project to investigate the reasons for these differences in the proportion of individuals that migrated and the timing of their migration, these discrepancies could be a result of human disturbances, and more specifically, hunting. Multiple studies have demonstrated that the timing of ungulate autumn migrations can be affected by anthropogenic disturbances (Root et al. 1988; Little et al. 2016; Rivrud et al. 2016; Rickbeil et al. 2019). Although both study sites were located on private property, the Middle Potlatch Creek site was within the confines of an Idaho Department of Fish and Game “Access Yes” program area, which permitted activities such as public hiking, ATV recreation, and hunting (pending open season). The Little Bear Ridge site was exclusively private and landowners omitted public recreational activities. General modern firearm season in Idaho begins October 10th of each year, which coincides with Middle Potlatch Creek departure dates of migratory individuals. On the contrary, Little Bear Ridge individuals were not exposed to the same degree of hunting pressure and thus most individuals were either year-round residents or migrated later in the season as a result of oncoming winter conditions.

We also found that plant phenology variability that occurred throughout the crop-growing season strongly affected WTD selection. Of the 9 predictor variables that were used within the SSF models, only 2 (slope and distance to agricultural field edge) had consistent selection patterns through the crop-growing season and across diel periods. WTD consistently selected for gentle slopes and close proximity to agricultural field edges (Table 2.3). Selection for close proximity to edges may reflect a preference for simultaneous access to high-quality forage (i.e., agricultural crops) and neighboring security cover (i.e., shrubland

and/or forest) (Williams and Hearth 1985; Rogerson et al. 2014). Consistent selection for gentle slopes could be a result of anti-predator behavior as previous studies have found that WTD rely on early predator detection and evade attacks through sprinting, with escape effectiveness decreasing on rugged terrain (Lingle and Pellis 2002; Kittle et al. 2008; Dellinger et al. 2018). Both ambush and coursing predators are present within the study area, and selection of gentle slopes could aid in early detection of and attack evasion of both predator species.

Selection among the 7 other predictive variables fluctuated throughout the crop-growing season, likely influenced by WTD reproduction cycles and the phenology of wild and agricultural plants. We found that early in the crop-growing season (mid-May to mid-June) WTD selected to be near grassland and shrubland areas, likely due to availability of natural forage and cover for fawns leading up to and immediately following parturition (Kunkel and Mech 1994). While fawns are immobile, females must make informed decisions as to where they conceal their offspring, how far to travel to obtain available forage, and satisfy lactation demands (Piccolo et al. 2010; Chitwood et al. 2017). Thus, during the early crop-growing season remaining close to the security of shrubland habitat is likely essential for survival of both offspring and adult females. However, as the summer season progresses, fawns become more mobile and are able to traverse the landscape and dependence on shrubland habitat may no longer be as vital. Similarly, grassland habitat was selected for in the spring, when it could provide high-quality forage (Wagner and Peek 2006), but as the crop-growing season progressed WTD avoided grassland habitat. Although avoidance could be caused due to a variety of reasons, other studies have found that ungulates species tend to avoid exposed, dry habitat types when temperatures are at a maximum (Sargeant et al. 1994;

Cain et al. 2008; Long et al. 2013) and due to decreases in natural forage availability (i.e., depletion or senescence) (Fryxell et al. 1988). The opposite was true for forested habitats, with WTD avoiding forested habitats during spring and fall, but preferred close proximity during summer months. Cover and reprieve from high temperatures are essential during summer months, when daytime temperatures average 26.6°C in our study area, and ungulates have demonstrated a stronger selection for dense canopies during times of high solar radiation (Godvik et al. 2009). However, dense canopy cover can also inhibit shade-intolerant understory species from growing (Hamberg et al. 2009), thus causing WTD to seek out forage in areas with higher availability, such as agricultural fields.

The 3 main crop types were all highly selected for in general, with deer showing particularly high probabilities of selection to be in or near pulse fields (Table 2.3; Figure 2.6). In addition, crop emergence and harvest strongly affected WTD selection. Agricultural crops that were planted the previous fall (i.e., winter wheat) can emerge as early as March and likely provide an important source of nutrition for WTD. We correspondingly found selection for winter wheat and hay to be greatest during spring, which may be a result of native forage still in winter dormancy (Figure 2.8). Numerous studies have shown that ungulates exploit agricultural crops that are highly digestible with greater nutritional content than surrounding native forage (Mould and Robbins 1981; Dostaler et al. 2011; DeVore et al. 2016; Hinton et al. 2020). Thus, WTD likely selected for agricultural crops during times when energy requirements (i.e., parturition/lactation) were high and nutritional content of forage was maximized (i.e., mature crops).

Selection of habitat variables not only vary within the crop-growing season, but also throughout the 24-hour daily cycle (Kammermeyer and Marchinton 1977; Kjaer et al. 2008;

Webb et al. 2010). Reponses to environmental factors related to nutrition and predation risk varied, resulting in differential patterns of selection among individuals such that some deer were risk-averse and sought to minimize exposure to predation risk by selecting for high-security habitats, while other deer were more active and bold (Bonnot et al. 2015), and prioritized selection for high-nutrition habitats. Agriculture, forestry, and human developments have created a mosaic landscape within our study area that enabled WTD to behaviorally shift habitat selection and resulted in different spatiotemporal trade-offs of maximizing forage consumption and minimizing predation risk among individuals (Kie 1999; Godvik et al. 2009; Hebblewhite and Merrill 2009). Individuals avoided certain potential risks during the day, such as hiding in security cover to minimize human contact, yet became bold at night. Although a few individuals employed a foraging driven strategy, most individuals utilized a combination strategy that balanced maximizing forage intake with also minimizing risk, or a security strategy that focused strictly on security factors. In addition, individuals switched between forage versus security strategies dependent on the time of day. Nocturnal predators, such as coyotes and mountain lions, have been identified as important regulators of WTD populations (Messier et al. 1986; Robinson et al. 2002; Robinson et al. 2014) and as a result, could be driving these behavioral shifts to prioritizing selection of safe habitat features during morning/evening and night hours.

Although our analyses highlighted important habitat selection factors for WTD during the crop-growing season at fine spatial scales, it was limited to a single spatial scale. Selection of certain habitat covariates can be scale-dependent and WTD are known to avoid certain habitat features at one scale while selecting for them at another (Dellinger et al. 2018). Thus, to obtain a well-rounded understanding of WTD habitat selection in Northern

Idaho, future research should work to characterize WTD selection within the home range (3rd order) and/or at the home range (2nd order) spatial scales. We also lacked data regarding predator densities and locations, WTD density, and fawning status. All 3 of these factors could help explain selection, movement patterns, and changes caused in year to year fluctuations. Further analyses connecting habitat features across multiple spatial scales with ecological driving factors, as well as with fitness outcomes, would be valuable for better understanding WTD ecology in human-modified landscapes.

MANAGEMENT IMPLICATIONS

One of the largest issues that wildlife managers face in Northern Idaho, and in many other areas of WTD range, is damage incurred to high-profit agricultural crops through WTD depredations. We found that WTD intensified their selection of high-profit fields later in the crop-growing season when the plants had reached maturity, and specifically during peak hours. Thus, our models can serve as baseline descriptions of WTD behavior, and offer a targeted time-frame for managers considering how to place a deterrent on the landscape to reduce agricultural depredations. In addition, we found that public hunting access may have an effect on the number of individuals within a hunted population that migrate, and the timing of migration from summer to winter range. Sixty-two percent of GPS-collared individuals inhabiting areas where public hunting is permitted migrated to winter range in early October, just prior to modern firearm season. However, only thirty-eight percent of individuals inhabiting private lands migrated, and migration did not occur until early December. Thus, hunting pressure could be a driving factor in both the number of individuals exhibiting migratory behavior, as well as the timing of migration to winter range. Potentially, regulating public hunting to enhance this source of fear could mitigate WTD damage, although we did not test this treatment in our work.

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TABLES

Table 2.1. Habitat variables considered for inclusion in models of white-tailed deer habitat use in Northern Idaho, USA. Prior to model development covariates were tested for multi-collinearity and variables marked with an asterisk (*) were not included in models. All variables were continuous and chosen because they were thought to be associated either with deer forage or security from predation.

Covariate Type	Habitat Variable	Model Abbreviation	Description
Forage			
	Grassland	grass	Distance to closest grassland polygon
	Hay	hay	Distance to closest alfalfa or timothy field
	Pulse	pulse	Distance to closest garbanzo bean, lentil, or pea field
	Winter wheat	wheat	Distance to closest winter wheat field
Security			
	Elevation*	-	Meters above sea level
	Slope	slope	Rate of change in elevation
	Road	road	Distance to nearest road (paved or gravel)
	Field Edge	edge	Distance to closest field edge
	Forest	forest	Distance to closest forest polygon
	Shrubland	shrub	Distance to closest shrubland polygon
	>40 Cover*	-	Distance to canopy cover >40%
	<40% Cover*	-	Distance to canopy cover <40%
	Low Cover*	-	Distance to 0-25% canopy cover
	Mid Cover*	-	Distance to 26-50% canopy cover
	High Cover*	-	Distance to 51-75% canopy cover

Table 2.2. Model selection for white-tailed deer step selection function during 5 separate 24-hour time periods. We ranked models using Akaike's Information Criterion (AIC), and identified the best performing model for each individual. Each individual was then categorized as using a behavioral strategy focused on forage, security, or combination of the two. We calculated the percentage of deer that exhibited each behavioral strategy per time period (column % Deer). We also used AIC scores to rank each model on a numbered scale (1 being the best ranked and 3 being the worst ranked) for each individual to obtain the average score per model across individuals (column Average Rank).

Model	**Average Rank**	**% Deer**
Midday		
Combination: edge+shrub+shrub*time+forest+forest*time+grass+hay+pulse	1.82	39
Security: edge+shrub+shrub*time+forest+forest*time	1.90	35
Forage: grass+hay+pulse	2.29	26
Crepuscular		
Combination: slope+road+edge+shrub+shrub*time+grass+grass*time+pulse+pulse*time	1.51	59
Security: slope+road+edge+shrub+shrub*time	2.04	29
Forage: grass+grass*time+pulse+pulse*time	2.45	12
Peak		
Combination: slope+road+road*time+edge+forest+hay+pulse+wheat+wheat*time	1.15	89
Security: slope+road+road*time+edge+forest	2.21	9
Forage: hay+pulse+wheat+wheat*time	2.64	2
Morning/Evening		
Security: edge+shrub+forest+forest*time	1.71	35
Combination: edge+shrub+forest+forest*time+grass	1.90	39
Forage: grass	2.41	26
Night		
Security: edge+shrub+shrub*time+forest	1.73	49
Combination: edge+shrub+shrub*time+forest+grass+grass*time+pulse+pulse*time	1.80	37
Forage: grass+grass*time+pulse+pulse*time	2.47	14

Table 2.3. Population-level averaged coefficients for the best fitting step selection function for each diel time period with a 90% confidence interval to portray significance of each covariate.

Period	Top Model	No. Deer	Covariate	Avg. β	90% CI Lower	90% CI Upper
Midday	Combination	19				
			Dist. Field Edge	-3.5810	-7.2183	0.0562
			Dist. Grassland	34.4918	19.7938	49.1899
			Dist. Hay	5.3980	-3.8307	14.6269
			Dist. Pulse	-6.1280	-20.7443	8.4883
			Dist. Shrubland	-20.355	-57.0326	16.3212
			Dist. Shrubland*Time	-44.766	-119.3952	29.8617
			Dist. Forest	-32.867	-70.1878	4.4535
			Dist. Forest*Time	4.9619	-68.5316	78.4556
Crepuscular	Combination	29				
			Slope	-0.1285	-0.5353	0.2782
			Dist. Field Edge	-3.3417	-4.9608	-1.7226
			Dist. Road	-1.5905	-2.701	-0.4793
			Dist. Grassland	-3.2717	-6.6228	0.0793
			Dist. Grassland*Time	11.2734	1.7436	20.8031
			Dist. Pulse	3.0637	-6.7160	12.8435
			Dist. Pulse*Time	-12.670	-30.8267	5.4857
			Dist. Shrubland	-3.8611	-9.6431	1.9208
			Dist. Shrubland*Time	1.8868	-9.8369	13.6106
Peak	Combination	42				
			Slope	-0.9306	-1.2673	-0.5938
			Dist. Field Edge	-6.2120	-7.8035	-4.62060
			Dist. Road	-0.1978	-1.5524	1.1568
			Dist. Road*Time	-1.4689	-3.847	0.9097
			Dist. Hay	-0.0265	-2.3884	2.3352
			Dist. Pulse	-10.423	-15.674	-5.1720
			Dist. Wheat	-2.3319	-5.775	1.1118
			Dist. Wheat*Time	5.9121	1.3370	10.4872
			Dist. Forest	2.1928	0.8992	3.4864
Morning/Evening	Security	17				
			Dist. Field Edge	-3.3053	-5.7645	-0.8462
			Dist. Shrubland	-31.274	-54.3372	-8.2125
			Dist. Forest	5.6813	-28.9042	40.2669
			Dist. Forest*Time	7.0740	-12.9747	27.1228
Night	Security	24				
			Dist. Field Edge	-6.3796	-8.4012	-4.3580
			Dist. Shrubland	-22.114	-57.766	13.5371
			Dist. Shrubland*Time	26.8874	0.5138	53.2610
			Dist. Forest	-8.9767	-26.4982	8.5448

FIGURES

Figure 2.1. Our two study sites were located in Latah County, Idaho, USA.

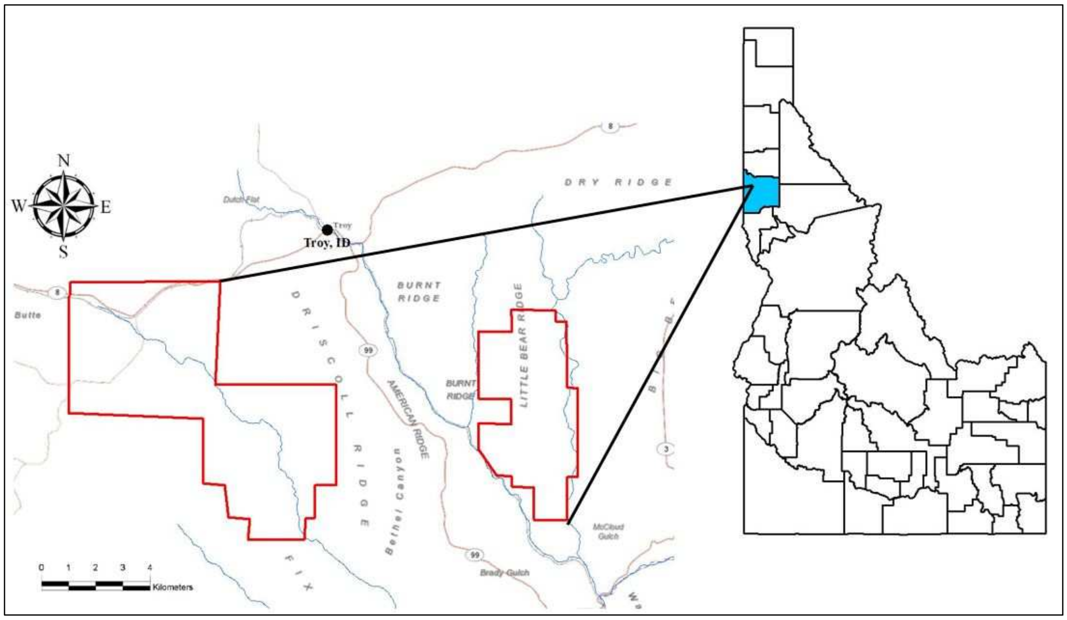


Figure 2.2. Movement locations from GPS-collared individuals in agricultural fields during a 24-hour period. Movement locations were separated into 5 time periods: morning/evening (2-3hrs after sunrise and 2-3hrs before sunset), midday (7-9hrs after sunrise), crepuscular (0.5hr before sunrise to .5hr after sunrise and 0.5hr before sunset to 0.5hr after sunset), peak (0.5hr before sunset to 1hr after sunset), and night (4.5-6.5hrs after sunset).

