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Development and Evaluation of a Habitat Suitability Model for White-tailed Deer in an Agricultural Landscape

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This thesis has been examined and approved by the following members of the student's committee.

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ABSTRACT

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White-tailed deer (*Odocoileus virginianus*) are an ecological, economical, and socially significant species that occupy a variety of ecoregions. White-tailed deer are mobile habitat generalists that prefer habitats containing woody cover. Deer have successfully adapted to habitat-fragmented, agricultural landscapes. As a result, deer are not uniformly distributed across intensively cultivated areas, which make field surveys difficult with often highly variable spatial data. To increase sampling efficiency (deer observed / sampling effort), the landscape can be stratified based upon preferred habitat types. Habitat suitability models (HSI) have been used to represent hypothesized wildlife-habitat relationships, and therefore the likelihood of deer being observed may likely vary based on HSI scores. My research objective was to improve field sampling efforts for spotlight surveys in an intensive agricultural landscape of southwest Minnesota, using HSI modeling to stratify the landscape. An HSI model previously created for white-tailed deer populations in Illinois (original HSI) and a modified HSI model that I created which included grassland habitats were utilized. Deer management unit (DMU) HSI scores were correlated with deer densities at the statewide level and the original HSI and modified HSI models explained much of the variation in DMU deer densities at the statewide level.

Spotlight surveys were conducted in spring 2015 and 2016 to test both models on a local level. The modified HSI model was more efficient at predicting where deer could be in agricultural landscapes, in large part, because the original HSI model ignored grassland habitats and many deer were observed in these habitats. The modified HSI model is recommended to stratify habitats for transect surveys to better predict the distribution and abundance of white-tailed deer in agricultural landscapes, which will improve sampling efficiency.

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INTRODUCTION

White-tailed deer (*Odocoileus virginianus*) are ecologically, economically, and socially significant throughout much of North America. White-tailed deer are mobile habitat generalists and are opportunistic in their habitat selection, but prefer habitat comprised of forest cover (Miranda and Porter 2003) and edge (locations with adjacent food and cover patches; Alverson et al. 1988). However, deer have successfully adapted to a variety of ecosystems which include intensive agricultural landscapes (Alverson et al. 1988) and urban areas (Grund 2001).

Evidence suggests deer have greater natal dispersal distances in highly fragmented landscapes than those in dense forested landscapes (Rosenberry et al. 2001). Brinkman et al. (2005) reported deer migrating a mean distance of 10.8 km (SE = 1.2, range = 2.0-29.9) to a summer range in early spring (31 March – 30 May), and a mean distance of 11.2 km (SE = 1.7, range = 1.6-30.4) to a winter range in autumn (31 October – 22 December). Deer migration in agricultural regions is influenced by large annual fluctuations in climate, as well as a highly fragmented landscape dominated by agriculture (Brinkman et al. 2005). Highly fragmented agricultural landscapes with little forest cover lead to a nutrition-rich landscape so deer are not limited by food resources. However, limited forest cover and greenspace areas create substantial competition among females for parturition sites (Ozoga et al. 1982, Nixon et al. 1991, Nixon et al. 2001). Females will typically prefer forests for parturition, which is limited when forest cover is scarce and cause about half of the females to search for alternative habitat (Nixon et al.

2001). In north-central South Dakota where agriculture is the dominant land-use, Grovenburg et al. (2010) located 52.5% of bed sites in grassland habitat types and only 3.3% in forest cover. Understanding white-tailed deer ecology in different landscapes can help managers choose appropriate survey techniques for estimating population density, which is important for setting harvest regulations that will help achieve population management goals.

Techniques for estimating deer densities vary depending on landscape composition. In semi-open or deciduous landscapes, aerial surveys are a practical way to estimate population size of large mammals ranging over extensive areas (Caughley and Sinclair 1994, Potvin et al. 2004, Pettorelli et al. 2007). Observability is critical for effective field surveys and favorable conditions include near absence of evergreen cover, small size of winter habitat patches, uniform background of snow cover, relatively low deer densities, and ability to readily detect deer tracks in the snow (Stoll et al. 1991).

In agricultural landscapes, spotlight surveys are performed to estimate white-tailed deer densities (Urbanek and Nielsen 2012). Fafarman and DeYoung (1986) reported low precision while evaluating spotlight counts in south Texas. Observability is important for spotlight surveys and favorable conditions include no fog, rain, snow or high wind speeds. Fog, rain and snow directly impair observer visibility, while high wind speeds can cause deer to change habitat preference from open grasslands to forests (Beier and McCullough 1990). Deer occupying forests are more difficult to observe because woody cover interferes with the spotlights, which minimizes the area surveyed. Deer are easiest to observe when they are active during sunset, but changes in deer activity at different times of the night could affect observability (Beier and McCullough 1990).

Compared to simple random sampling, stratification will usually improve precision and optimize sampling effort by focusing sampling effort on areas with a greater probability of observing the targeted species (Gasaway et al. 1986, Ward et al. 2000). Fieberg and Lenarz (2012) used land-cover data as predictors of observed moose density in northwest Minnesota to stratify the landscape for aerial surveys and found a correlation between land-cover data and moose numbers, but were unable to improve upon the previous stratification scheme based on expert opinion. Model-based stratification, which simulates wildlife-habitat relationships to identify areas with greater likelihood of supporting survival and reproduction of a target species, can improve the probability of detecting individuals on the landscape (Edwards et al. 2005). Identifying habitat relationships for white-tailed deer in agricultural landscapes would provide information for stratifying the landscape and optimizing sampling efficiency.

Modeling habitat suitability can be an important tool for predicting the potential presence, density, or viability of a population (Loukmas and Halbrook 2001, Amici et al. 2010). Habitat suitability index (HSI) models are defined as a set of mathematical formulas constructed for the estimation of the ability of a specified unit of habitat to support survival and reproduction of a focal species (National Arizona University 2007). Habitat suitability index values are calculated using a mathematical formula that represents hypothesized wildlife-habitat relationships (Amici et al. 2010). The development of geographic information systems (GIS) has improved the ability to create sophisticated HSI models by providing a tool for analyzing relationships at multiple spatial scales. Management applications of GIS coupled with HSI modeling include developing maps in poorly sampled areas, identifying and prioritizing areas for conservation, protecting or assessing impacts of environmental change (Brown et al. 2000, Loukmas and Halbrook 2001), and assessing the degree of habitat connectivity in fragmented landscapes (Battisti 2003). Habitat suitability index models have been used to predict statewide deer population densities at the deer management unit (DMU) level (Roseberry and Woolf 1998, Miranda and Porter 2003). Even though HSI models have been used at finer scales for conservation efforts (Brown et al. 2000, Loukmas and Halbrook 2001), using HSI models to predict the distribution and abundance of deer at local sites is not well documented.

The goal of this research was to develop and evaluate an HSI model to describe the habitat relationship with deer in an intensely agricultural landscape. An HSI model previously created for the statewide white-tailed deer population in Illinois was modified for use in southwest Minnesota. Study objectives were to 1) compare the performance of 2 HSI models for predicting white-tailed deer densities at the statewide level, 2) stratify the landscape by comparing the performance and efficiency (number of deer observed per unit of sampling effort) of 2 HSI models at the local site level via observing deer while conducting spotlight surveys, 3) and determine if wind speed or time of night impacts sampling efficiency by analyzing the relationships with deer observations during spotlight surveys.