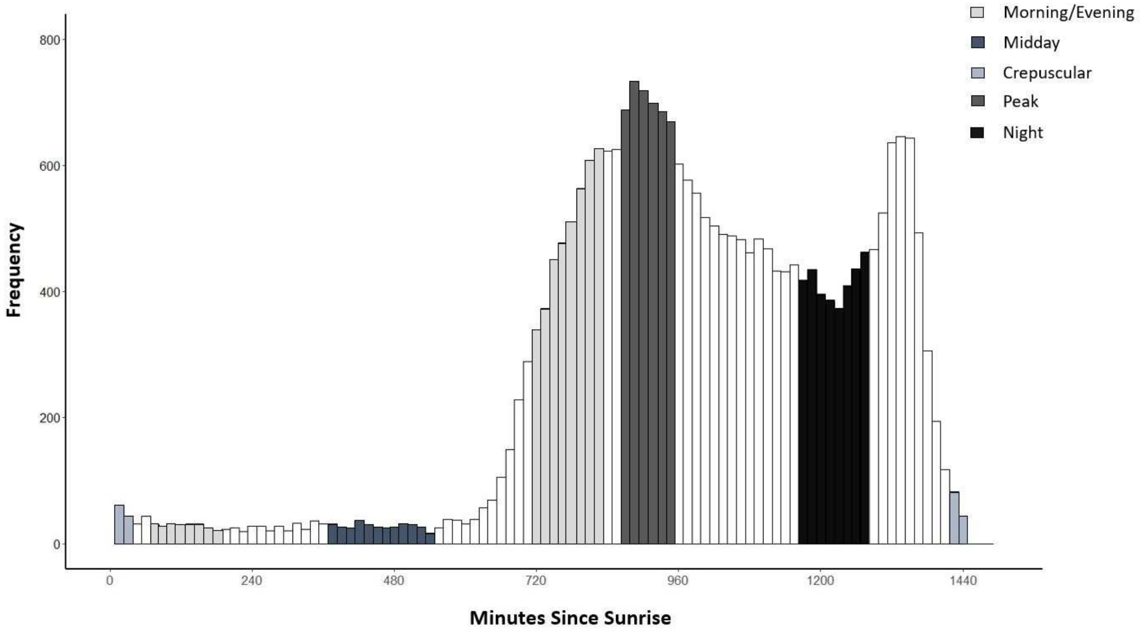
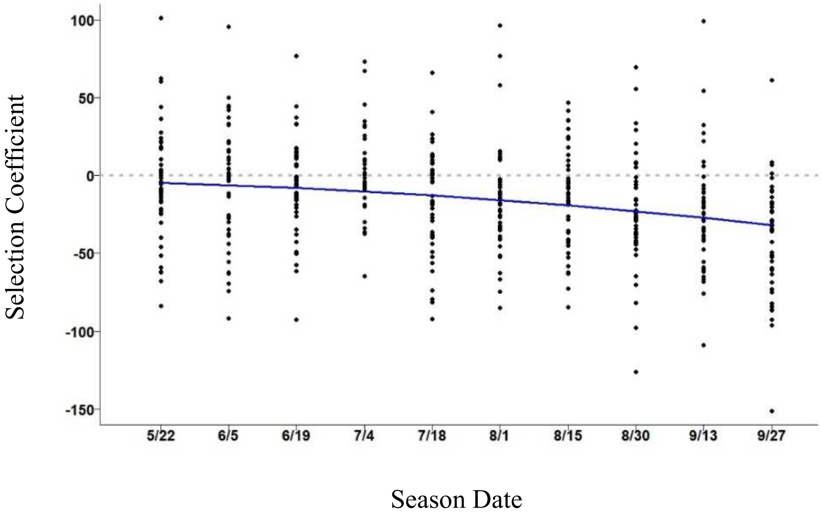
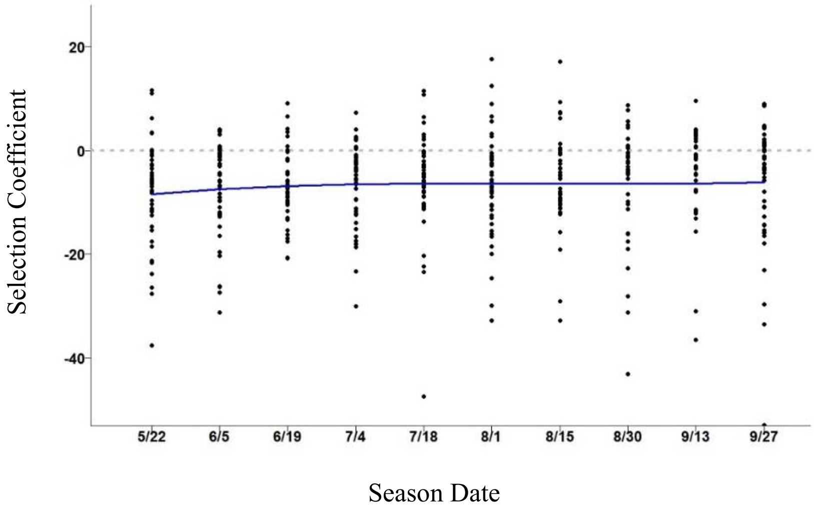


Figure 2.3. Single covariate models were fit to each individual deer (each deer's coefficient of selection is represented by a black dot) within each time period to verify if: 1) selection was evident, but varied throughout the crop-growing season by either increasing or decreasing, and therefore a seasonal interaction was included (A); 2) selection was evident, but constant throughout the season (B); or 3) no selection was evident at the population level (across individuals) and the covariate was excluded from models including multiple predictor covariates (C). The average selection across individuals throughout the crop-growing season is represented by the blue line, which either increased or decreased (A), remained constant (B), or was not significantly different than 0 (C).

A)



B)



C)

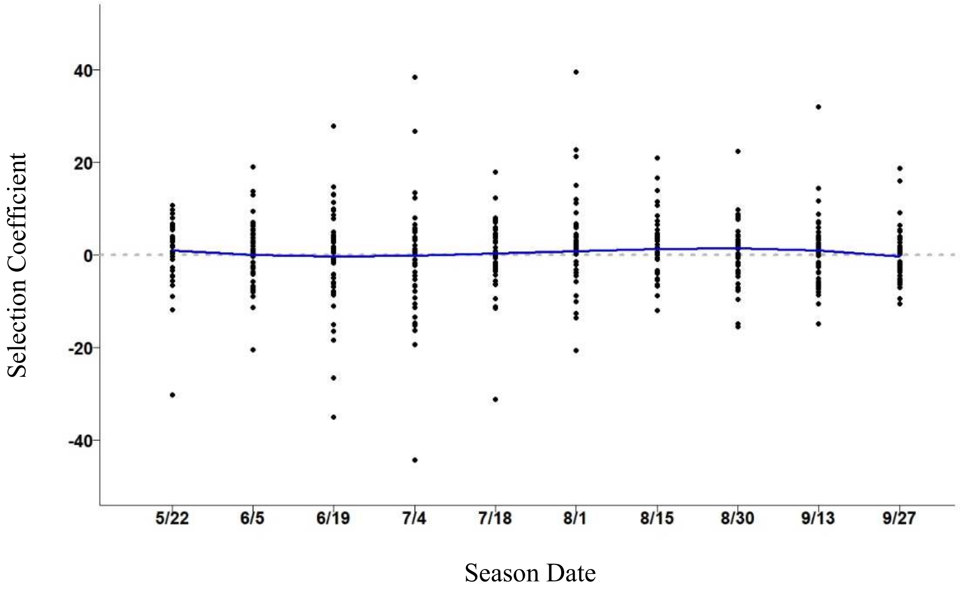


Figure 2.4. The net squared displacement (NSD) measurements for each individual deer describing migratory behaviors. Each line represents a single individual, with red lines representing individuals within the Little Bear population and blue lines representing individuals within the Middle Potlatch Creek population. Increasing displacement values represent a movement away from summer range, while decreasing values represent a movement towards summer range.

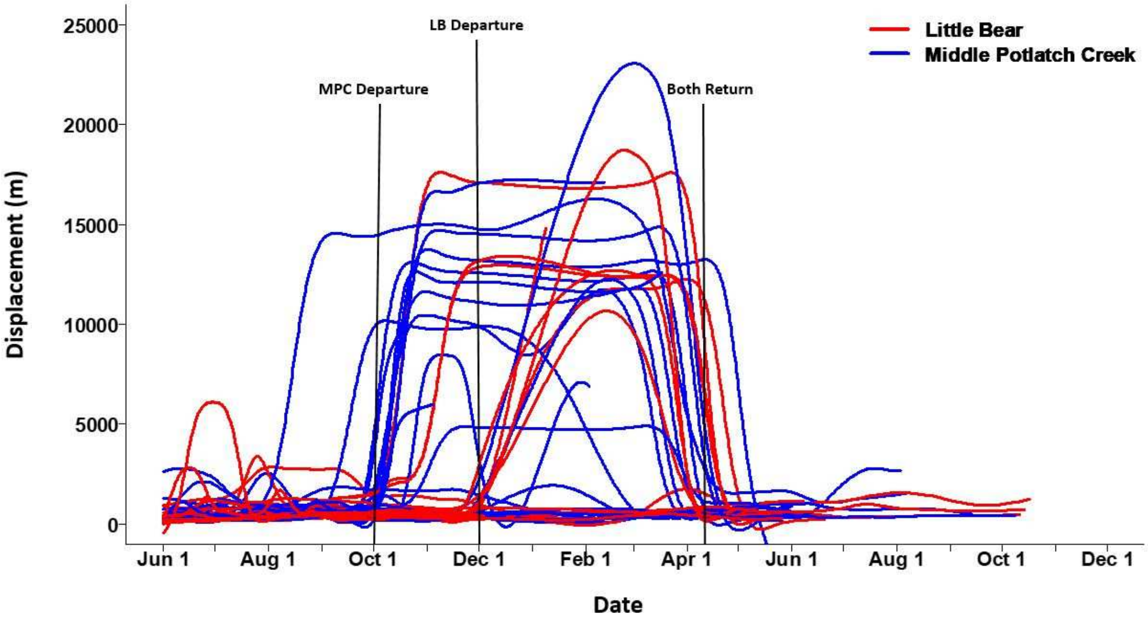


Figure 2.5. Step selection model results for each covariate included within the model during peak hours. An average beta value was calculated across individuals for each covariate with 90% confidence intervals. Statistically significant covariates did not have confidence intervals overlapping zero. Covariates with time interactions were not included.

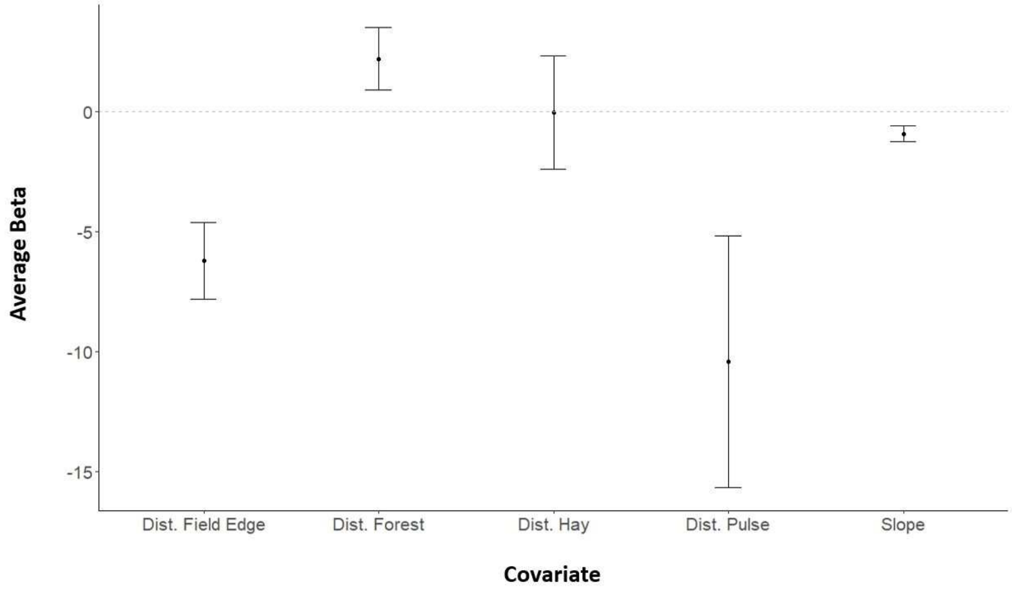


Figure 2.6. Female WTD relative probability ratios (and 90% CIs) for distance to a pulse (garbanzo bean, lentil, or pea) field during peak hours. Probability ratios represent the relative difference in probability of selection between two locations (points A and B) with contrasting environmental variable values that an individual had the opportunity to move to within a 15-minute time period. For example, an individual is ~3 times more likely to be in a pulse field than 0.9km away from it during peak hours.

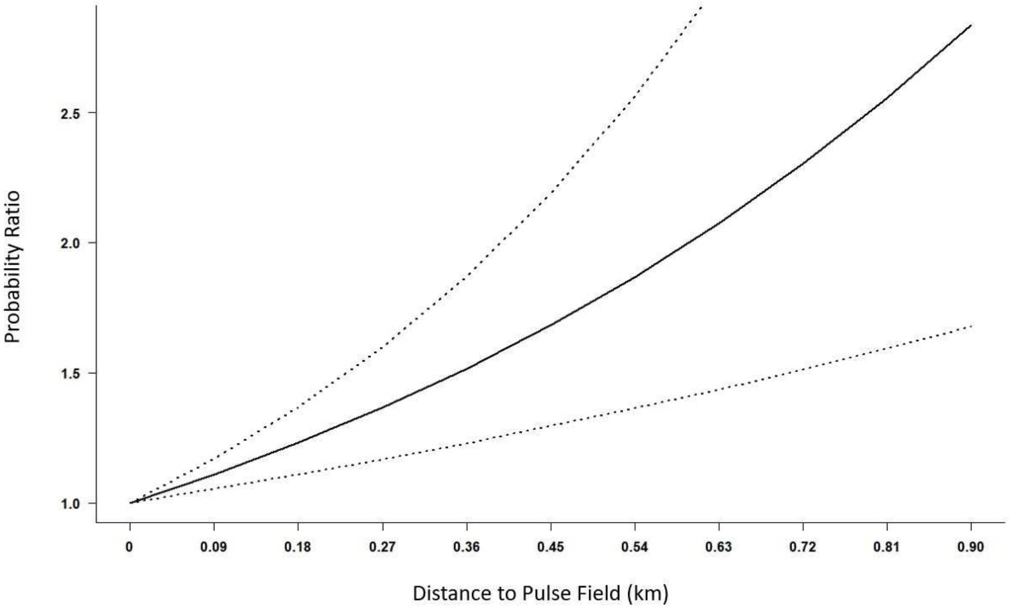
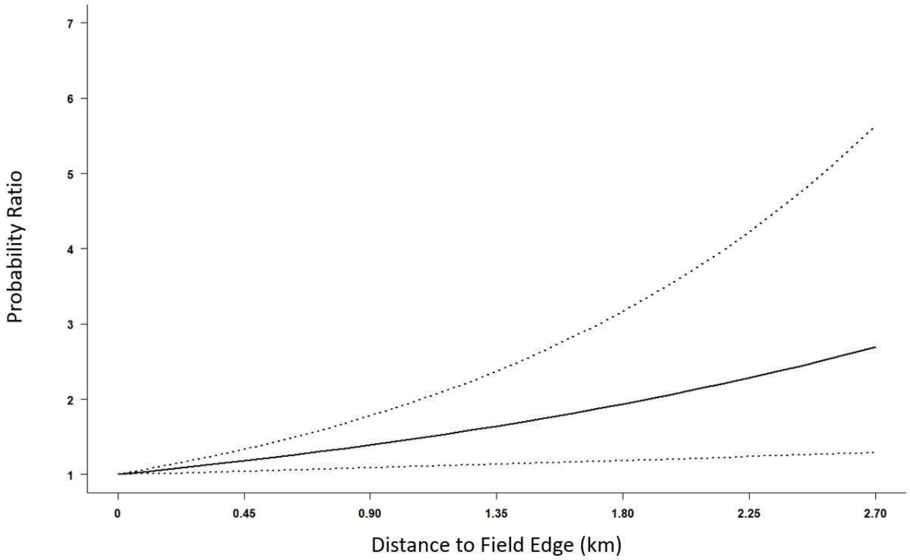
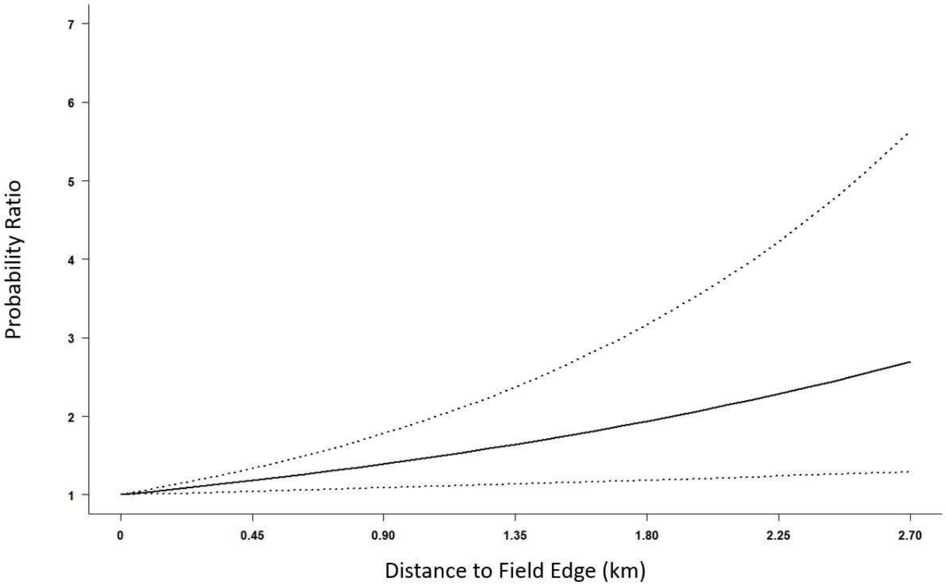


Figure 2.7. Female WTD relative probability ratios (and 90% CIs) for distance to an agricultural field edge during morning/evening, midday, crepuscular, peak, and night hours. When compared to 2.7km away from a field edge, WTD were ~2.7 times more likely to be located on a field edge during morning/evening, midday, and crepuscular hours, ~6.4 times more likely during peak hours, and ~6.8 times more likely during night hours.

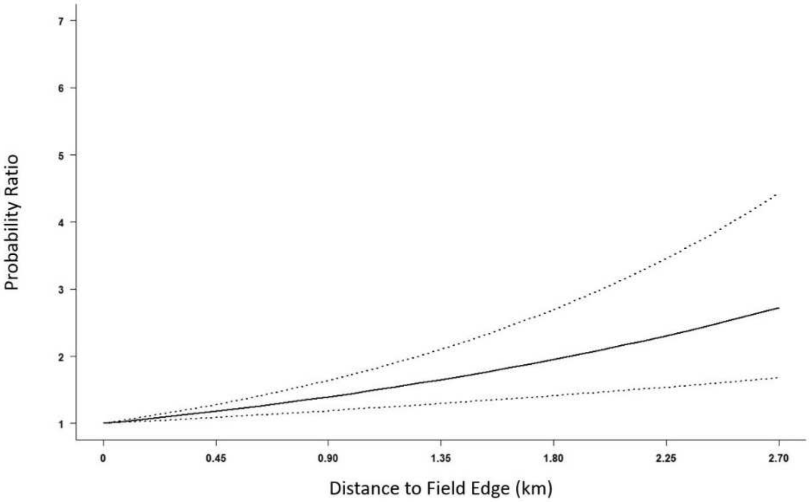
A) Morning/Evening



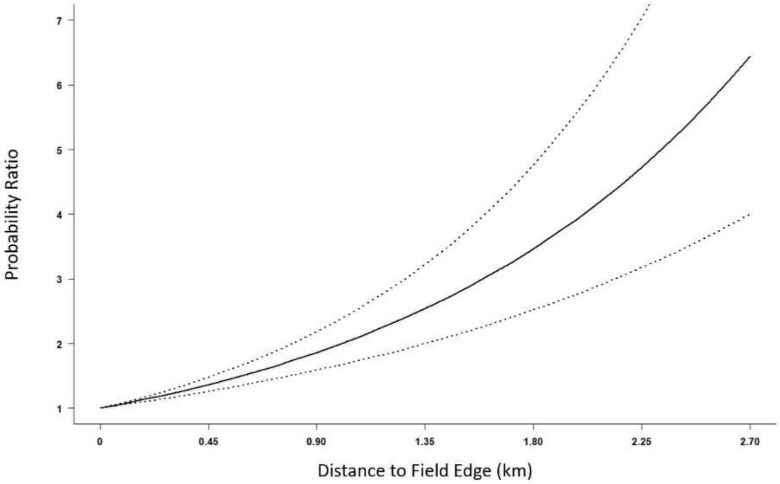
B) Midday



C) Crepuscular



D) Peak



E) Night

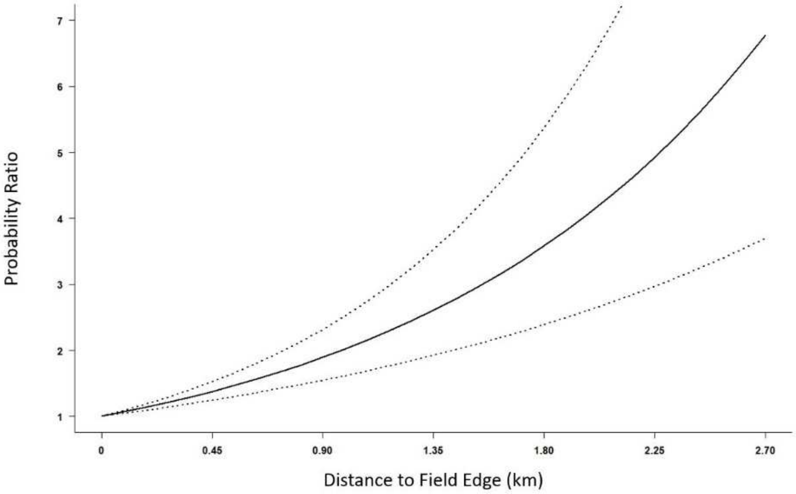
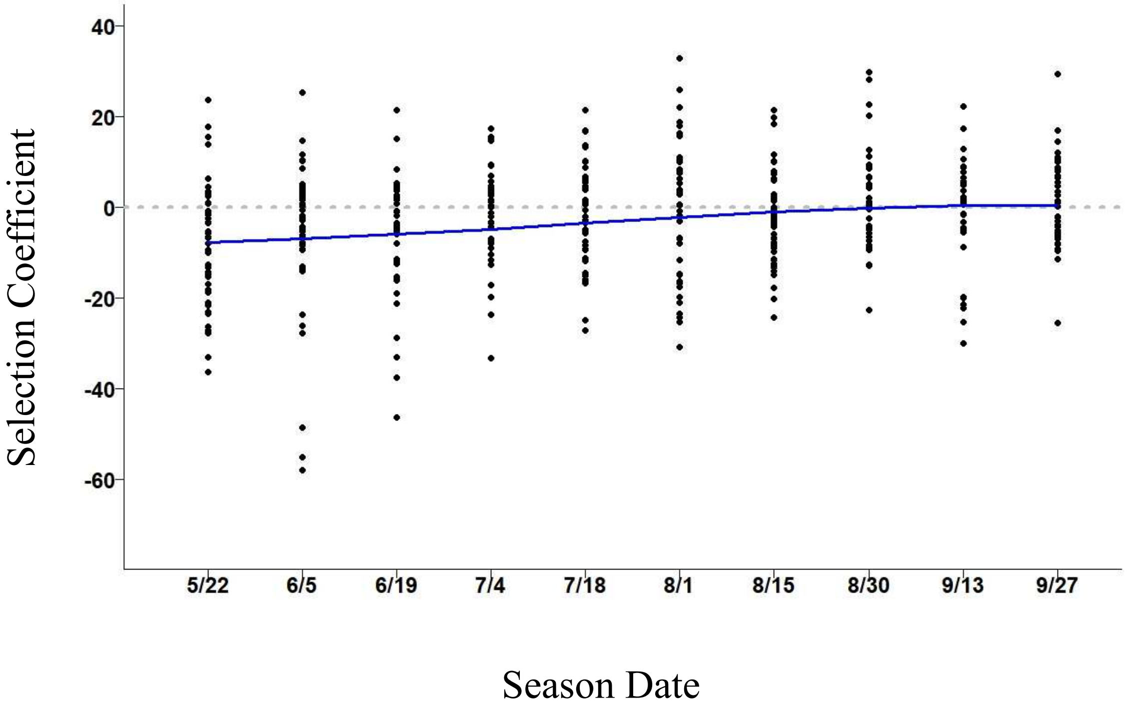


Figure 2.8. A SSF model was fit across 49 WTD (each individual's selection coefficient is represented by a black dot) to determine that WTD preferred to be near winter wheat fields during the spring and that this preference declined as the crop-growing season progressed.



CHAPTER 3: Effect of two novel deterrent systems on white-tailed deer agricultural field use

ABSTRACT

In the Clearwater region of northern Idaho, white-tailed deer (*Odocoileus virginianus;* WTD) cause significant damage to high value agricultural crops. To reduce wildlife caused damages, wildlife managers seek effective, cost-efficient deterrent methods. To date, few deterrent methods have successfully reduced agricultural field use. Thus, our goal was to evaluate the efficacy of 2 types of novel deterrent systems designed to reduce WTD use of crops. Our deterrents consisted of a fear-enhancing deterrent and a physical exclusion barrier. Our fear-enhancing deterrent was comprised of 3 components that targeted auditory, olfactory, and visual cues, while our physical exclusion deterrent was a 4-strand electric fence that partially enclosed the agricultural field. We treated 4 agricultural fields with the fear-enhancing deterrent and 3 agricultural fields with the electric partial fence. Based on GPS-location data we found that WTD behavior and movement patterns were influenced by our fear-enhancing deterrent system, and that WTD use of treated fields was reduced by 23%. Based on track counts, we found that our 4-strand electric partial fence reduced WTD field use by 30%. Both of our deterrent treatments may be suitable tools for reducing WTD crop damage and aid in keeping a positive working relationship between agricultural producers, wildlife enthusiasts, and wildlife agencies.

INTRODUCTION

Sustainable wild cervid populations provide ample opportunities for recreationalists, and are critical for ecological and economic growth. However, in some areas of the United States, conservation has led to the overabundance of certain species, leading to habitat degradation (Coté et al. 2004), wildlife aircraft and vehicle collisions (Belant et al. 1996; Bissonette et al. 2008), spread of zoonotic diseases (Gortázar et al. 2006), and substantial agricultural and private property damage (Belant et al. 1996; Blackwell et al. 2012; Phillips et al. 2012; Johnson et al. 2014). In rural areas wild cervid diets may be heavily supplemented by agricultural crops, nursery plants, and ornamental plantings due to easy access and higher levels of attainable crude protein (Mould and Robbins 1982; Ward and Williams 2010; Johnson et al. 2014). As a result, agricultural producers report damages incurred by cervids and expect compensation for lost profits.

The extent of crop damage and depredation varies depending on the crop species, desirability of the crop species, cervid population density, availability of native forage, and landscape configuration in regards to proximity to safe or risky areas (Hegel et al. 2009; Johnson et al. 2014). If wildlife caused damages exceed a 10% profit loss, agricultural producers typically seek out ways to reduce further damages (VerCauteren et al. 2006*b*; Hildreth et al. 2012). In an attempt to reduce damages, wildlife agencies have implemented a variety of field deterrents including taste repellents (Byers et al. 1990; Kimball et al. 2005), scare tactics (Beringer et al. 2003), physical barriers (Webb et al. 2009; Hildreth et al. 2012; Phillips et al. 2012), and lethal removal (Hildreth et al. 2012; Moneith et al. 2019). Although lethal removal and permanent fencing have proven to be effective (Palmer et al. 1985; VerCauteren et al. 2006*b*; Phillips et al. 2012), they can also be controversial and cost-prohibitive in areas with rotational crops and substantial field sizes (VerCauteren et al. 2006*b*; Johnson et al. 2014). After careful synthesis of previously deployed deterrents, we explored two novel methods to reduce the amount of time white-tailed deer (WTD hereafter), spend in high profit pulse (i.e., garbanzo bean, pea, and lentil) fields.

We tested the efficacy of 2 deterrents, a fear-enhancing scare tactic and a physical exclusion fence that partially enclosed the agricultural field. The goal of our fear-enhancing deterrent was to target 3 main senses (auditory, olfactory, and visual) with enough false signals of increased predation risk to pressure deer to forgo foraging within a treated area. For the second deterrent type, we used an electric partial fence schematic to reduce fencing material and labor costs, while still being able to target the canyon/field interface where WTD field crossings are typically concentrated.