STUDY AREA

The study area consisted of a 10,350-km^2 region in southwest Minnesota (Figure 1). The study area was comprised of 78% cultivated cropland (U.S. Geological Survey 2006) dominated by row crop production of corn (*Zea mays*) and soybeans (*Glycine max*;

72% of cultivated croplands; National Agricultural Statistics Service 2012). Land cover other than cropland included 7% grassland, 6% developed, 2% wetland, 1% open water and 1% forest (Homer et al. 2015). Native tall grass prairies in the study were comprised of big bluestem (*Andropogon geradii*), little bluestem (*Schizachyrium scoparium*), indiangrass (*Sorghastrum nutans*), switchgrass (*Panicum virgatum*), tall dropseed (*Sporobolus asper*), and sideoats gama (*Bouteloua curtipendula*; Johnson and Larson 1999). Forested areas were composed of eastern cottonwood (*Populus deltoides*), green ash (*Fraxinus pennsyulvanica*), basswood (*Tilia americana*), and bur oak (*Quercus macrocarpa*; Brinkman et al. 2004). The elevation ranged from 229 m to 608 m above sea level and was considered mostly flat with some rolling topography, which are conducive environmental conditions for agriculture (Albert 1995). Mean annual temperature was 7˚C, ranging from -11˚C in January to 22˚C in July. Mean annual precipitation was 68 cm with an average annual snowfall of 101 cm (Midwest Regional Climate Center 2002).

METHODS

MODEL CREATION

ArcMap 10.2 was used to create HSI models and National Land Cover Database 2011 (pixel size = 30m x 30m resolution; Homer et al. 2015) was used to derive land-cover data. Minnesota Deer Permit Area layer (MNDNR 2012) was used to define study area and DMU boundaries. A HSI model previously created for Illinois (original HSI; Roseberry and Woolf 1998) was compared to the same model with some adjustments that provided more appropriate value to grassland habitats used by deer in intensively farmed regions in the upper Midwest region (modified HSI). Model adjustments were based on field observations, expert opinion and information from the literature. The original HSI model was previously created using the procedure and algorithm defined by Roseberry and Woolf (1998). Based on how deer utilize the habitat, land-cover types were reclassified as cover, forage or other (Table 1). Each pixel within a patch of forage ≥2 ha was given a value of 1 if the distance from nearest cover was ≤200 m, a value of 0.9 to 0.1 if the distance from nearest cover was 200 to 500 m, and a value of 0 if the distance from nearest cover was >500 m (Figure 2). Each pixel within a patch of cover ≥2 ha was given a value of 1 if the distance from nearest forage was ≤500 m, a value of 0.9 – 0.1 if the distance to nearest forage was 500 to 1,000 m, and a value of 0 if the distance to nearest forage was >1,000 m (Figure 3). Each land cover type was then multiplied by a coefficient to calculate the final pixel value (Table 2; Roseberry and Woolf 1998).

In agricultural landscapes, white-tailed deer will use grassland habitat types in the absence of forest cover (Ozoga et al. 1982, Beier and McCullough 1990, Nixon et al. 1991, Nixon et al. 2001, Klaver et al. 2008, Hiller et al. 2009, Grovenburg et al. 2011). Therefore, the original HSI model was adjusted by reducing the minimum patch size to 0.5 ha and including grassland, shrubland and wetlands as cover (coefficient = 0.5) to create the modified HSI model. For statewide HSI model comparison, the mean pixel value was calculated within each DMU for both HSI models.

For local-level model comparison, the pixel values were averaged for both HSI models within a 500-m buffer placed around each transect. A transect was defined as a 1.6-km road segment because the road network was already in a grid-like fashion with intersections every 1.6 km. Road network information was provided by Minnesota

Department of Transportation (Mn/DOT 2009). I arbitrarily used a 500-m buffer width based on the approximate distance the spotlight became practically ineffective for observing deer under lowlight conditions.

To select survey routes, 5 DMUs were each divided into 6 equal sections. One DMU (295) was divided into 8 equal sections because it was larger than the other DMUs in the study area. Within each section, 20 transects were selected to make up a single route. To distribute sampling effort equally along the scale of HSI scores transects with an original HSI score ≥0.3 were selected first. If there were <20 high valued (≥0.3) transects selected, the remaining transects were randomly selected to reach the total of 20. Each route was driven twice per year with the second route driven in reverse order to account for potential changes in deer activity at different times of the night (Beier and McCullough 1990).

SPOTLIGHT SURVEYS

Transects were surveyed using spotlights from 30 March through 7 May, 2015, and 18 March through 22 April, 2016. Surveys were conducted during these times because deer were expected to be on their summer range, there was no interference with hunters, and visibility was high because there was no leaf cover (McCullough 1982, Nelson et al. 2004). Deer are more active and are easier to detect at sunset (Volk et al. 2007) so the surveys began at sunset and concluded when all 20 transects were completed. Surveys were not conducted when weather conditions impaired visibility, such as fog, rain or snow. Each survey crew consisted of 2 individuals, a driver and passenger, both observing on opposite sides of a marked MNDNR vehicle. Vehicles were driven at low speeds (10-16 km/hr) and the vehicle was stopped after a deer was observed and the distance was estimated using a laser rangefinder. A digital protractor was then used to estimate the angle from transect to deer. Universal transverse mercators were recorded at points of observation. Using a handheld digital weather meter, wind speed was recorded at the start of each transect, and temperature was recorded at the start and end of each route.

STATISTICAL ANALYSIS

Similar to the statewide evaluation procedure used by Roseberry and Woolf (1998), mean deer densities (2011 – 2014) were regressed against the mean HSI scores from the original and modified models for each DMU (Grund 2014). Deer management units in northeast Minnesota were excluded because the contiguous forest habitat does not exist in Illinois and severe winters have a significant impact on white-tailed deer populations in northeastern Minnesota (Figure 4). Thus, the remaining landscape was dominated by agriculture, much like Illinois. A t-test was used to compare deer densities and percentage of forest between DMUs in the agricultural dominated region of southwest Minnesota and DMUs in southeast Minnesota, with a higher percentage of forest cover (Figure 5).

For the local-level analysis, transects were grouped into HSI categories of 0.0, 0.1, 0.2, 0.3, 0.4 and ≥0.5. The mean number of deer observed per transect within each HSI category was regressed against original and modified HSI values. To estimate sampling efficiency, the percentage of transects that yielded 0, 1, 2, 3, 4, and ≥5 deer observed within each HSI category was calculated (Table 3). To compare between HSI categories, the number of transects surveyed within each HSI category was standardized by assuming there were 100 transects surveyed in each category and the total number of deer observed was projected based on the proportion of transects that yielded 0, 1, 2, 3, 4 or ≥5 deer observed (Table 4). To make comparisons between HSI models the percentage of all available transects throughout the study area (sampled and not sampled) was calculated within each HSI category of 0.0, 0.1, 0.2, 0.3, 0.4 and ≥0.5 (Table 5). These percentages were multiplied by the projected total number of deer observed for each respective HSI category within each HSI model (Table 4) to calculate the total projected number of deer observed on all transects in the study area within each HSI category. The resulting products for each HSI category were summed within each HSI model to estimate the projected total number of deer observed throughout the study area if sampled according to the proportions of transect HSI scores available for each HSI model (Table 6). Monte Carlo simulations were used by repeating these steps 25 times for each HSI model after randomly selecting 100 surveyed transects and calculating new percentages of transects that yielded 0, 1, 2, 3, 4, and ≥5 deer observed. A t-test was used to compare means of the 25 simulations of the projected number of deer observed between original HSI and modified HSI models.

The mean number of deer observed per transect was regressed against wind speed in increments of 3.2 km/hour. The number of deer observed was regressed against minutes after sunset to assess if there were changes in deer activity at different times of the night (Beier and McCullough 1990).

RESULTS

STATEWIDE

Deer densities and HSI scores were calculated for 87 DMUs. Mean scores for the original and modified HSI models were 0.23 (SD = 0.19) and 0.48 (SD = 0.17), respectively. The original HSI model had a positive, curvilinear relationship (R^2 = 0.82, P < 0.0001; Figure 6). The modified HSI model also had a positive, curvilinear relationship (R^2=78, P < 0.0001; Figure 7). Deer management units in southeast Minnesota had higher deer densities and contained more forested cover than DMUs in southwest Minnesota (Table 7).