As part of early detection and evasion of predators, WTD rely on acute auditory skills to procure cues and noises from not only approaching predators (Lynch et al. 2015), but conspecifics as well (Lingle and Wilson 2001). Although white-noise machines had yet to be tested on ungulates, they had been proven effective at deterring birds from airfields (Swaddle et al. 2016). We chose to use white-noise as the projected acoustic sound because previous studies had shown that distress and alarm calls were not effective in reducing agricultural depredations, likely due to habituation (Gilsdorf et al. 2004). However, because the intention behind white-noise was not to be a scare factor itself, but to instead mask important communication channels and vocalizations, we predicted that habituation would be greatly reduced. Previous studies have shown that prey species are prone to avoiding areas of recognized predator odors such as urine or scat remains (Swihart et al. 1991; Kuijper et al. 2014). Fresh urine and fecal samples contain volatile components, and as time progresses these volatile components are the first to evaporate thus informing prey species that the immediate danger has since passed (Parsons et al. 2018). Although we had originally intended to use only the volatile components found in urine due to a high success rate in evoking fear related behaviors such as tail-flagging, flight, and jumping in Hokkaido deer in

Japan (Osada et al. 2014) , we were not able to successfully manufacture the chemical mixture in large enough quantities to fill the automated scent pumps. Thus, instead of using volatile components to fill our automated scent pumps we used mountain lion urine that was expelled every 6 hours to ensure constant freshness and replenish odors. Lastly, WTD use tail flagging as a conspicuous single to warn conspecifics of potential predators (Hirth and McCullough 1977). To imitate this behavior we strung up white, flapping flagging in an attempt to increase anti-predator behavior causing WTD to flee the treated area.

METHODS

Study area

Our study area was located in Latah County, in Northern Idaho and encompassed ~906 square km. Dominant land use consisted of agricultural and forestry practices, with 74% of the county being privately owned (Idaho Department of Fish and Game 2016). We studied 2 populations of GPS-collared individuals at 2 study sites (Figure 3.1). The topography of these sites was characterized by deep forested canyons surrounded by rolling agricultural fields, with elevation ranging from 430m at the canyon bottoms to 830m at the highest field points. The climate was characterized by warm, dry summers (July-September) followed by cool, wet winters (December-February). During our study, the mean temperature during summer was 26.6°C, and mean total precipitation was 1.6cm (PRISM Climate Group).

The area was a dryland agriculture and coniferous habitat type with areas of interspersed agriculture fields, coniferous forest, shrublands, and grasslands (Idaho Department of Fish and Game 2016). Dominant overstory species included ponderosa pine (*Pinus ponderosa*), Douglas fir (*Psuedotsuga mensiezii*), Western larch (*Larix occidentalis*), grand fir (*Abies grandis*), and lodgepole pine (*Pinus contorta*), while the understory species consisted of shrubs, forbs, and grasses. The major agricultural crops planted were non-irrigated winter and spring wheat, peas, oats, barley, garbanzo beans, lentils, alfalfa, and timothy. The growing season for these crops typically lasts approximately 150 days with fall plantings occurring in late September and spring plantings occurring in mid-April. All crops were typically harvested by mid-September. Although observed, no data was recorded for other mammalian species co-inhabiting the study area, which included mountain lions (*Puma concolor*), black bears (*Ursus americanus*), coyotes (*Canis latrans*), and elk (*Cervus canadensis*).

Triple Threat Deterrent System

We evaluated a fear-enhancing deterrent that simultaneously targeted 3 main WTD senses (auditory, olfactory, and visual) to create a false sense of increased predation risk. We investigated whether the triple threat deterrent system could be used to reduce WTD use of pulse fields by evaluating the effects of the deterrent system on the movements and space use of GPS-collared female WTD.

Animal capture and handling

We captured yearling and adult (>1 year) female WTD between April 2017 and April 2018. Most individuals were captured by helicopter net-gunning and Clover trapping (Clover 1956). We net-gunned individuals in open agricultural fields while Clover trapped individuals were trapped on ATV routes within the study site canyons. We checked Clover traps daily and baited with a variety of food-related items including apples, alfalfa, oats, and mineral licks. Captured individuals were restrained and blindfolded to reduce animal stress and ensure safe handling. Once safely restrained, each individual received ear identification tags and was fit with a temporary GPS radio collar (Lotek Litetrack420), which was equipped with a drop-off mechanism and projected to fall off in September of 2019. During the summer months of 2017 we also captured individuals by ground-darting. Individuals were darted with either 2mL of BAM (Butorphanol, Azaperone, and Metatomidine) or a mixture of 1.8mL Ketamine and 0.4mL of Xylazine (Idaho Department of Fish and Game 2017). Chemically immobilized individuals were positioned in a sternal recumbent position and vitals were monitored while identification tags and a drug tag were placed in each ear, and a GPS-collar was fit. Upon data process completion individuals were reversed with an intramuscular injection of 0.5mL of Naltrexone and 4.0mL of Atipamezole (BAM reversal) or 1.4mL of Tolazoline (Xylanzine reversal) (Idaho Department of Fish and Game 2017). Following reversal, individuals were monitored until it was determined that appropriate body functions and reactions had fully returned. Capture, animal handling, and monitoring was approved by the Institutional Animal Care and Use Committee at the University of Idaho (IACUC-2017-70).

Description of deterrent system

Each triple threat system consisted of 1 white-noise machine, 3 automated scent pumps, and a total of 400m (i.e., 200m per side of the white-noise machine) of white, flapping flagging. We obtained white-noise machines from SonicNets (Williamsburg, Virginia) and Flock Free Bird Control (Lakewood, New Jersey) who have manufactured a solar powered speaker system that has proven successful in reducing the amount of birds located on or near active airfields (Swaddle et al. 2016). Each speaker system projected white-noise continuously for 8-10 hours a night (turning on 1hr prior to sunset and lasting until the batteries died), and was powered by a 175-watt solar panel (NextGen Electric, Coeur d'Alene, Idaho) and 2 12-volt batteries (Apex Battery, Las Vegas, Nevada). The automated scent pumps (Idaho Department of Fish and Game, Lewiston, Idaho) expelled mountain lion urine (Fleming Outdoors, Ramer, Alabama) every 6 hours onto an absorbent towel to keep the scent as fresh and as long lasting as possible. Lastly, white, flapping flagging was included to imitate WTD warning behavior. Flagging was placed every 15m and was comprised of three 30.2L white plastic garbage bags that were secured to camouflaged string ~1.3m above ground. Each individual triple threat deterrent system cost $1,050, and because 3 systems were deployed per treated field, the total cost was $3,150 per field.

We deployed triple threat deterrent systems on 4 garbanzo bean fields that were greater than 0.5km apart to minimize dependence among treated fields (Gilsdorf et al. 2004; Hildreth et al. 2012). We selected treated fields based on the crop type planted (i.e., pulse crop species), suitable canyon/field interface, and fields that were consistently used by GPS-collared individuals. Specific locations for each system were chosen by examining GPS-collared individuals and identifying shared routes used to enter and/or exit the 4 chosen fields. A single white-noise machine and 1 automated predator scent pump were placed at the most commonly used entry and/or exit site, and then 2nd and 3rd automated scent pumps were placed 200m to the left and right. White, flapping flagging was strung along vegetation or rock outcroppings filling in the space between the central location and 2 side pumps (Figure 3.2). Preliminary analysis of GPS-collar location data from the previous year suggested that peak agricultural field usage began in August and lasted through October (Figure 3.3). To encompass peak field usage, we deployed the triple threat deterrent systems beginning August 8, 2018 and removed them by October 5, 2018. We operated on 1-week intervals, alternating between treatment and non-treatment periods where 2 fields would be "on" while the other 2 fields would be "off." During off periods, white-noise machines, automated predator scent pumps, and flagging were completely removed from the treated field. However, solar panels and batteries were left on-site at each of the 4 treated fields throughout the field season due to the extensive size and logistics of moving them for each on/off period.

Statistical analysis

We evaluated the effectiveness of the triple threat deterrent system using 2 analyses, one that evaluated overall field usage by WTD and another that evaluated whether WTD avoided the area around the deterrent system. If a GPS-collared individual was using a field that had been treated with a triple threat deterrent system we described it as a "treated individual" and if an individual was using an untreated field we described it as an "untreated individual". For the first analysis we were interested in answering 2 questions: 1) did field usage between treated and untreated individuals change after deterrent systems were deployed?; 2) did field usage change for treated individuals when deterrent systems were on compared to when they were off? Preliminary analysis of GPS-collar location data from the previous year suggested that peak field usage hours occurred 1 hour before sunset to 2 hours after sunset (Figure 3.4). To answer the first question, we counted the number of GPS-locations for individuals in fields during peak field usage hours and then modeled the count as a Poisson distributed random variable:

$$N_{i,t} \sim Poisson\left(\lambda_{i,t}\right)$$

where $N_{i,t}$ =number of GPS-locations in field for an individual (i; i = 1:18) during week (t; t =1:14) and

$$\lambda_{i,t}=\exp\{\beta_0 \times W_t + \beta_1 \times ID_i + \beta_2 \times AD_{i,t} + \beta_3 \times D_{i,t}\}$$

where $AD_{i,t}$ = 1 if individual i was a treated individual and t was ≥ the week the deterrent was deployed for that individual, and 0 otherwise; and $D_{i,t}$ = 1 if individual i was a treated individual and the deterrent was deployed during week t for that individual, and 0 otherwise. To account for seasonal changes in use, we included a categorical time covariate where W_t = weeks 1:14. To account for individual variability in field usage, we included a categorical ID covariate where ID_i = 1:18. We used 6 competing models that included different combinations of predictor variables. The models were ranked using Akaike's Information Criterion (AIC-Symonds and Moussalli 2011).

For the second analysis, we were interested in how the distance between GPS-location points and deterrent systems changed as treated individuals could have been avoiding the area around the deterrent system, yet still moving within the field. Because the distribution of our observed distances were generally large and far from zero, we modeled the distance between GPS-locations and the center of the deterrent system as a normally distributed random variable:

$$D_{i,t} \sim Normal\ (\mu_{i,t}, \sigma^2)$$

where $D_{i,t}$ = distance between GPS-locations and the deterrent system for an individual (i; i = 1:18) during week (t; t = 1:14) and

$$\mu_{i,t} = \beta_{0,t} + \beta_1 \times ID_i + \beta_2 \times AD_{i,t} + \beta_3 \times D_{i,t}$$

where $AD_{i,t} = 1$ if $t \geq$ the week the deterrent was deployed for individual i, and 0 otherwise; and $D_{i,t} = 1$ if the deterrent was deployed during week t for individual i, and 0 otherwise. To account for individual variability between WTD, we included a categorical ID covariate where $ID_i = 1{:}18$. We used 5 competing models that included different combinations of predictor variables. The models were ranked using Akaike's Information Criterion (AIC-Symonds and Moussalli 2011).

4-Strand Electric Partial Fence

Description of fence

We treated 3 garbanzo bean crop fields of similar size from July 15, 2019 through September 13, 2019. The average size of treated fields was 14ha and the average distance between treated fields was 2km. To minimize dependence among fields we maintained a distance of at least 0.5km between fields, as well as ensuring that other separating landscape features such as a canyon or different varieties of crop fields occurred between treated fields (Gildorf et al. 2004; Hildreth et al. 2012). Treated fields had ~1.6km long canyon/field interface with the other 3 sides exposed to other crop fields or access roads. Treated fields were selected within areas of high WTD use informed by preliminary analysis of GPS-collar location data and previous complaints of high levels of crop damage by ungulates.

We installed a 4-strand electric partial fence to create a physical barrier along the entire 1.6km canyon/field interface. We refer to the treatment as a partial fence because it did not fully enclose the entire field perimeter and was instead only present along the interface where the highest concentration of WTD crossings occurred. We inserted 2.5m metal t-posts every 7.5m along the fence line and anchored each end post with an h-brace assembly. We stretched 4 strands of offset electric 14 gauge smooth wire along the entire fence line and secured the wire to t-posts using standard snug-fitting t-post insulator clips. Wires were placed 30cm, 96cm, 142cm, and 185cm above ground with the top strand protruding towards the canyon at a 45° angle to discourage deer from jumping up and over the fence. We constructed extension pieces using PVC pipe with a fiberglass stay clip attached to the end securing the electrified wire. Each PVC extension was secured to the t-post with wood screws to reduce any movement during unfavorable weather conditions or animal impediment. Each fence was powered by a Gallagher S100 Solar Charger (Gallagher, Oswego, Illinois) on the wildlife control mode that operated with a fast pulse day and night to ensure wildlife exclusion. When electric wires were up and on, fences were checked with a digital fault finder to ensure high voltage continually travelled the length of the fence line. Fence checks were conducted simultaneously with track survey counts to reduce the amount of human disturbance that occurred at the treated sites. Bright pink and orange flagging strips were attached to electric wires every 8m to enhance fence visibility. We also conducted maintenance checks along the fence lines every few days to mend breakage points, remove vegetation, tighten wires, and replenish visible warning flagging. The 2 end posts of each fence line were extended roughly 50m into neighboring fields to discourage deer from simply entering on exposed corners. All fences were constructed before July 15th when treatments began and cost ~$2,200 per field.

Fence wires were rotated between being “up and on” to “down and off” on 2-week intervals, alternating between treatment and non-treatment periods. During “down and off” periods wires were removed from t-post insulator clips, bundled together, and secured to the base of each t-post to ensure that wires did not prohibit entries or exits from the treated field.

To assess the efficacy of the fence we obtained count data through track surveys and night-time drone surveys using an attached thermal camera. Track surveys were conducted every 2 to 3 days per treated field throughout the entire treatment period. A 1.5m dirt swath around the entire border of each treated field was left unplanted, and was groomed after every count with a 1.8m Yard Tuff spike drag with leveling bar and drag mat to keep the dirt light and formable. We counted every set of WTD tracks that entered or exited the treated field along the entire border and averaged the 2 counts to obtain a mean crossing count. If multiple days had passed since the last survey was conducted we divided the total by the number of days that had surpassed to obtain a mean daily crossing count.

We also conducted night-time drone surveys with a thermal camera and video recorder. Each field was surveyed twice per week and each survey lasted 15-20 minutes. We obtained a Daylight Operation Waiver with the Federal Aviation Administration that allowed us to fly after legal flight operation hours had expired, and each flight occurred ~45 minutes post sunset. We used an Ag-Bot2 multi-rotor sUAS fitted with a FLIR 640 Pro Sensor and stabilization gimbal to conduct the surveys. We used a Tarranis X9D radio controller (with DragonLink TX4*90) and sUAS's with a 433 Ghz RC controller to maintain communications and system information, which allowed us to launch the drone up to 750m away ensuring that deer were not disrupted before or during the survey. The drone flew ~91m above the treated field at 13mph. If adverse weather conditions occurred (high winds or rain) surveys were postponed until the following night. We programmed the survey route to cover the entirety of each treated field in 90m swaths. Counts were obtained through careful analyses of recorded flight footage, in which deer were counted if they were observed within a treated field or on the track survey pathway. Throughout the course of the season we did not observe deer fleeing from the drone or that the drone caused any sort of disturbance.

Statistical analysis

We modeled the natural logarithm of the mean daily number of WTD field crossings as a normal distributed random variable:

$$ln(Count_{f,t}) \sim Normal\ (\mu_{f,t}, \sigma^2)$$

where $ln(Count_f)$ = the natural logarithm of the mean number of field crossings per treated field (f; $f = 1:3$) during the number of days since planting (t; $t = 1:53$) and

$$\mu_{f,t} = \exp\ \{\beta_{0,f} + \beta_1 \times ID_f + \beta_2 \times DO_{f,t} + \beta_3 \times T_{f,t}\}$$

where $DO_{f,t} = 1$ if fence was up and on for field f at time t, and 0 otherwise; and $T_{f,t}$ was a continuous covariate that represented the number of days that had surpassed since crop planting. We used 6 competing models that included different combinations of predictor variables. The models were ranked using Akaike's Information Criterion (AIC-Symonds and Moussalli 2011).

RESULTS

Animal capture and handling

We captured a total of 53 yearling and adult (>1 year) female WTD between April 2017 and April 2018. In 2017, 34 individuals were captured via net-gunning, 4 individuals via Clover trapping, and 2 individuals via ground-darting. In 2018, we captured 13 individuals via Clover trapping. GPS-collar battery life was expected to last the entire span of the 2-year study, however, because of a software malfunction a majority of the GPS-collars deployed in 2017 immediately switched to mortality mode causing the batteries to expire much earlier than anticipated. Due to this malfunction, most GPS-collars were not useful for the 2019 field season and we thus had to use track and drone survey counts for data analysis instead.

2018: Triple Threat Deterrent System

The best fitting model included seasonality, ID, and deterrent deployment effects (Table 3.1). Variation of weekly field use among individuals was high. To characterize the expected field usage of an "average" WTD, we added the B_0 value to each ID_i beta value, and then took the average of these values across all 18 individuals (ID_{Avg}). In week 9, the mean expected number of locations for an untreated WTD within a field was ~16, compared to ~12 locations for a treated WTD (Figure 3.5). The expected number of locations within a field was reduced by 23% after the triple threat deterrent had been deployed (Figure 3.5).

We found that distance from the triple threat deterrent system was dependent on whether the system was on or off as the best fitting model included field ID and deterrent deployment effects (Table 3.2). The mean expected distance was 298m when the deterrent system was on and 262m when the deterrent system was off ($\beta_0 = 348.61$, $ID_{Avg} = -85.91$, $AD_{i,t}=34.96$). Thus, the "average" treated deer preferred to be ~35m further away from deterrent systems when they were on compared to when they were off.

2019: 4-Strand Electric Fence

For our track survey data, the best fitting model included both a treatment and seasonality effect (Table 3.3). The number of WTD crossings in treated fields varied across treatment and non-treatment periods, although counts were consistently lower when the fence was up and on versus when it was down and off (Figure 3.6). When the fence was up and on, deer crossings were reduced by 30% ($\beta_0 = 2.1088$, $\beta_2 = -0.3640$, $\beta_3 = 1.328$), resulting in a difference of ~400 crossings by the end of the crop-growing season (Figure 3.7).

Drone counts, albeit analyzed the same way, produced contrasting results. The best fit model for this dataset included a seasonality only effect (Table 3.4). Thus, as the time since planting progressed throughout the crop-growing season, the number of WTD present in a pulse field increased (Figure 3.8).

DISCUSSION

Multiple deterrent methods have been tested in hopes of reducing damage caused by wildlife. However, management of crop depredating populations is often complicated by trying to find a sustainable balance of maintaining the population size yet reducing the amount of private property damage, typically through a non-lethal method. An array of frightening devices have been used to try and scare wildlife away from particular sites, including the use of propane exploders, animal-activated scare crows, and lasers (Beringer et al. 2003; Gilsdorf et al. 2004; VerCauteren et al. 2006*a*). Although most successful deterrents include an associative negative consequence, such as death, ensuing sickness, or slight injury (i.e., rubber bullets) (Brown et al. 2000; Visscher et al. 2017), the triple threat deterrent system did not produce any direct negative consequences. It did, however, contain enough high-risk factors (reduced hearing, fresh predator scent, and visible warning signs) that WTD chose to avoid moving through areas where a deterrent system had been placed. This could have been due to indirect consequences of predation. Because natural predators (specifically mountain lions) co-inhabited the same areas as the treated deer, deer may have chosen to avoid areas containing the deterrent system in an attempt to avoid perceived increased predation risk. Previous studies have found that predation risk, and resulting anti-predator behaviors, can influence spatial distribution of ungulates (Theuerkauf and Rouys 2008; Thaker et al. 2011; Gulsby et al. 2018). This may be the case for the triple threat deterrent system where the increased perceived predation risk was powerful enough to influence both spatial distribution along the landscape (i.e., choosing a different area to move through) and within the agricultural field (i.e., moving in areas outside of the auditory range).

The distance between the center of the triple threat deterrent system and treated individuals locations was also considered an important factor of deterrent efficacy because the average treated field size was 47ha and each triple threat deterrent system was not audible from every location within the field. Thus, it could have been probable that an individual was still present in the field, but moving further away from the activated system. Although treated individuals preferred to occupy areas outside the likely audible radius of a noise machine both before and after the deterrent systems were deployed, the distance became even larger once the deterrent systems had been deployed.

The track survey data for our partial electric fence supported our prediction that WTD used treated fields less when the fence was active (up and on) versus when it was inactive (down and off). The fence reduced WTD crossings by 30% over the course of the crop-growing season. Although we were not able to quantify exactly how much crop damage each individual causes in a pulse field per crossing, we would expect that a reduction of 400 crossings would significantly reduce damage caused by WTD consumption or trampling and trailing through the fields. The potential reduction in damage likely offsets the initial first year price of the fencing materials, and because the fence is movable, it could be reused in subsequent years with minimal maintenance costs. Previous studies have also found that partial (i.e., winged) and electric fences reduce cervid damage to agricultural fields (Hildreth et al. 2012; Johnson et al. 2014). Similar to our study, partial fencing was erected along the field edge that borders natural vegetation and proved to be effective at reducing the number of deer from accessing the crops (Hildreth et al. 2012). Because our track surveys encompassed the entire perimeter of a treated field, we were able to observe certain areas of high crossing activity. When the fence was down activity was concentrated along the field/canyon interface. However, when the fence was erected, activity was low along the fence line and more concentrated along unfenced portions of the field perimeter. DeVault et al. (2008), along with Johnson et al. (2014), observed that deer were simply traveling around the partially fenced areas until an opening to the field was available. Although we too observed this behavior, along with break-ins (i.e., deer moving through the gaps in the electric wires), we did not observe it occurring on a frequent basis.

Seamans and VerCauteren (2006) reported that deer are capable of jumping, crawling under, or going through fencing material, and as time since our wires were erected increased, so did the number of break-ins. Break-ins could be a result of reduced voltage and habituation to the fence. Because our fence chargers were solar powered, sufficient daily sunlight was required to fully recharge the battery to keep the voltage consistently running throughout the nighttime hours. If the battery was not able to adequately charge, the wires were not as powerful and deer passing through the fence did not receive as vigorous of a shock as they would have otherwise. Thus, deer may have learned to break through fences when battery charges were lower as sunrise approached.

Treatment effects were undetected with our drone survey data likely due to notably less count data to model with. Due to flight logistics and drone battery life we were only able to survey one field per night (~20 minute flight time) and occasionally missed flights due to inclement weather, technological difficulties with the thermal camera, or had missed the opportunity window of observing a deer in the field.

Crop damage caused by WTD is highly variable on both a temporal and spatial scale, and finding an effective, low maintenance, low-cost strategy to deter deer can be extremely challenging. Areas prone to high WTD damage may fluctuate on a yearly basis, and because of this, agricultural producers often desire temporary, fine-point solutions that can be replicated and moved according to where the highest amount of crop damage is occurring. Thus, both of our deterrent methods were aimed at highlighting these motives and finding an effective method to recommend. Both the triple threat deterrent system and the 4-strand electric partial fence did reduce the number of WTD in pulse fields and could be effective in reducing WTD caused crop depredations.

MANAGEMENT IMPLICATIONS

We found that the triple threat deterrent system reduced WTD field usage on pulse crops. However, it is important to realize that our WTD sample size and the amount of deterrent systems protecting the fields were limited. To increase effectiveness more deterrent systems could be added along the field edge, thus creating a geo-fence effect. Because we only had the deterrent system out for one field season, our results may not accurately represent the habituation and behavior of WTD across multiple years. Further research could evaluate the effects of the deterrent system on a more substantial number of treated individuals through numerous field seasons, as well as documenting reactions through camera footage. Lastly, our results were constrained to fine-scale selection, and further analyses should be conducted to evaluate deterrent effectiveness at larger home range scales.

We also found that temporary, 4-strand electric partial fencing reduced WTD field usage on pulse crops and could be used as a non-lethal management option. Partial fencing allowed for the availability of a seasonal, cost effective deterrent for limiting the number of individual crossings. This fencing technique was easy to assemble and disassemble, allowing for it to be moved from year to year following crop rotations and minimizing disturbances to long-distance animal movements or distributions across the landscape. However, because effectiveness can be based on deer densities, abundance of available natural forage, landscape configuration, and desirability of the crop species, wildlife managers and agricultural producers will need to thoroughly examine all components of the impacted area before selecting this deterrent method. Furthermore, additional research should be conducted to evaluate co-implementation of the fence with other potentially effective deterrents such as taste-aversions, audible noise or visual obstructions, or guard dogs.

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TABLES

Table 3.1. Six candidate Poisson distributed linear models were used to estimate the effectiveness of our triple threat deterrent system at reducing white-tailed deer pulse crop field usage. Count-number of GPS-locations within a pulse crop field; Week- number of weeks since July 4; ID-individual GPS-collared deer; Deterrent-before or after deterrent deployment; WeeklyDeterrentStatus-deterrent is on or off.

Model	**AIC Score**
Count ~ Week+ID+Deterrent	2141
Count ~ Week+ID+Deterrent+WeeklyDeterrentStatus	2142
Count ~ Week+ID+ WeeklyDeterrentStatus	2144
Count ~ Week+ID	2146
Count ~ Week	4062
Count ~ 1	4400

Table 3.2. Five candidate linear models were used to estimate if the distance between GPS-locations and triple threat deterrent systems was affected by our triple threat deterrent system. Distance-distance (m) between GPS-locations in a pulse crop field and location of triple threat deterrent system; ID-individual GPS-collared deer; Deterrent-before or after deterrent deployment; WeeklyDeterrentStatus-deterrent is on or off.

Model	**AIC Score**
Distance ~ Deterrent+ID	1125
Distance ~ WeeklyDeterrentStatus+ID	1128
Distance ~ Deterrent+WeeklyDeterrentStatus+ID	1129
Distance ~ Deterrent	1163
Distance ~ 1	1164

Table 3.3. Six candidate log linear models were used to estimate the effectiveness of the 4-strand electric partial fence at reducing white-tailed deer pulse crop field usage through track count survey data. Count-number of WTD entering or exiting a treated field; Time- number of days since crop planting; FieldID-individual treated fields; Fence_On_Off-fence is up and on or down and off.

Model	**AIC Score**
Count ~ Fence_On_Off+Time	79
Count ~ Time	88
Count ~ Fence_On_Off+Time+FieldID	89
Count ~ Time+ID	90
Count ~ Fence_On_Off	114
Count ~ 1	135

Table 3.4. Six candidate log linear models were used to estimate the effectiveness of the 4-strand electric partial fence at reducing white-tailed deer pulse crop field usage through night-time drone survey data. Count-number of WTD located within a treated field; Time-number of days since crop planting; FieldID-individual treated fields; Fence_On_Off-fence is up and on or down and off.

Model	**AIC Score**
Count ~ Time	164
Count ~ Fence_On_Off+Time	165
Count ~ 1	166
Count ~ Fence_On_Off	167
Count ~ Time+FieldID	168
Count ~ Fence_On_Off+Time+FieldID	169

FIGURES

Figure 3.1. Our two study sites were located in Latah County, Idaho, USA. Agricultural fields treated with triple threat deterrent systems are indicated in purple (with each associated black dot representing an individual deterrent system), and fields that were partially fenced are indicated in green.

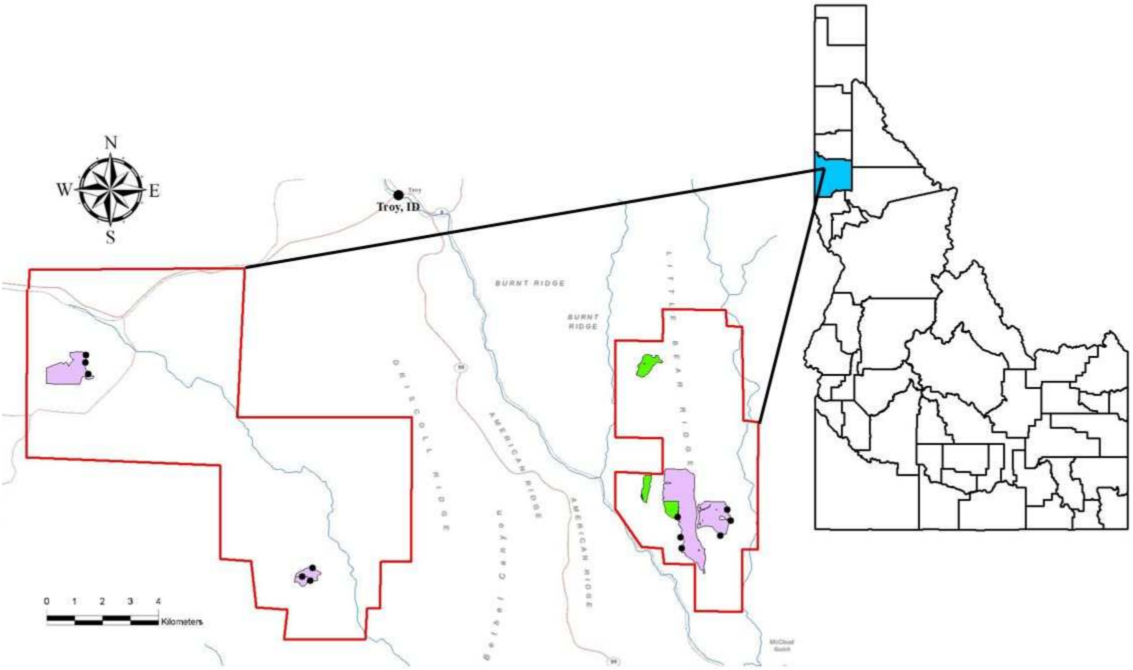


Figure 3.2. White, flapping flagging was strung along areas near white-noise machines and automated predator scent pumps to simulate a white-tailed deer tail flashing a warning signal. Flagging extended for 200m on each side of a white-noise machine.

Figure 3.3. Frequency of movement locations from GPS-collared WTD in agricultural fields from May 1st through November 1st. Crop harvest occurred in mid-September.