LOCAL-LEVEL

A total of 2,914 transects were surveyed during the study, totaling 4,690 km in length. The total number of deer observed was 8,506, with no difference (P = 0.32) in mean number of deer observed per transect between 2015 ($\bar{x}$ = 3.0, SE = 0.1) and 2016 ($\bar{x}$ = 2.8, SE = 0.1). The mean original HSI score for surveyed transects was 0.13 (SD = 0.16), and the mean modified HSI score was 0.43 (SD = 0.17). The original and modified HSI models assigned scores can be found in Table 5. The original HSI model had a positive, curvilinear relationship (R^2=0.95, P = 0.001), when correlated with the mean number of deer observed per transect surveyed in HSI increments of 0.1 (Figure 8). The modified HSI model had a positive, curvilinear relationship (R^2=0.95, P = 0.01), when correlated with the average number of deer observed per transect surveyed in HSI increments of 0.1 (Figure 9). There was a significant difference in mean projected number of deer observed between the original HSI (11,818 deer) and modified HSI (14,073 deer) models (P < 0.0001; Figure 10).

Wind speed was collected on all 2,914 transects, with a mean of 9.6 km/h (SD = 0.14). There was a negative, linear relationship between mean number of deer observed per transect and wind speed (R^2 = 0.64, P = 0.009; Figure 11). There was no significant relationship between the number of deer observed and number of the minutes past sunset (P = 0.30).

DISCUSSION

STATEWIDE

The results from the original HSI model were similar to those found by Roseberry and Woolf (1998) in Illinois, where the HSI model explained 81% of the variation in deer densities at a county-level. This outcome was expected because deer in Illinois have similar ecological demands as do deer in Minnesota. Due to the similarities in climate and landscape composition in both Illinois and Minnesota, deer behavior was expected to be similar. The original model was a good predictor of deer densities at a DMU-level because it considered forest cover as high-quality deer habitat. Forest cover is the critical element that allows deer densities to be high.

When comparing southwest Minnesota, an intensively farmed landscape, to southeast Minnesota with a higher percentage of forest cover, it was clear that more forest cover leads to higher deer densities (Table 7). However, forest cover in the Midwestern United States is dependent on agricultural activity that is driven by topography and soil type and quality. If topography and soil type are favorable, the landscape will likely be converted to agriculture. Otherwise, the land cover will likely consist of forest due to habitat succession. In southwest Minnesota, the relatively flat topography and rich soils are ideal for agricultural activity that has reduced the amount of forest cover, leading to low deer densities (Table 7). In southeast Minnesota, the topography consists of many peaks and valleys with steep slopes unfavorable for agricultural activity, leading to a high percentage of forest cover and higher deer densities.

LOCAL-LEVEL

Both HSI models had significant positive, curvilinear relationships with deer observations per transect during spotlight surveys. However, >90% of transects had an HSI score of <0.1 in the original HSI model. Thus, there were few available transects to survey near high-quality deer habitat. The modified HSI produced >30% of available transects with an HSI score ≥0.5, providing more available transects with high-quality deer habitat to survey. Therefore, the modified HSI model yielded more practical spatial data for stratifying the landscape because it distinguished between transects with high and low-quality deer habitat. In contrast, the original HSI model identified virtually all transects were low-quality because the model exclusively considered forest habitat as cover. Also, the modified HSI had fewer average number of deer observed on transects with low-quality deer habitat (HSI = 0.0-0.1), while the original HSI produced an average of nearly 2 deer on transects with low-quality deer habitat (HSI = 0.0-0.1). By including grassland habitat, the modified HSI made a clear distinction between low and high-quality deer habitat and was a better representation of the wildlife-habitat relationship with white-tailed deer in an intensely agricultural landscape. This provides further evidence to support the habitat use of grasslands by deer in landscapes containing limited forest cover. Thus, the modified HSI model performed better when predicting deer observations during spotlight surveys in intensively farmed landscapes.

The modified HSI was more efficient than the original HSI to predict where deer would be observed during spotlight surveys. There were very few transects with an original HSI score >0.5 (<1%) available to sample throughout the study area, which made sampling equally along the range of HSI scores difficult. The major differences between the 2 models was reducing the minimum patch size to 0.5 ha and classifying grassland and shrubland as cover. The changes made in the modified HSI model increased the value of grassland habitat for white-tailed deer and reduced the quantity of transects with low HSI scores (≤0.2). Therefore, the modified HSI model had better sampling efficiency because sampling effort could be focused on transects with high-quality deer habitat, while the original HSI produced few such transects.

White-tailed deer are habitat generalists and can be opportunistic in their habitat selection. I agree with Roseberry and Woolf (1998) that white-tailed deer populations are higher when more forest cover is available. However, white-tailed deer are opportunistic and will use grassland habitat types for cover in the absence of forest habitat (Klaver et al. 2008, Hiller et al. 2009, Beier and McCullough 1990, Grovenburg et al. 2011). Grovenburg et al. (2011) found no difference in survival rates of white-tailed deer between forest (20% forest) and grassland (1.9% forest) regions in eastern Minnesota and westward in north-central South Dakota. It is necessary to account for this opportunistic behavior and to consider grasslands when attempting to evaluate fine-scale habitat and predict the distribution of white-tailed deer in agricultural landscapes.

Surveys were conducted in early spring, when white-tailed deer were moving back to their summer range. During early spring, white-tailed deer have high energy demands to prepare for the fawning season. Agricultural landscapes typically have abundant forage resources. However, in early spring crop fields were not planted and have been fed upon by wildlife throughout winter. White-tailed deer likely prefer grassland and shrubland habitat as their primary forage source because crop fields are less productive at that time of year. In an agricultural landscape of southern Michigan, white-tailed deer used shrubland habitat more often during the non-growing season, compared to the growing season (Hiller et al. 2009), providing evidence for the opportunistic behavior of white-tailed deer. Beier and McCullough (1990) found white-tailed deer to prefer open vegetation types during dusk, night and dawn, and females made greater use of open woodlands and grasslands than males. In the central Black Hills, South Dakota, where habitat quality was considered poor (Sieg and Severson 1996, Osborn and Jenks 1998), deer diets composed of 30% grass and 20% shrubs (Klaver et al. 2008). In the absence of forest cover, females will use grassland habitats for parturition (Ozoga et al. 1982, Nixon et al. 1991, Nixon et al. 2001). These findings further suggest deer become opportunistic and utilize grassland and shrubland habitat types for cover, forage and parturition in poor-quality habitat.

In agricultural landscapes, grasslands in the Conservation Reserve Program (CRP) are converted to agricultural production, reducing and fragmenting permanent cover (Grovenburg et al. 2010). This research provides additional evidence to support the importance of grassland habitat for white-tailed deer in agricultural landscapes. If increasing white-tailed deer population size is the management objective, then this research supports the argument for conserving CRP grasslands for white-tailed deer habitat use.

WIND SPEED & TIME

The number of deer observed had a negative correlation with increasing wind speed (Figure 11), suggesting deer activity decreased with increased wind speed. Similar studies have found contrasting results, as Beier and McCullough (1990) found no correlation between deer activity and wind speed. On the George Reserve, Michigan, there was also no relationship between wind speed and number of deer observed on transects (Newhouse 1973). However, Newhouse (1973) reported deer moving from open habitats to closed forests when wind speeds increased, suggesting deer change their habitat selection in response to high wind speeds, rather than decrease activity. Considering this, the negative relationship I found with wind speed and average number of deer observed per transect was likely caused by deer using forested habitat that interferes with spotlight survey visibility during windy conditions. My results indicate that the probability of observing deer decreased once wind speeds exceeded 20 km/hour. To increase sampling efficiency, I would suggest avoiding spotlight surveys during windy conditions.

There was no correlation between time and number of deer observed during spotlight surveys. Beier and McCullough (1990) found differences in deer activity at different times of the night. Further research that implements a more appropriate research design for evaluating changes in deer activity over time in agricultural landscapes is needed.

CONCLUSION

Both HSI models explain a high percentage of variation in deer densities at a DMU-level in Minnesota. Landscape stratification has been shown to increase efficiency and precision of population estimates (Gasaway et al. 1986, Ward et al. 2000, Edwards et al. 2005). In intensively farmed landscapes, white-tailed deer habitat is fragmented, and using the modified HSI model to stratify agricultural-region habitat patches can increase deer sampling efficiency during spotlight surveys. I suggest using the modified HSI model to stratify the landscape when defining survey routes in agricultural regions for deer spotlight surveys. Spotlight surveys should be avoided when wind speeds exceed 20 km/hour because deer appear to reside in forest patches that reduce spotlight effectiveness. More research should be conducted to evaluate deer activity during different times of the night.

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TABLES & FIGURES

Table 1. Land-cover classes and their major components categorized based upon white-tailed deer usage as defined in Roseberry and Woolf (1998) for use in creating the original habitat suitability index model for white-tailed deer in Minnesota. Land cover classes and definitions from National Land Cover Database 2011 (Homer et al. 2015).

Class	Predominant component	Category
Water	Lakes, rivers, streams	Other
Developed, open space	Parks, golf courses, planted vegetation	Forage
Developed, low intensity	20% to 49% impervious surface	Other
Developed, medium intensity	50% to 70 % impervious surface	Other
Developed, high intensity	80% to 100 % impervious surface	Other
Barren	Bedrock, desert pavement	Other
Deciduous Forest	Tree species shed foliage seasonally	Cover
Evergreen Forest	Canopy never without green foliage	Cover
Mixed Forest	Equal composition of deiduous and evergreen	Cover
Shrubland	True shrubs, young trees, stunted trees	Forage
Grassland	Gramanoid or herbaceous vegetation	Forage
Pasture	Grasses, legumes planted for livestock graxing	Forage
Cultivated Crops	Corn, soybeans, tilled land	Forage
Woody Wetlands	Forest or shrubland periodocially covered with water	Cover
Emergent herbaceous Wetlands	Perennial herbaceous vegetation periodically covered with water	Other

Table 2. Coefficient values assigned to each land-cover class defined by the National Land Cover Database 2011 (Homer et al. 2015) for the original habitat suitability index model created for white-tailed deer populations in Minnesota in early spring 2015 and 2016. Coefficient values represent the value of each land cover class for white-tailed deer survival. A coefficient of 1.0 is the most valuable and a coefficient of 0.0 is the least valuable. Coefficient values were previously defined by Roseberry and Woolf (1998).

Class	**Coefficient**
Water	0.0
Developed, open space	1.0
Developed, low intensity	0.0
Developed, medium intensity	0.0
Developed, high inetnsity	0.0
Barren	0.0
Deciduous Forest	1.0
Evergreen Forest	0.5
Mixed Forest	1.0
Shrubland	1.0
Grassland	1.0
Pasture	1.0
Cultivated Crops	0.5
Woody Wetlands	0.5
Emergent herbaceous wetlands	0.0

Table 3. Percentage of transects surveyed during spotlight surveys in southwest Minnesota from early spring 2015 and 2016 that yielded 0, 1, 2, 3, 4 and ≥5 deer observed within each original and modified HSI transect category of 0.0 – 0.1, 0.1 – 0.2, 0.2 – 0.3, 0.3 – 0.4, 0.4 – 0.5 and ≥0.5. Transects were defined as a 1.6-km road segment with a width of 500 m and transect HSI scores represent the mean HSI value of all pixels within the transect.

	Original HSI						**Modified HSI**					
Transect HSI	0	1	2	3	4	5+	0	1	2	3	4	5+
0.0-0.1	70	3	5	3	3	14	92	2	2	1	0	2
0.1-0.2	56	4	5	6	3	24	84	1	5	3	1	6
0.2-0.3	54	5	7	5	5	24	78	3	5	3	2	8
0.3-0.4	24	6	8	8	9	46	69	3	5	3	4	15
0.4-0.5	17	8	9	1	8	57	60	5	6	5	4	18
0.5+	11	5	6	4	10	64	40	5	6	6	5	37

Table 4. Projected number of deer observed per 100 transects (1.6-km road segment) of white-tailed deer spotlight surveys during early spring 2015 and 2016 in southwest Minnesota within each original and modified HSI category. Transect HSI scores represent the mean HSI value of all pixels within 500 meters of the transect. Transects were categorized into original HSI scores of 0.0 – 0.1, 0.1 – 0.2, 0.2 – 0.3, 0.3 – 0.4, 0.4 – 0.5 and ≥0.5. The percentage of transects that yielded 0, 1, 2, 3, 4 and ≥0.5 deer observed within each original HSI category (Table 3) was used to calculate the projected number of deer observed per 100 transects surveyed.

	Original HSI							**Modified HSI**						
Transect HSI	0	1	2	3	4	5+	**Sum**	0	1	2	3	4	5+	**Sum**
0.0-0.1	0	3	10	12	11	73	108	0	3	3	3	0	13	21
0.1-0.2	0	5	11	19	17	122	170	0	1	9	9	6	19	25
0.2-0.3	0	5	13	15	21	120	174	0	3	10	9	8	39	70
0.3-0.4	0	6	16	24	36	229	310	0	3	11	10	16	77	117
0.4-0.5	0	8	18	3	32	283	345	0	5	13	16	18	93	144
0.5+	0	5	13	11	40	319	388	0	5	12	17	22	186	242

Table 5. Percentage of all transects (1.6-km road segment) available for white-tailed deer spotlight surveys during early spring 2015 and 2016 in southwest Minnesota categorized into HSI of 0.0 – 0.1, 0.1 – 0.2, 0.2 – 0.3, 0.3 – 0.4, 0.4 – 0.5 and ≥0.5. Transect HSI scores represent the mean HSI value of all pixels within 500 meters of the transect. Original HSI and modified HSI percentages were calculated separately.

Transect HSI	**Original HSI percent**	**Modified HSI percent**
0.0 – 0.1	90	9
0.1 – 0.2	5	9
0.2 – 0.3	3	14
0.3 – 0.4	1	18
0.4 – 0.5	< 1	20
0.5 +	< 1	30

Table 6. Projected total number of white-tailed deer observed while conducting spotlight surveys during early spring 2015 and 2016 in southwest Minnesota after distributing sampling effort according to transect (1.6-km road segment) availability throughout southwest Minnesota (Table 7) for original and modified HSI models. Transect HSI scores represent the mean HSI value of all pixels within 500 meters of the transect.

Transect HSI	**Original HSI efficiency**	**Modified HSI Efficiency**
0.0-0.1	9,766	181
0.1-0.2	827	500
0.2-0.3	495	954
0.3-0.4	284	2,088
0.4-0.5	192	2,929
0.5+	197	7,363
Sum	11,760	14,015

Table 7. Comparison of percent forest cover and white-tailed deer population density (deer/km^2; 2011 – 2014) between deer management units (DMUs) in an agricultural dominated region (southwest Minnesota) and a region with a higher percentage of forest cover (southeast Minnesota).

	Southeast			**Southwest**	
DMU	Density	% Forest	DMU	Density	% Forest
341	3.9	16.6	234	0.8	0.7
342	5.3	22.0	237	1.1	0.7
343	3.9	10.6	286	1.3	0.7
345	3.3	24.4	288	1.0	0.9
346	9.9	47.6	294	0.7	0.4
347	3.0	14.4	295	0.8	0.6
348	5.3	24.2			
349	9.4	35.2			
Mean	5.5	24.3		1.0	0.7
95% CI	3.3-7.7	14.3-34.3		0.8-1.2	0.6-0.8