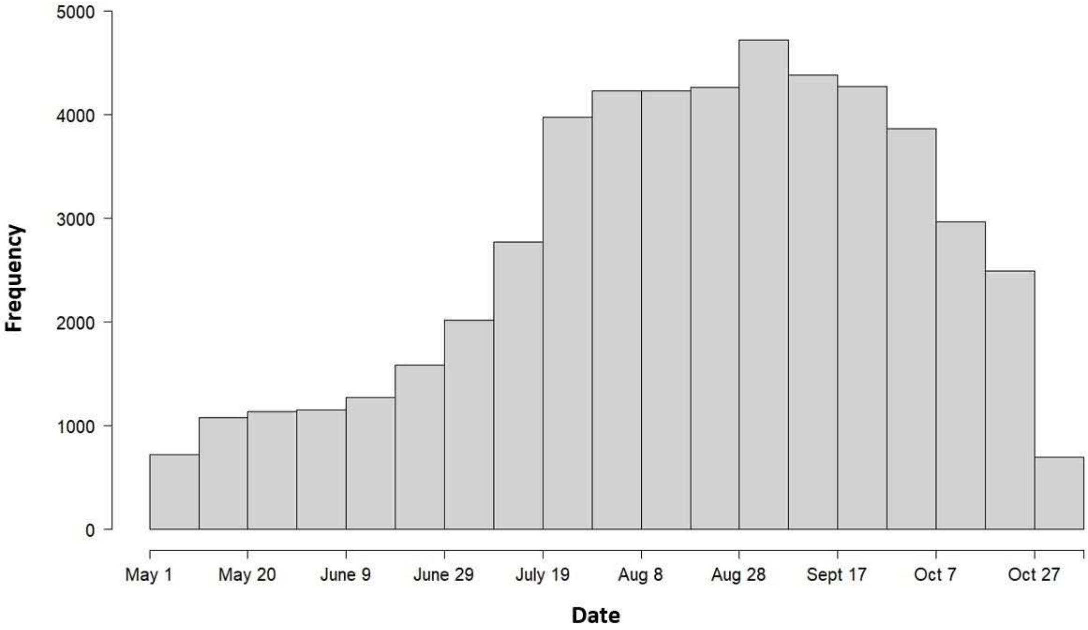


Figure 3.4. Frequency of movement locations from GPS-collared deer in agricultural pulse fields throughout a 24 hr diel cycle.

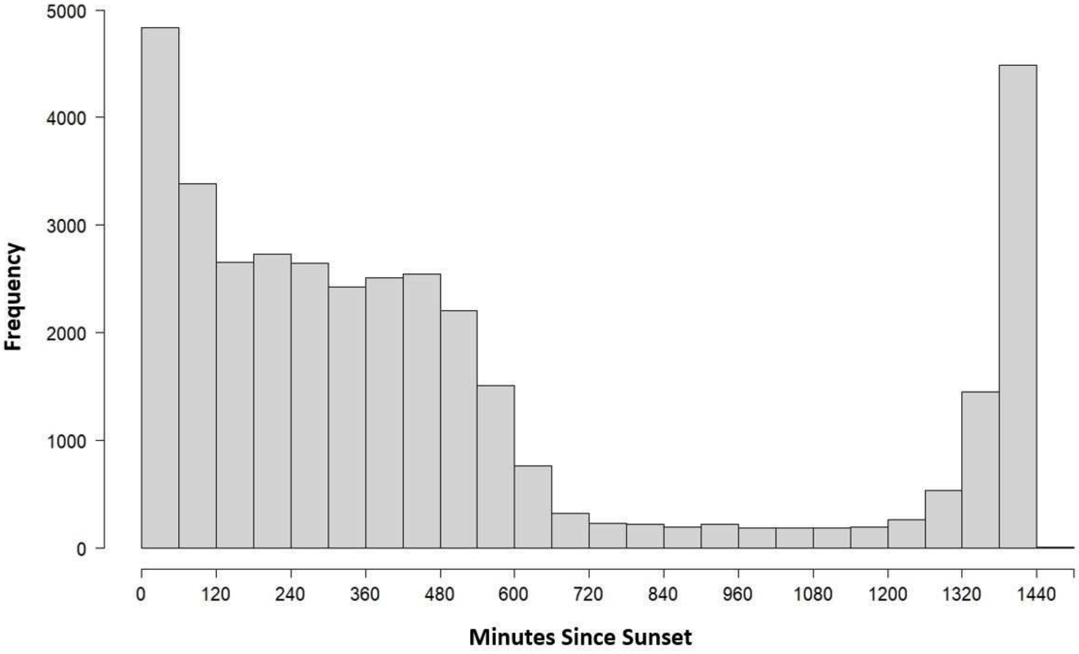


Figure 3.5. Number of locations in pulse fields during peak hours for untreated deer and the predicted number of locations once the triple threat deterrent systems had been deployed.

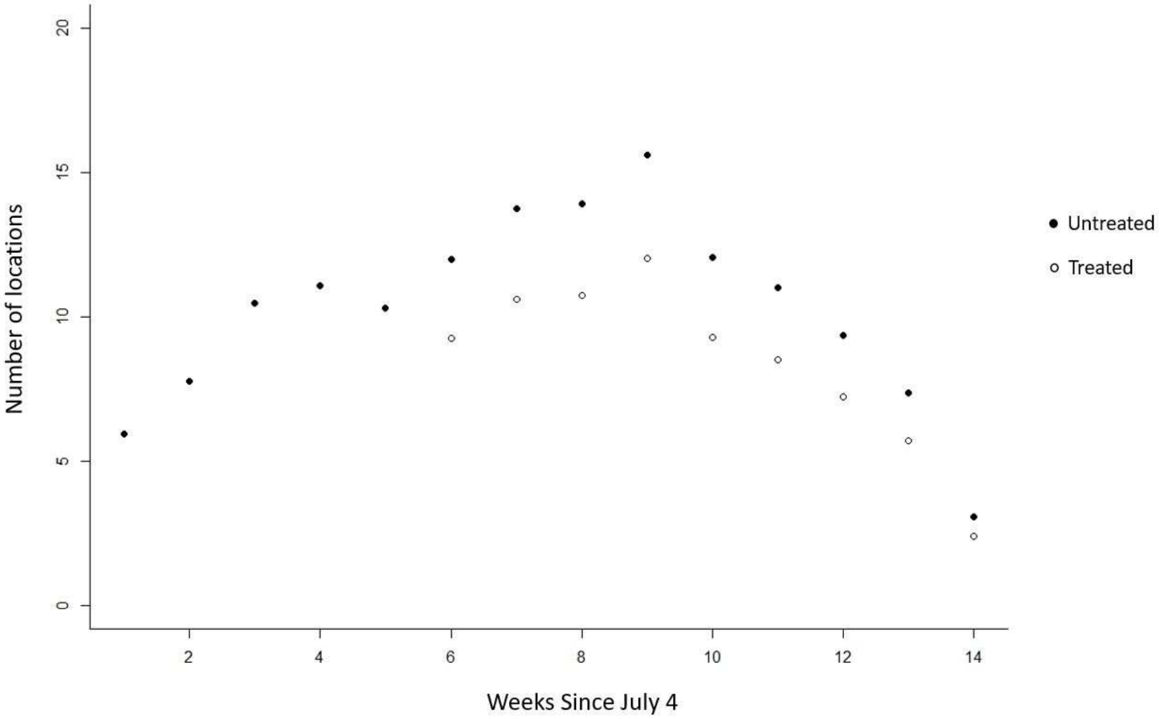


Figure 3.6. Mean number of WTD crossings (black dots) in treated pulse fields when the fence was up and on versus when the fence was down and off throughout the crop-growing season with a 90% confidence interval.

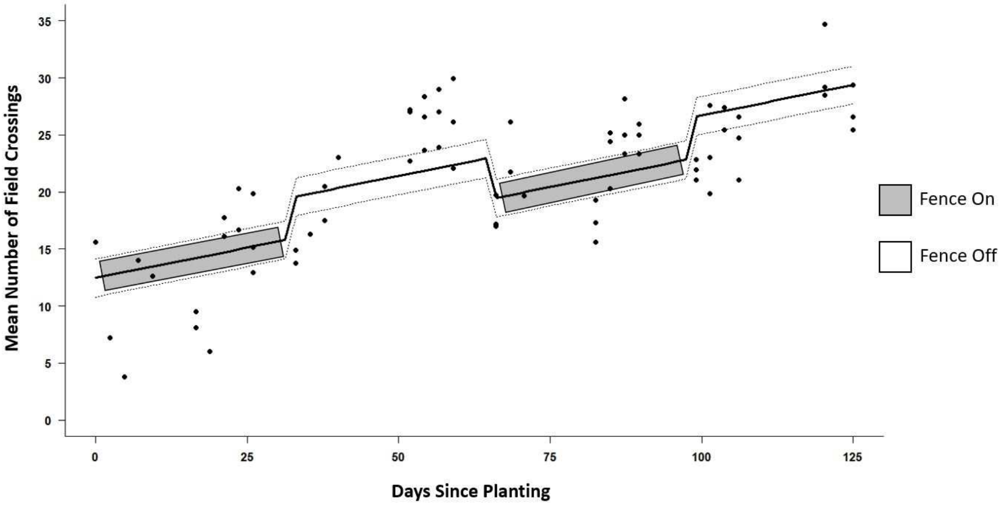


Figure 3.7. Predicted number of WTD crossings in a pulse field per day when the fence is up and on versus when the fence is down and off with a 90% confidence interval.

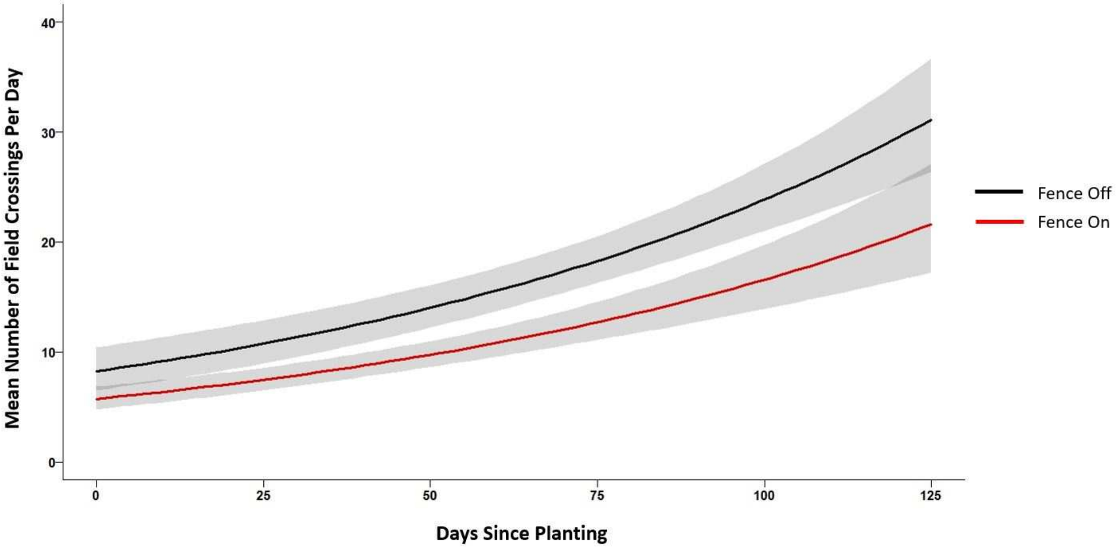
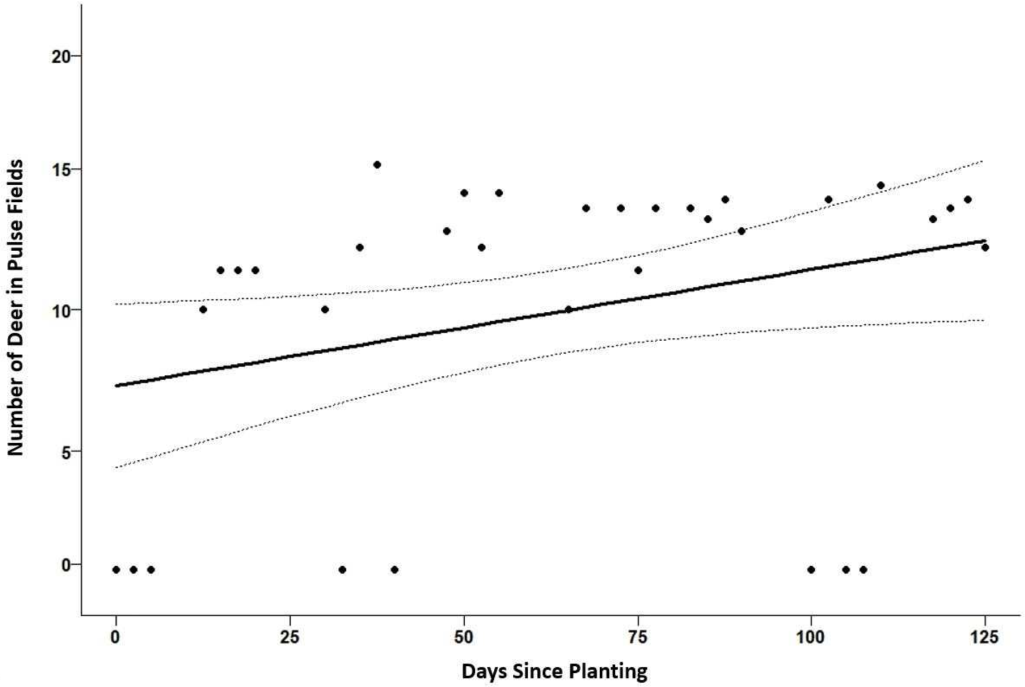


Figure 3.8. The number of WTD located within a pulse agricultural field during the crop-growing season based on counts conducted by a drone fit with infra-red video camera flown 45-60 minutes after sunset.



CHAPTER 4: Residual effects of lithium chloride in muscle and organ tissues of sheep

ABSTRACT

Conditioned taste aversions (CTA) occur when animals associate gastrointestinal distress with particular food resources. Lithium chloride (LiCl) is a compound that is commonly used as a CTA agent within the livestock industry, but has yet to be tested on wild ungulates. Because LiCl has yet to be tested in an open field setting we needed to first determine lithium concentration withdrawal periods and toxicity. Withdrawal periods and toxic dosages are important factors to know if human consumption is intended following animal LiCl ingestion. We administered LiCl (150 and 450mg LiCl/kg body weight) orally to adult domestic sheep to determine withdrawal periods in muscle and organ tissues. Biopsy samples were extracted from individuals at predefined time intervals and lithium concentrations were measured using Inductively Coupled Plasma-Optical Emission Spectroscopy (ICP-OES). Lithium concentrations reached a maximum level (7.8µg/g) in muscle tissue 25 hours post-ingestion at a low dosage, and returned to basal level 240 hours post-ingestion. High mortality (14 out of 16 individuals; 88%) occurred following high dose administration, and lithium concentrations reached a maximum level (45µg/g) in muscle tissue 73 hours post-ingestion. Lithium concentrations never returned to basal level by the end of the 10 day (240 hours) study after high dose administration. We were unable to determine maximum concentration levels within organ tissues, but did not find statistically significant differences among the muscle and organ tissue types. Thus, it is important to acknowledge that the toxic threshold for domestic sheep, and likely other small ruminants, occurs between 150-450mg LiCl/kg body weight.