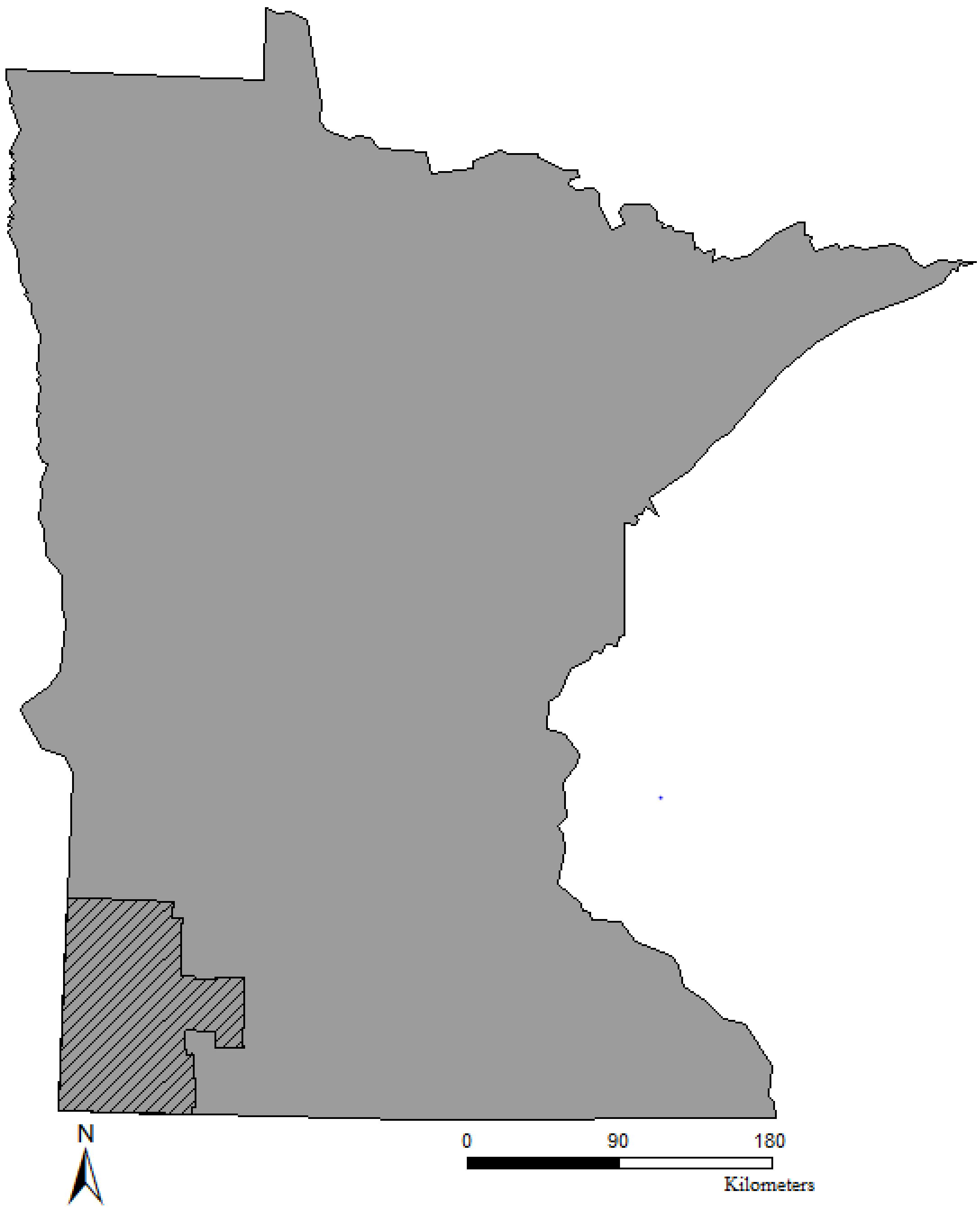

Figure 1. Study area boundary (hashed area) for white-tailed deer spotlight surveys in southwest Minnesota during early spring 2015 and 2016.

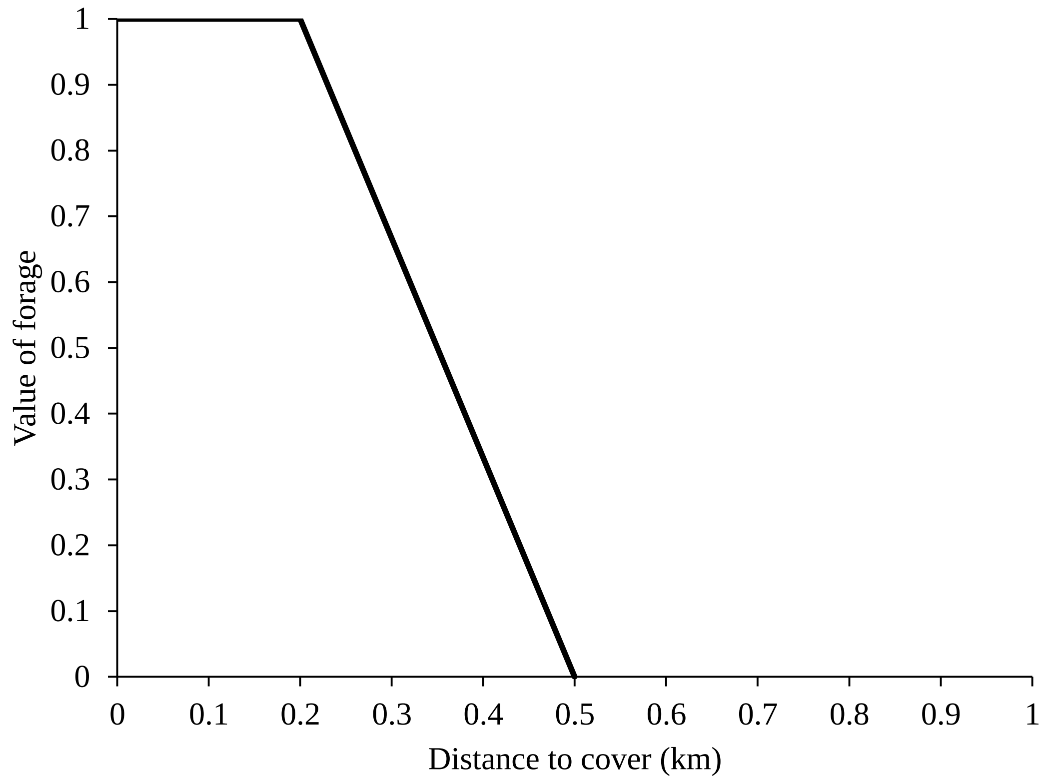

Figure 2. Relative value of forage pixels for calculating HSI scores based on distance to nearest cover for original and modified HSI models created for conducting white-tailed deer spotlight surveys during early spring 2015 and 2016 in Minnesota (Roseberry and Woolf 1998).

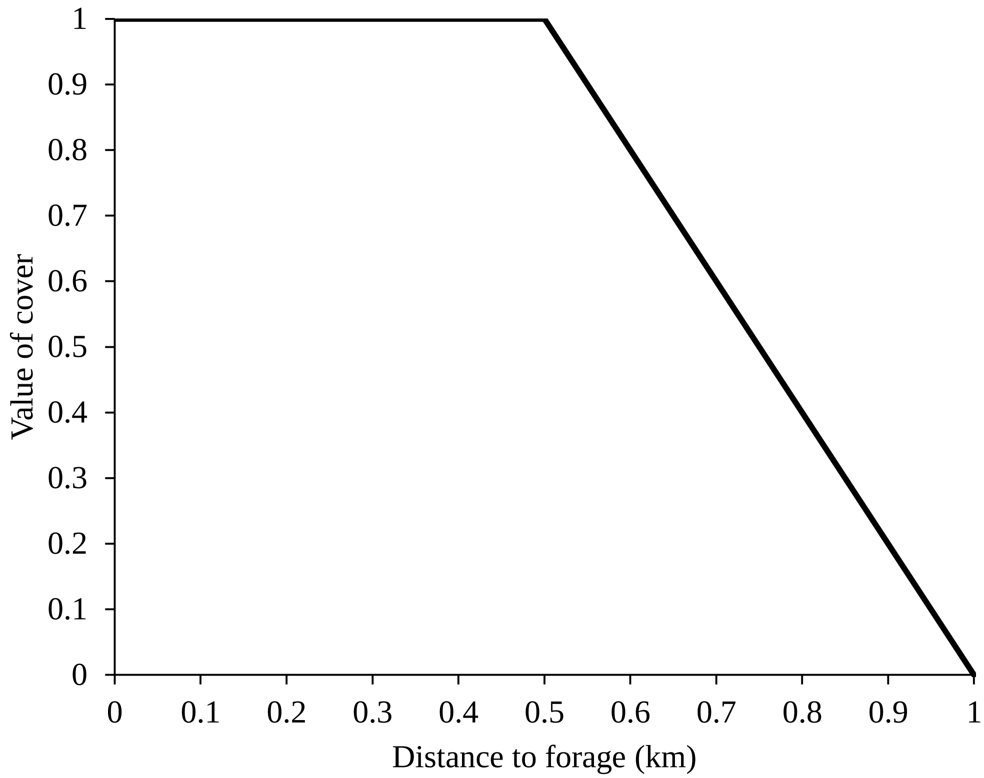

Figure 3. . Relative value of cover pixels for calculating HSI scores based on distance to nearest forage for original and modified HSI models created for conducting white-tailed deer spotlight surveys during early spring 2015 and 2016 in Minnesota (Roseberry and Woolf 1998).