INTRODUCTION

White-tailed deer (*Odocoileus virginianus;* WTD, hereafter) are one of the most widespread large mammal species of North America, with correspondingly large impacts on society, both positive (e.g., hunting, wildlife viewing) and negative (e.g., car collisions, crop depredation). They inhabit a variety of areas, occurring almost anywhere digestible forage is available and accessible habitat cover is nearby. In recent years, population numbers have drastically increased in many areas of the Western United States, potentially due to their extreme adaptability and versatility (Idaho Department of Fish and Game 2013). High population densities have been thought to increase dispersal and movement rates, likely causing them to travel further across the landscape in search of available resources (Lesage et al. 2000). As deer movement and dispersal rates increase, more encounters with agricultural fields containing nutritious crops occur (Lesage et al. 2000), resulting in an increase in crop depredation rates.

In order to mitigate costs of abundant deer while maintaining recreational and economic benefits, there is a pressing need to find effective deer deterrents. In the past, multiple deterrent methods targeted at reducing deer damage have been tested, including propane exploders and other frightening devices, fencing, and lethal removal (Hygnstrom and Craven 1988; Gilsdorf et al. 2004; Williams et al. 2008). Although previously tested deterrents have resulted in a wide range of effectiveness, wildlife managers are still searching for a deterrent method that is cost-effective with high efficacy rates across a multitude of wildlife species. One promising method that has yet to be tested in an open field setting for deterring WTD is lithium chloride (LiCl), which is a gastrointestinal toxicant that has successfully been used to create taste aversions to specific food items in both carnivores and ruminants.

Previous studies have shown high efficacy in reducing the amount of food consumed after LiCl was ingested as treated animals associated targeted food sources with gastrointestinal distress (Olsen et al. 1989; Du Toit et al. 1991; Ralphs 1997; Brown et al. 2000). However, most of these studies were conducted in controlled, captive feeding trials where ruminants, as well as carnivores, were given the choice to consume food items pre- and post-ingestion of LiCl (Burns 1980; Burritt and Provenza 1991; Ralphs 1997; Brown et al. 2000). Due to LiCl creating strong taste aversions across multiple species, we hypothesized that it had potential of being a successful deterrent method in reducing WTD crop depredations.

Before implementation of LiCl as depredation deterrent in an open field setting occurred, key issues regarding toxicity and accumulation in deer tissues needed to be addressed. One challenge with using LiCl was that crop depredation season overlaps with hunting season in many parts of WTD habitat range (i.e., late summer through fall). As a result, it was important to first understand withdrawal factors in different types of animal tissues that may be consumed by humans. A literature search was completed and pharmacokinetic data in small ruminants was severely lacking, which compelled the need for this study prior to using LiCl as a deterrent in an open field setting.

Although the intent was to use LiCl as a deterrent on WTD, domestic sheep were used in this study as a surrogate due to logistics and cost. Domestic sheep have been used in a variety of feeding trials to test the efficacy and necessary dosage needed of LiCl to create an effective aversion (Burritt and Provenza 1989; Scott et al. 1995; Wang and Provenza 1997). Higher dosages often result in a greater aversion effect (Launchbaugh and Provenza 1994), but toxicity levels and tissue withdrawal times have yet to be reported. Thus, we addressed the following research questions: 1) What are the concentration levels and withdrawal time of LiCl in differing body tissues at realistic dosages that may be consumed by a deer in an open field setting?; 2) What is the maximum realistic dosage that could be consumed in a field setting toxic for small ruminants?

METHODS

We tested the kinetics and toxicity of LiCl using domestic sheep located at the University of Idaho Sheep Center in Moscow, Idaho. Suffolk, Targhee, and Targhee/Polypay crossbred individuals were used in the trials, and all trials were conducted at the Sheep Center. Animal use and protocols were approved by the Institutional Animal Care and Use Committee at the University of Idaho (IACUC-2017-70). Treated individuals were housed in an indoor/outdoor covered barn, and feed and water were available ad libitum. Grain was provided once a day after biopsy samples had been collected.

Before each trial began individuals were weighed on an electric platform scale (+/- 1 kg), so that the appropriate dosage of LiCl for each trial and individual could be determined on a per-kg basis. Depending on the trial dosage and weight of each individual, the appropriate amount of LiCl was dissolved in cold water, and administered via drenching (i.e., orally inserting a lubricated stomach tube to the level of the abomasum). We conducted a series of 3 trials to analyze withdrawal periods and toxicity to compare lithium concentration levels among kidney, liver, and muscle tissues at a low and high dosage. Details of each trial's methodology are described below. All tissue samples were analyzed at the University of Idaho toxicology lab.

Trial 1: Effects of low dosage LiCl on muscle concentrations through time

Eleven adult sheep were used to assess the kinetics and depletion of lithium in muscle tissue at a 150mg LiCl/kg of body weight dosage, which we considered a low dose (du Toit et al, 1991; Brown et al. 2000; Pacífico da Silva and Soto-Blanco 2010). On the first experimental day each treated individual was orally drenched with a single dose of LiCl (du Toit et al, 1991; Brown et al. 2000). Muscle biopsy samples (~1g per sample) were extracted from each triceps and upper thigh for concentration analysis. Animals were physically restrained during muscle tissue sampling. Once restrained, the location of the biopsy was sterilized and a local anesthetic (Lidocaine) was administered. Each 1g sample of muscle tissue was placed into a sterile, labeled Whirlpak and frozen until all samples for the trial had been collected.

It had been reported that the maximum level of LiCl in blood occurs 4-8 hours post-ingestion (Okusa and Crystal 1994; Manuelian et al. 2016), and that individuals were completely cleared of LiCl after 240 hours (Manuelian et al. 2016). We thus collected muscle biopsy samples at 4, 8, 12, 24, 48, 96, 192, and 240 hours post LiCl ingestion to cover the entire time span between maximum peak levels and complete LiCl metabolism. To allow sufficient time for recovery from local anesthesia and the muscle biopsy procedure, treated individuals were split into 2 groups (A and B), with 4 individuals in each group. A total of 11 individuals were treated during this trial (8 treated with LiCl and 3 control individuals). Group A individuals were biopsied at 4, 12, 48, and 192 hours post LiCl ingestion, while group B individuals were biopsied at 8, 24, 96, and 240 hours post LiCl ingestion.

Trial 2: Effects of high dosage LiCl on muscle concentrations through time

Sixteen adult sheep were used to assess the kinetics and depletion time at 3x the recommended 150mg LiCl/kg body weight dosage. On the first experimental day each individual was orally drenched with 450mg LiCl/kg body weight. Muscle biopsies were once again collected following the protocol previously described for Trial 1. If an individual died during the trial a necropsy was immediately conducted and 1g of kidney, liver, and muscle samples were each collected from the deceased individual. During the necropsy all other major organs and muscle groups were observed by veterinarian staff to determine if the ingested LiCl had caused notable damage.

Trial 3: Effects of low dosage LiCl on muscle and organ tissues through time

Nine adult sheep were used to analyze lithium concentrations within kidney, liver, and muscle tissues, at time intervals surrounding the peak lithium concentration for the low dose. On the first experimental day all individuals orally received a single dosage of 150mg LiCl/kg body weight. Based on the results from Trial 1, the peak lithium concentration occurred ~25 hours post-ingestion. Thus, individuals were mechanically dispatched at intervals surrounding this peak concentration time. Group 1 (n=3) was harvested 7 hours post LiCl ingestion, group 2 (n=3) 25 hours post LiCl ingestion, and group 3 (n=3) 97 hours post LiCl ingestion. Tissue samples (1g) from the kidney, liver, and muscle were collected from each individual. Whole-body necropsies were also conducted to search for abnormalities that may have been caused by LiCl ingestion.

Chemical Analysis

To measure lithium concentrations in tissues, a PerkinElmber® Optima 8300 Inductively Coupled Plasma-Optical Emission Spectroscopy (ICP-OES) was used. The ICP-OES equipment determined the lithium concentration within each tissue sample using plasma and a spectrometer (operating conditions; plasma: 15L/min, auxiliary: 0.2L/min, nebulizer: 0.73L/min, flow rate: 1.5mL/min, and wash rate: 2.00mL/min) (Anderson et al. 2018). Equipment was calibrated with concentrated redistilled trace metal grade nitric acid and water (Anderson et al. 2018). Tissue samples were frozen until all samples for the trial had been collected. At the end of the study all samples were tested consecutively to avoid recalibrating equipment multiple times. All samples were analyzed on a wet weight basis, and 1g of tissue sample was added to, and mixed with, 3mL trace metal grade nitric acid in a 10mL test tube (Anderson et al. 2018). The tubes were then heated for 6 hours at 30°C, then 1 hour at 70°C, and finally for 8 hours at 120°C (Anderson et al. 2018). The tubes were then cooled, vortexed, and centrifuged as needed to produce transparent solutions to prevent clogs from occurring within the nebulizer (Anderson et al. 2018). If particles remained within the solution a 0.45 Acrodisc filter was used to eliminate the remaining particles (Anderson et al. 2018).

Pharmacokinetic Calculations

All lithium concentrations in muscle tissue samples were corrected for the basal lithium concentration, which was calculated as a mean from the 3 control sheep. Following LiCl ingestion we predicted that a positive curved distribution of tissue concentrations would occur as the amount of lithium would increase from basal level, reach a maximum peak, and decrease as it was metabolized and excreted. However, the time at which peak concentration occurred and the exact shape of the curve was unknown. To allow for a flexible concentration curve with these properties we used the following model:

$$\ln(concentration) = \beta_0 + \beta_1 (Hour+1)\wedge^{(1/\alpha)} + \beta_2 (Hour+1)\wedge^{(1/\alpha)^{2}}$$

where *ln(concentration)* = lithium concentration of the sample and *Hour* = the amount of time that had passed since LiCl ingestion. We estimated the parameters of the model using maximum likelihood with the package mle in the statistical program R (Muyung 2003; R Core Team 2019). All plots and data were analyzed in R version 3.6.1 (R Core Team, 2019).

RESULTS

Trial 1: <u>Effects of low dosage LiCl on muscle concentrations through time</u>

Lithium concentration in muscle tissue after ingesting a single dose of LiCl at 150mg LiCl/kg body weight peaked (7.8µg/g) ~25 hours post-ingestion (Figure 4.1). Lithium concentrations declined thereafter, and reached basal level ~240 hours post-ingestion.

Trial 2: <u>Effects of high dosage LiCl on muscle concentrations through time</u>

Lithium concentration in muscle tissue after ingesting a single dose of 3x the recommended dosage of 150mg LiCl/kg body weight (i.e., 450mg/kg body weight) peaked (45µg/g) 73 hours post-ingestion (Figure 4.2). Lithium concentrations slowly declined thereafter, and never reached basal level by the end of the 10-day (240 hours) study. We observed a high mortality rate at this dosage (14 out of 16 total treated, ~88% mortality) and a majority of the mortalities occurred after the concentration peak. Thus, kidney and liver samples were only obtained after the peak and we were unable to construct a complete depletion curve for this concentration (Figure 4.3). We did not find statistically significant differences in lithium concentration among the 3 tissue types.

Trial 3: Effects of low dosage LiCl on muscle and organ tissues through time

Lithium concentration in kidney and liver tissue after receiving a single dose of 150mg LiCl/kg body weight varied among individuals (Figure 4.4). However, the amount of lithium concentration within kidney tissue was larger than liver and muscle samples per individual at all 3 time intervals. Concentration differences among tissue types was found to be statistically significant prior to the peak only.

DISCUSSION

We selected to use 150mg LiCl/kg body weight as the low dose due to previous reports of effectiveness in creating a taste aversion in domestic sheep, cattle, and caribou (Ralphs 1992; Provenza et al. 1993; Brown et al. 2000). Administering LiCl dosages greater than 300mg/kg body weight is rare within the literature, and an exact toxic dosage in small ruminants has yet to be determined. Toxicity in mice occurred at a 600mg LiCl/kg body weight dosage (Zakaria et al. 2010), and to avoid exceeding the toxic threshold for ruminants we reduced our high dosage to 450mg LiCl/kg body weight. However, this amount still exceeded the toxic threshold, and multiple mortalities occurred post-ingestion.

Maximum lithium concentration levels and withdrawal periods within muscle tissue varied by dosage, and among individuals to an extent. At the low dosage, lithium concentration increased within muscle tissue starting with the first biopsy samples taken and concentration levels continued to increase until the maximum concentration value occurred. Following the peak, lithium concentrations quickly declined and returned to basal levels by the end of the 10-day study period. These results are similar to withdrawal periods of LiCl in different types of excreta in sheep and goats reported by Manuelian et al. (2015). Feed and water intake pre- and post-ingestion were not directly quantified, but treated individuals were visually observed to detect behavioral changes. Although previous studies have observed signs of malaise (head droop and inactivity) (Manuelian et al. 2014) and an aversion to food post LiCl ingestion (du Toit et al. 1991; Launchbaugh and Provenza 1994), we did not observe either of these traits. Treated individuals were observed eating provided alfalfa immediately following LiCl drenching and continued to do so throughout the study period.

Similar to low dose muscle tissue results, high dose lithium muscle concentrations showed an increase from basal level within 4 hours post-ingestion. However, maximum concentration was delayed and occurred ~48 hours after the maximum concentration was reached for the low dose. Only 2 of the 16 individuals that received this dosage did not succumb to toxicity, and after 240 hours post-ingestion muscle tissue samples from the surviving individuals had yet to reach basal level. Thus, a complete withdrawal time for a dosage of 450mg LiCl/kg body weight was not determined. Behavioral observations were once again recorded for treated individuals following LiCl ingestion. Treated individuals appeared unaffected until 24 hours post-ingestion when they stopped eating, drinking, and moving around the containment area. A significant portion of the mortalities occurred between 36 and 193 hours post-ingestion. Multiple symptoms of toxicity were observed including lack of appetite, malaise, severe dehydration, hypoglycemia, muscular tremors, increased heart rate, and extreme diarrhea. Necropsies were conducted by certified veterinarian staff members, and cause of death was determined for each deceased individual. It was determined that all individuals had died due to LiCl overdose and that 450mg LiCl/kg body weight was a lethal dose for small ruminants. Other organ and muscle groups did not appear to be damaged by the ingested LiCl for either dosage.

Acute lithium toxicity was likely the cause of death for mortalities that occurred during the high dose trial. Although treated individuals only received a single dosage of LiCl, the high level potency of the chemical compound resulted in death as the physiological responses in the body, and especially the kidneys, were not able to process and excrete excess LiCl resulting in accumulation and eventual death. Kidneys are the main processing organ that excretes LiCl (Okusa et al. 1994; Timmer and Sands 1999), and excess lithium can disrupt the absorption of salt and water, often leading to polyuria (Myers et al. 1980). If the kidneys are not able to process and excrete the ingested amount of lithium, excess amounts begin to accumulate in other tissues (Okusa et al. 1994). This is likely what occurred in the high dose trial and why our results show no statistically significant difference in lithium concentrations among the tissue types. Once lithium levels in the kidney exceeded maximum intake, surplus lithium was deposited in the liver and muscle tissues, resulting in all 3 tissue types containing high concentration levels. However, in the low dose, the highest lithium concentrations were located in the kidneys, followed by liver, and the least amount of lithium concentration was in muscle tissue. This was likely due to the kidneys being able to function correctly with a manageable intake of lithium. Overdosing was not an issue as the amount of ingested lithium was processed and excreted by the kidneys without excess accumulation. Although we did not observe complete withdrawal with kidney and liver samples from the low dose, at 96 hours post-ingestion there was not a statistically significant difference of lithium concentrations among the tissues. Thus, most of the lithium had been metabolized and excreted leaving behind small residual amounts in all tissues.

MANAGEMENT IMPLICATIONS

A low dose of 150mg/kg body weight of LiCl administration to small ruminants was completely metabolized from muscle tissues 240 hours post-ingestion. However, we were not able to determine the withdrawal period within the liver and kidney for this dosage. Likewise, high dose withdrawal periods for all 3 tissue types were undetermined due to 450mg LiCl/kg body weight being lethal for many individuals. We found that kidney tissues retain the greatest amount of lithium, followed by liver tissues, and lastly muscle tissues. However, at high dosages, concentration levels among all 3 tissue types are not statistically significantly different. Thus, it is important to acknowledge that the toxic threshold for domestic sheep, and likely for other small ruminants, lies between 150-450mg LiCl/kg body weight.

Although we did not observe an immediate aversion to food items following LiCl ingestion we believe this chemical compound could be an effective deterrent used in reducing WTD crop depredations. We caution that while sheep and deer are similar in body size and rumen capacity, toxicity effects and withdrawal periods for each tissue type may vary among species. We offer a suggested withdrawal period in muscle tissue for a low dose of LiCl in domestic sheep, however, our analyses for other tissue types at low dosages, and all tissue types for high dosages were inconclusive. Therefore, we warn that before field implementation and human consumption of an animal that has ingested LiCl, more trials are necessary that include longer time periods, larger samples sizes, and incorporate a variety of ruminant species.

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FIGURES

Figure 4.1. Concentration of lithium in sheep muscle tissue after receiving a single dose of 150mg LiCl/kg body weight of lithium chloride. Each data point represents a muscle sample from one individual and dashed lines represent a 90% confidence interval.

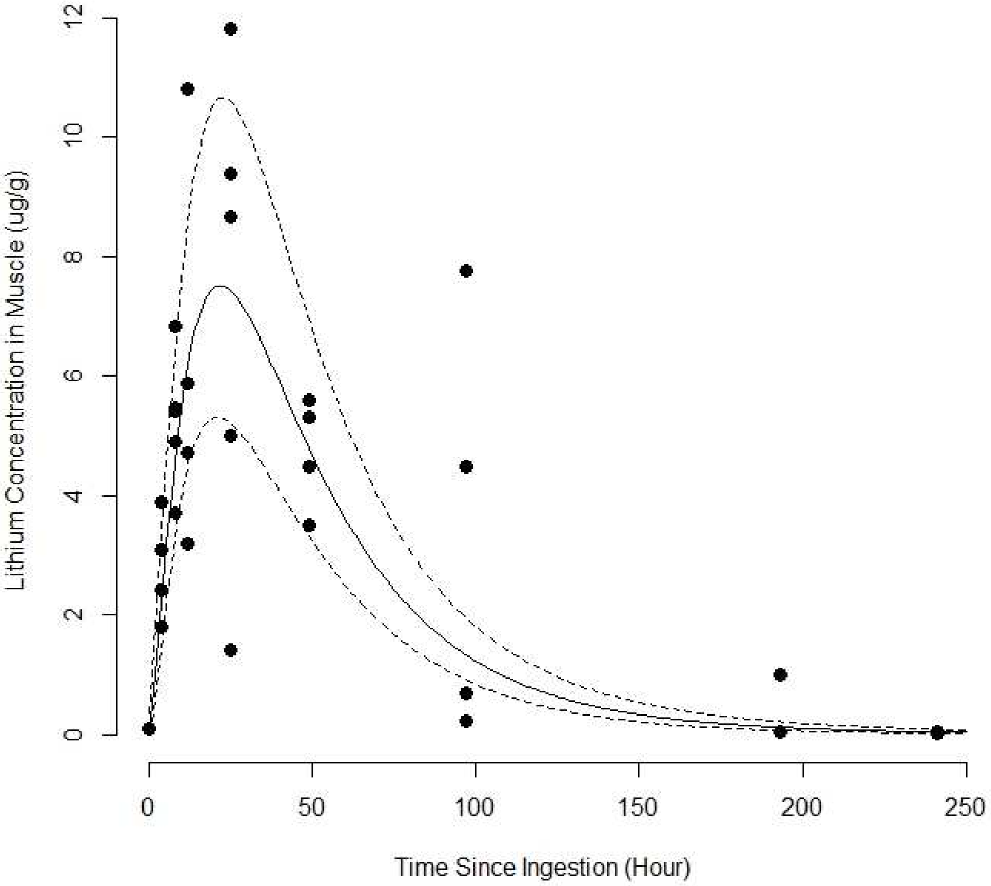


Figure 4.2. Concentration of lithium in sheep muscle tissue after receiving a single dose of 450mg LiCl/kg body weight of lithium chloride. Each data point represents a muscle sample from one individual and dashed lines represent a 90% confidence interval.

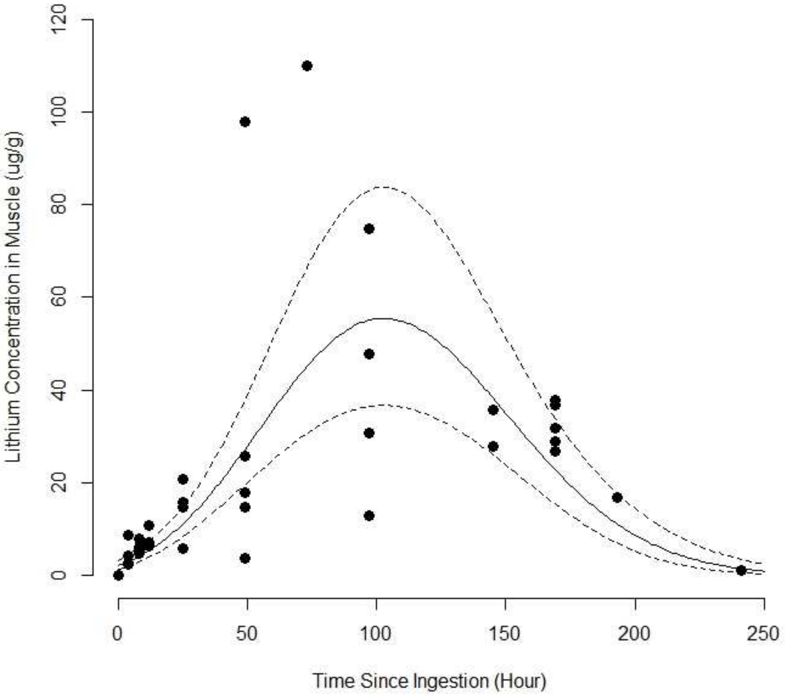


Figure 4.3. Concentration of lithium in kidney, liver, and muscle tissue after receiving a single dose of 450mg LiCl/kg body weight of lithium chloride. Each data point represents one individual and dashed lines represent a 90% confidence interval.

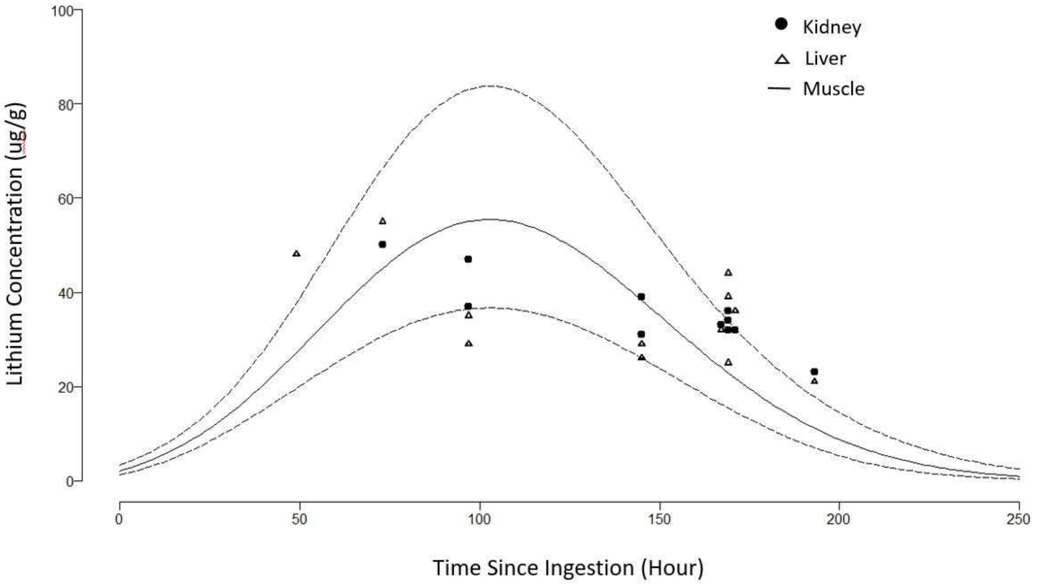
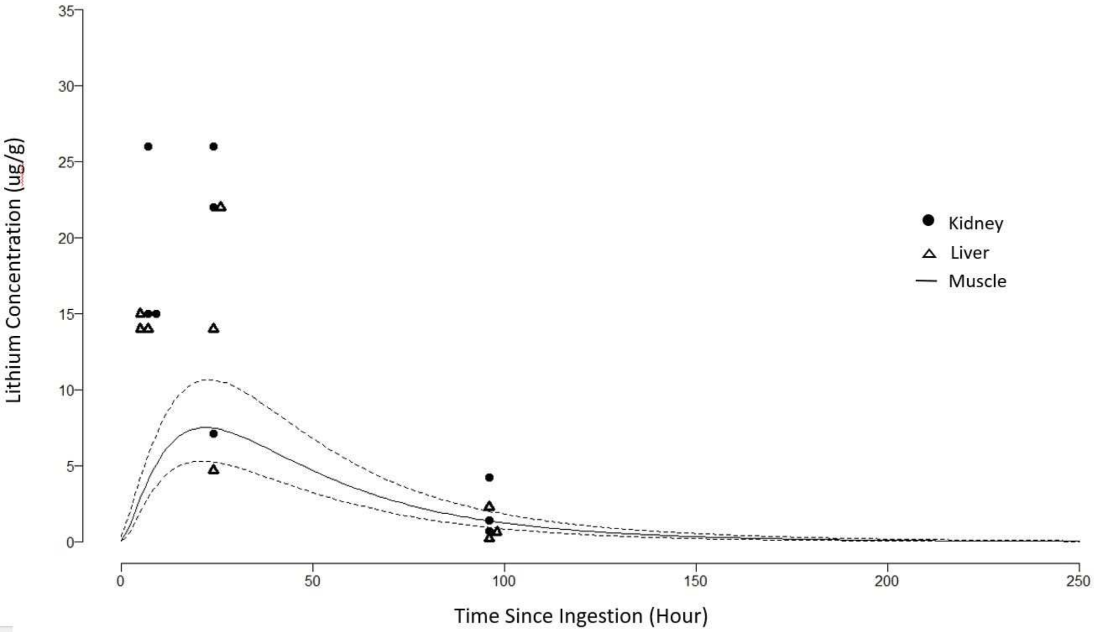


Figure 4.4. Concentration of lithium in sheep kidney and liver tissue after receiving a single dose of 150mg LiCl/kg body weight of lithium chloride. Each data point represents one individual. For reference, we also show the predicted concentration of lithium in muscle tissue after receiving a single dose of 150mg LiCl/kg body weight of lithium chloride (see Figure 4.1).



CHAPTER 5: Conclusions

Before we started this research project, knowledge on WTD ecology in Northern Idaho was limited. Our goal was to fill in habitat and behavioral ecology gaps through methodical analysis of habitat use in an agriculturally dominated area, as well as determine how 2 types of novel deterrents affect behavior patterns. We used fine-scale GPS data and count survey data to identify movement patterns, habitat selection, peak agricultural field use time periods, and the efficacy of the deterrents. We were also able to determine the kinetics of a taste-aversion deterrent (i.e., lithium chloride). Outcomes of this project provide wildlife managers with viable ways to determine when wildlife species optimize agricultural field use, where to place deterrent systems on the landscape, and 2 new deterrent methods that reduced WTD field use.

Our WTD habitat analysis indicated that a combination of anthropogenic effects, predation risk, and nutritional resource availability drive WTD movements in an agriculturally dominated area of Northern Idaho. By using step selection function models we were able to determine that selection throughout the crop-growing season (May-October) varied substantially, and also among individuals. Some individuals were described as forage driven (i.e., preferred areas that maximized forage intake), security driven (i.e., preferred areas that minimized predation or disturbance risk) or a combination of the two, and an individual’s chosen strategy varied throughout the diel cycle. In general, WTD selected for gentle slopes, to be within close proximity of agricultural field edges, and to be near crops. The 3 main crop types grown in our study area (hay, pulse, and wheat) were all highly selected for, likely due to easy access and availability, high digestibility, and all are rich in nutritional content (Mould and Robbins 1981; Dostaler et al. 2011; DeVore et al. 2016; Hinton et al. 2020).

With WTD densities on the rise (Kimball and Nolte 2006; Monteith et al. 2019), and their high preference to select for agricultural fields, WTD have become a prominent crop depredation issue (Monteith et al. 2019). We found that WTD select to be within close proximity to pulse fields, and because of this, we tested the efficacy of 2 novel deterrent types on reducing pulse field use. Both deterrent methods, a fear-enhancing scare tactic and a physical exclusion barrier, reduced WTD use of pulse fields. Both of these deterrent methods are suitable tools for reducing WTD crop damage and by having a more comprehensive understanding of WTD ecology and behavioral patterns we can help guide wildlife managers into choosing viable deterrent methods.

Although we were not able to test the efficacy of lithium chloride as a taste-aversion deterrent, we were able to learn valuable information on muscle and organ tissue kinetics. Maximum lithium concentration levels and withdrawal periods within tissues varied by dosage, and among individuals to an extent. All individuals who received a low dosage (i.e., 150mg/kg body weight) did not portray signs of toxicity, and lithium was undetectable in body tissues by 240 hours post-ingestion. However, 88% of our individuals that received a high dosage (i.e., 450mg/kg body weight) succumbed to toxicity, and lithium concentrations in muscle and organ tissues never returned to basal levels. Thus, although lithium chloride has been proven to be an effective taste-aversion deterrent method (Olsen et al. 1989; Du Toit et al. 1991; Ralphs 1997; Brown et al. 2000), more scrutinized research is needed to determine dosages that are safe, yet effective, and how to limit individuals into consuming the appropriate amount while in an open field setting.

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