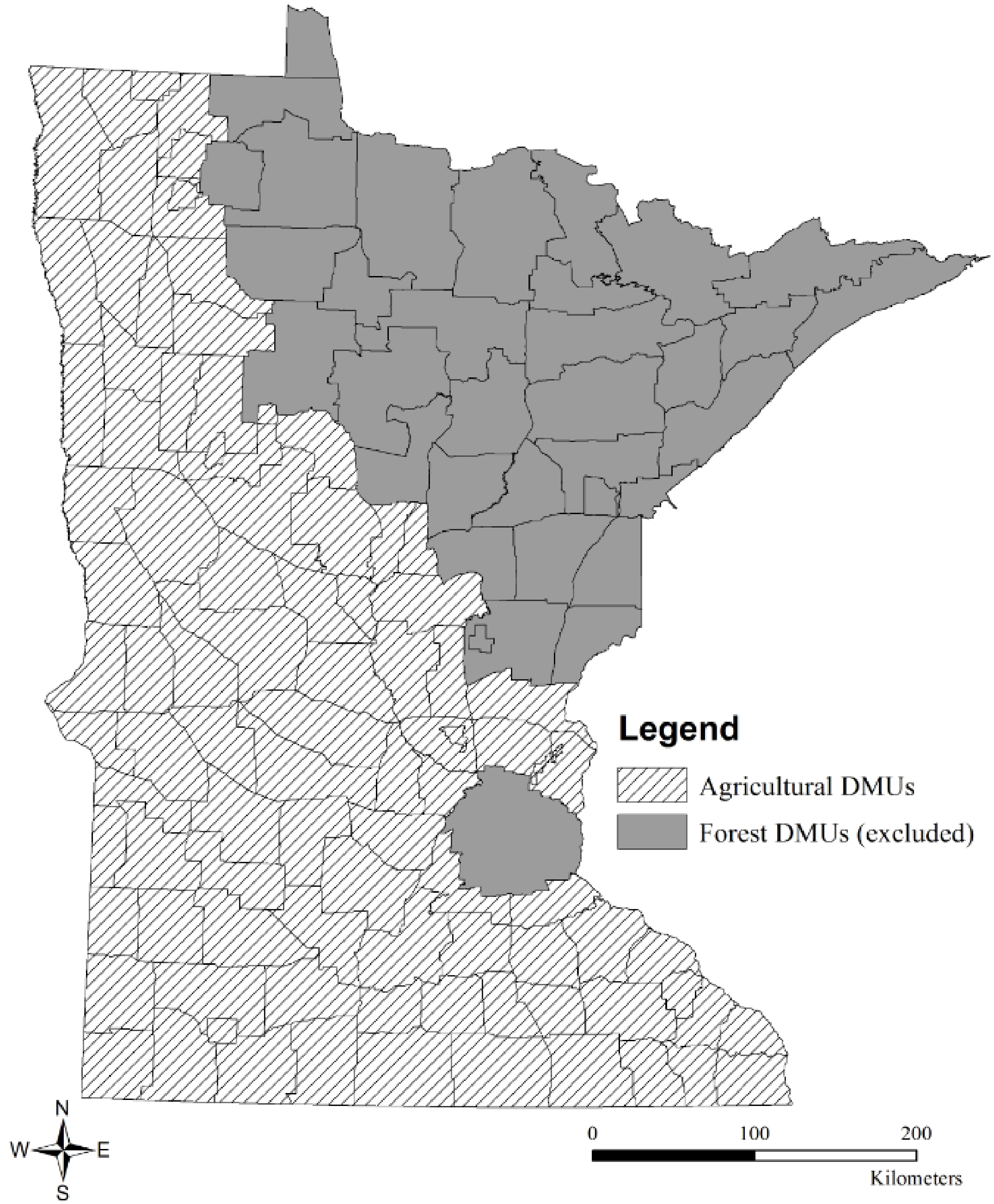

Figure 4. Deer management units used to compare average deer densities (2011 – 2014) and habitat suitability index values at the statewide level in Minnesota.

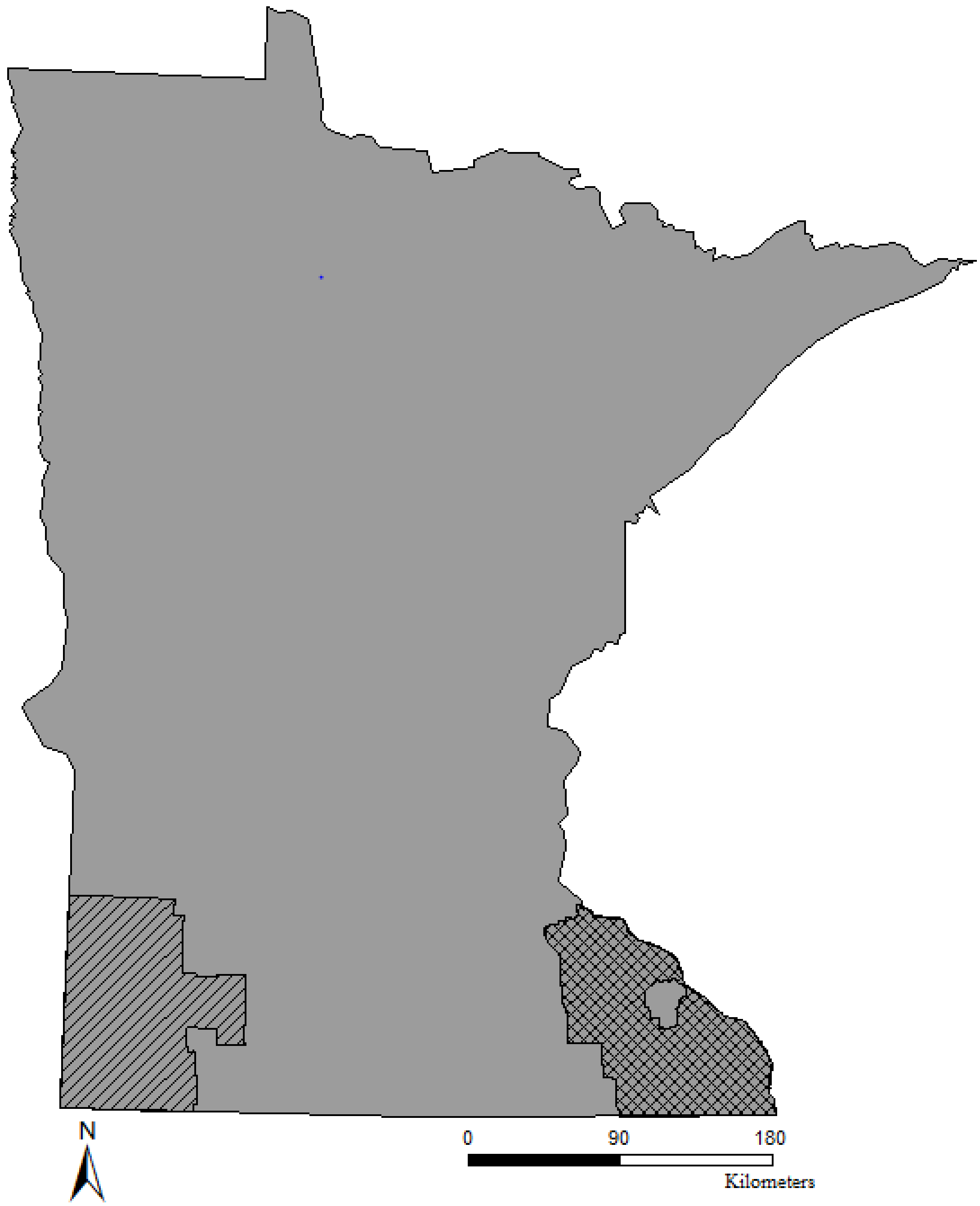

Figure 5. Boundaries of southwest (hashed area) and southeast (checkered area) Minnesota used for comparing mean deer densities (deer/km^2) from 2011 through 2014 (Grund 2014) and forest cover (%) between the two regions.

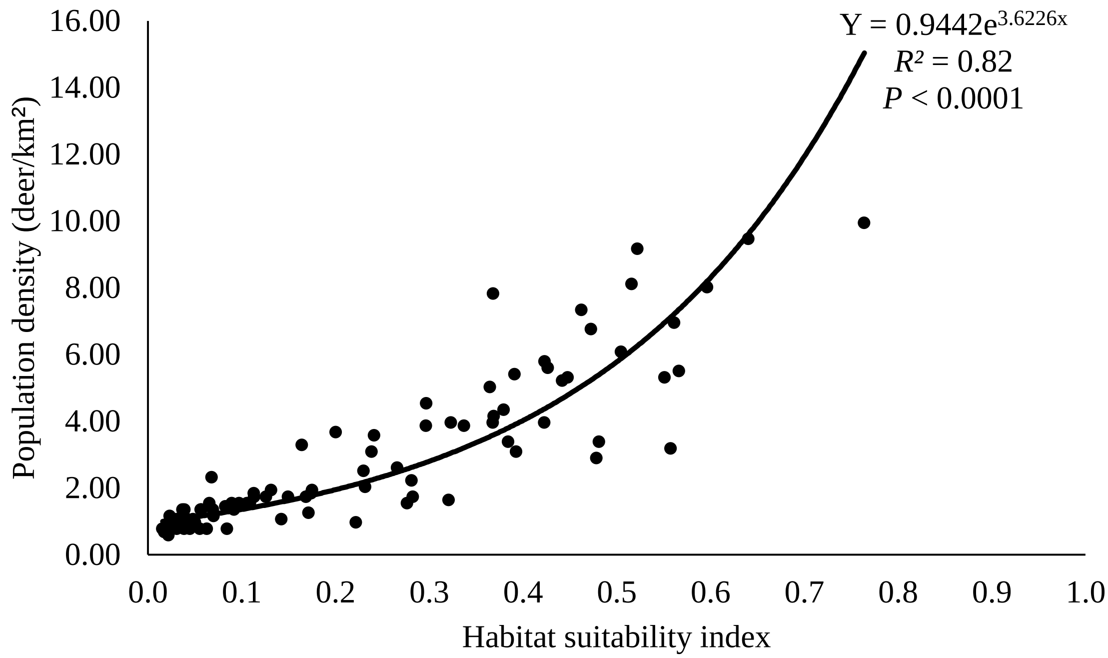

Figure 6. Mean white-tailed deer population density (deer / km^2) in Minnesota deer management units (DMU) from 2011 through 2014 regressed against mean original HSI scores for each DMU (Grund 2014).

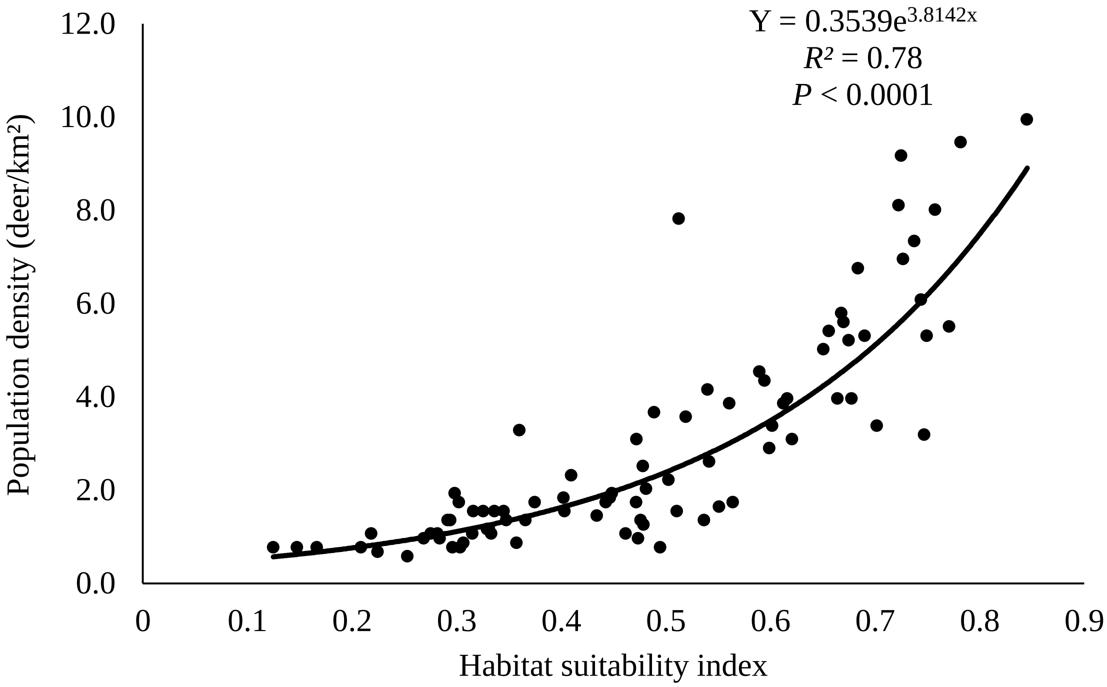

Figure 7. Mean white-tailed deer population density (deer / km^2) in Minnesota deer management units (DMU) from 2011 through 2014 regressed against mean modified HSI score for each DMU (Grund 2014).

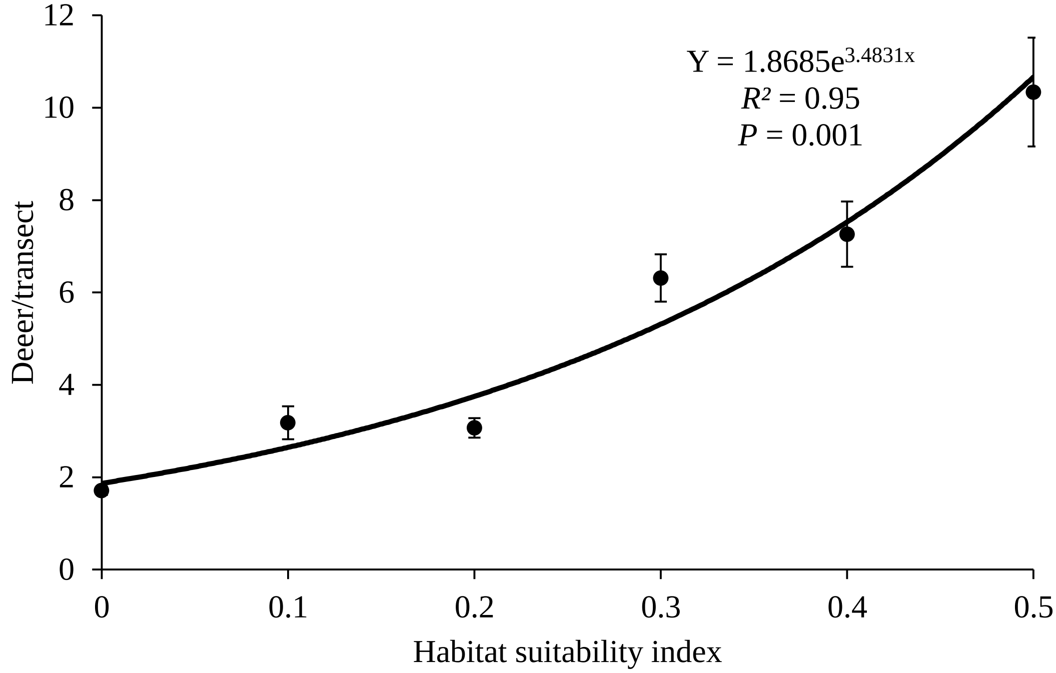

Figure 8. Relationship between mean number of deer observed per transect and transect original HSI score in southwest Minnesota while conducting white-tailed deer spotlight surveys during early spring 2015 and 2016.

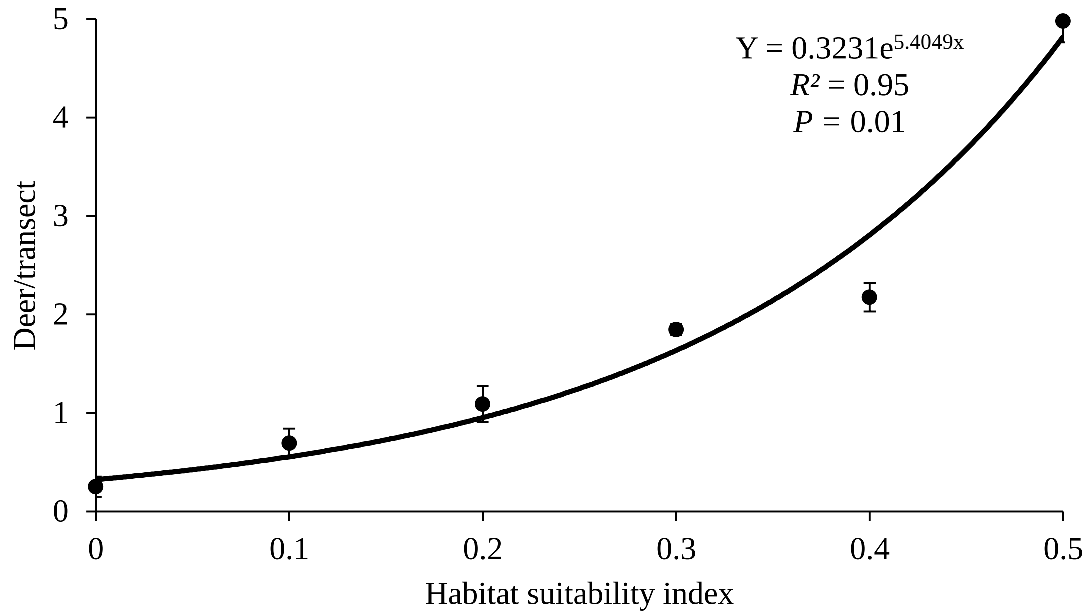

Figure 9. Relationship between mean number of deer observed per transect and transect modified HSI score in southwest Minnesota while conducting white-tailed deer spotlight surveys during early spring 2015 and 2016.

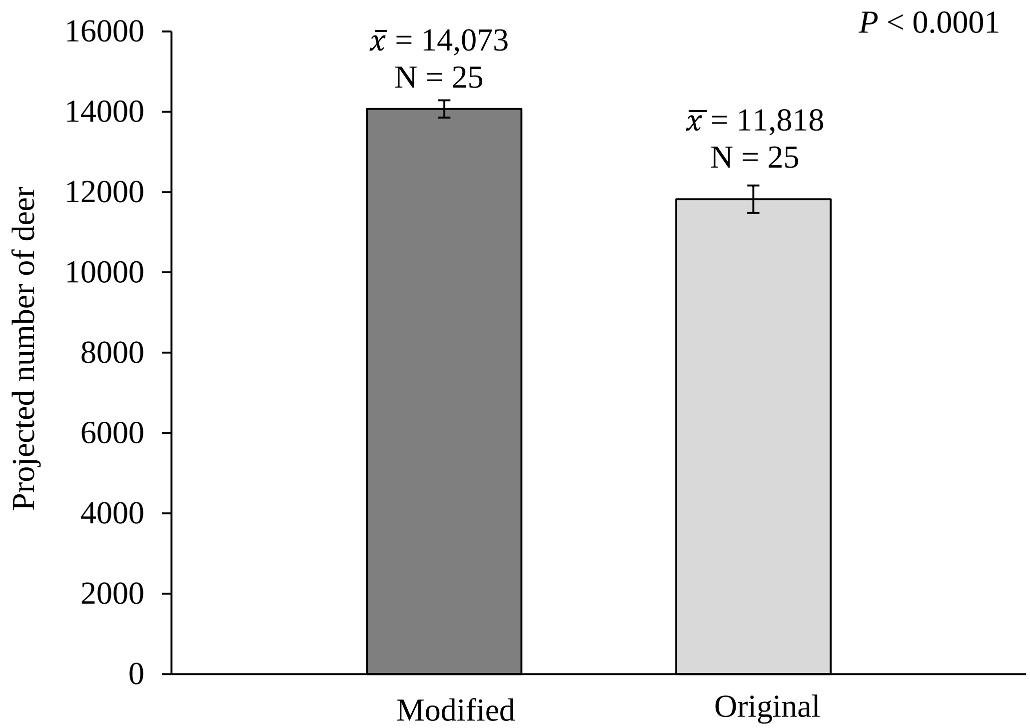

Figure 10. Mean projected number of white-tailed deer observed after 25 simulations of spotlight surveys conducted during early spring 2015 and 2016 in southwest Minnesota for the original and modified HSI models.

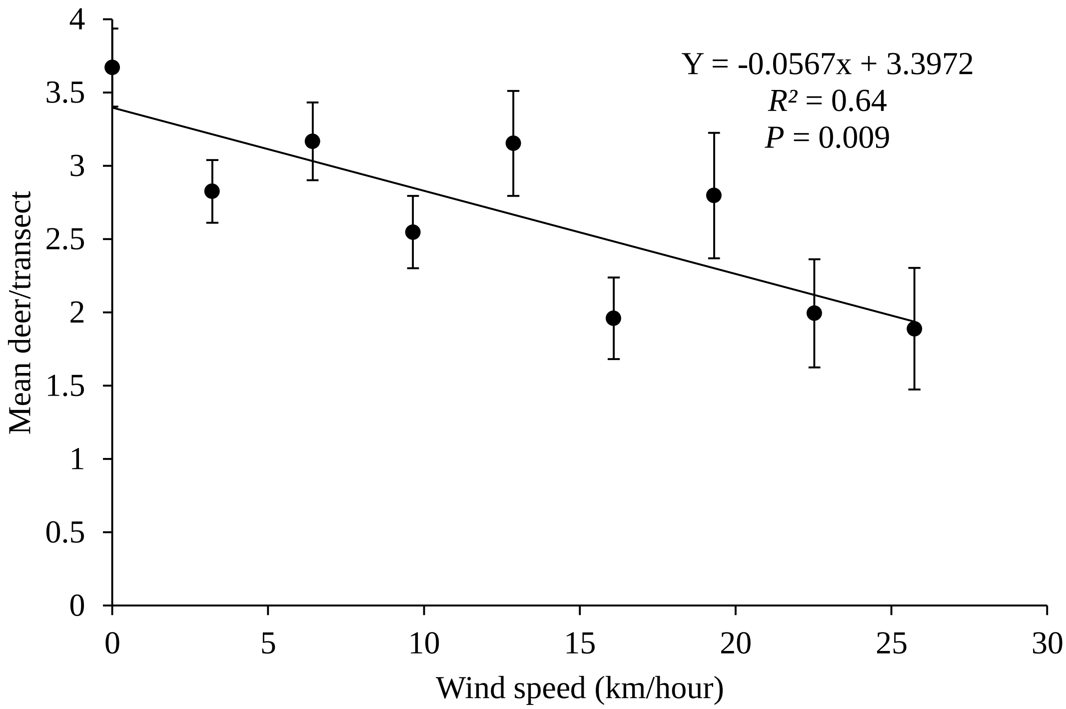

Figure 11. Relationship between mean number of deer observed per transect in wind speed increments of 3.2 km/hour and wind speed (km/hour) while conducting white-tailed deer spotlight surveys in southwest Minnesota during early spring 2015 and 2016.