# THE RELATIONSHIP BETWEEN GRASSLANDS, CONSERVATION RESERVE PROGRAM (CRP) ENROLLMENTS, AND GREATER PRAIRIE-CHICKEN *(Tympanuchus cupido pinnatus)* POPULATIONS IN MINNESOTA

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# Dedication

“If a child is to keep alive his inborn sense of wonder, he needs the companionship of at least one adult who can share it, rediscovering with him the joy, excitement, and mystery of the world we live in” – Rachel Carson

*This work is dedicated to my parents. Thank you for nurturing my curiosity and sharing the joy of the world with me.*

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## Chapter 1

### Multiscale Associations between Greater Prairie-Chickens, Grassland Conservation Reserve Program Enrollments, and Landscape Composition in Northwestern Minnesota

***Overview****:* Both the abundance of greater prairie-chickens (*Tympanuchus cupido pinnatus)* and the area in grassland Conservation Reserve Program (CRP) in northwestern Minnesota have undergone recent declines. Although wildlife conservation is a stated objective of the CRP, the impact of CRP grassland on greater prairie-chicken populations has not been quantified. To address that information need, I evaluated the association between greater-prairie chicken lek density (leks/km$^2$) and the number of males at leks (males/lek) and CRP enrollments in the context of landscape structure and composition in northwestern Minnesota using data from standardized prairie-chicken surveys and land-cover in 17 42-km$^2$ survey blocks during the period 2004-2016. I used a mixed-effect model and a layered approach in an information-theoretic framework at multiple spatial scales to identify covariates related to prairie-chicken abundance. At the landscape scale, the amount of CRP grassland; state-, federal-, and The Nature Conservancy (TNC)-managed grasslands; CRP wetland; state-, federal-, and TNC-managed wetlands, “other” wetlands; the contiguity of grasslands; and the number of patches of grasslands and wetlands in each survey block in each year best explained lek density (leks/km$^2$). At the lek scale, the amount of CRP grassland; state-, federal-, and TNC-managed grasslands; CRP wetland; state-, federal-, and TNC-managed wetlands; “other” wetlands; forests; developed areas; shrubs; and the contiguity of CRP grassland best explained the number of males at leks. These results suggest that increasing the quantity of grassland and wetland CRP contracts throughout the existing range of greater prairie-chickens in northwestern Minnesota and aggregating CRP grassland contracts in areas of known lek sites may increase greater prairie-chicken abundance.

***Key Words****:* Greater prairie-chicken, *Tympanuchus cupido pinnatus,* landscape, grassland, Conservation Reserve Program, Minnesota

## INTRODUCTION

Greater prairie-chickens (*Tympanuchus cupido pinnatus*) are obligate grassland birds that were once considered the leading game bird in central North America (Robel et al. 1970a; McNew et al. 2015). Although southern Minnesota marks the northern boundary of their pre-European settlement distribution, they were distributed across most of the state by 1880 (with the exception of northeastern and north-central Minnesota) in response to land-use conversion to agriculture and logging, which increased the extent of grasslands (Partch 1973; Svedarsky et al. 1997) and other open cover types. Over much of their distribution, greater prairie-chicken abundance has declined since the early 20th Century, resulting in heightened conservation concern and focused management efforts to increase and re-establish sustainable populations. In Minnesota, prairie-chicken hunting was closed in 1942 (Svedarsky et al. 1997), prairie-chickens were designated as a Species of Special Concern in 1984, and a limited-participation hunting season was reinitiated in 2003 (Roy 2014).

Declines of greater prairie-chicken abundance are strongly associated with decreases in the extent of the tallgrass prairie ecosystem, which once spanned over 380,000 $km^2$ in the Midwestern United States (Noss et al. 1995; Steiner and Collins 1996; Ryan 2000). The conversion of the tallgrass prairie plant community to row-crop agriculture production or pasture and invasion of exotic grass led to alteration and losses of between 83 and >99% of its area throughout the Midwestern United States (Noss et al. 1995; Herkert et al. 1996; Steiner and Collins 1996; Ryan 2000; Burger et al. 2006). For example, in Minnesota, the tallgrass prairie ecosystem once covered 1/3 of the state and now < 2% of that area remains as tallgrass prairie (Minnesota Prairie Plan Working

Group 2011) and >90% of the loss of tallgrass prairie results from conversion to row-crop agriculture. Other grassland-cover types are also declining across many agricultural landscapes; in Minnesota agricultural grasslands such as hay, pasture, and small grain crops were lost at a rate of 6% per year from 1987-1997 (Guidice and Haroldson 2007). Although the spread of row-crop agriculture is typically negatively associated with greater prairie-chicken abundance, a small amount of agriculture conversion amid extensive grasslands seems to benefit greater prairie-chicken populations by providing both plentiful food and cover, as can be seen with the expansion of the range of greater prairie-chickens statewide in response to European settlement in the late 1800s (Partch 1973; Svedarsky et al. 1997). However when agriculture row-crop becomes the dominate land-cover, grasslands become subsequently more isolated and the area becomes less suitable for greater prairie-chickens.

Greater prairie-chicken conservation in Minnesota and elsewhere has focused on maintaining and re-establishing grassland-cover types within large landscapes. Prairie-chickens use grasslands during all portions of their life history, including for nesting, brood rearing, roosting, concealment from predators, mating rituals, and foraging (Kobriger 1965; Merrill et al. 1999; Niemuth 2000). Prairie grouse (greater prairie-chickens, lesser prairie-chickens [*T. pallidicinctus*], and sharp-tailed grouse [*T. phasianellus*]) are generally resident, area-sensitive, and usually settle near their natal areas; for example, greater prairie-chickens have been found to occur within an ~2-km radius surrounding leks (Merrill et al. 1999; Niemuth 2011) throughout their breeding cycle. Therefore, landscape characteristics such as amount, types, and configuration of land-cover are expected to have a large effect on the presence, abundance, and persistence of greater prairie-chickens at various spatial scales (Merrill et al. 1999; Niemuth 2000; Niemuth 2003; Larson and Bailey 2007; Niemuth 2011; Hovick et al. 2015a).

In the face of loss, fragmentation, and isolation of tallgrass prairie and other grassland-cover types, federal and state agricultural policy and programs have the potential to influence prairie-chicken abundance and distribution in landscapes with extant greater prairie-chicken populations. Specifically, the Conservation Reserve Program (CRP) can dramatically influence the amount of grassland in an agriculture-dominated landscape. The CRP is the largest federal private land retirement program in the United States (Stubbs 2014). Established in 1985, the CRP is authorized to remove land from crop production with the objectives to reduce soil erosion, improve water quality, and restore and protect wildlife habitats by providing financial incentives to reseed agricultural land to sod-forming or ecologically native vegetation for a period of 10 to 15 years. A variety of CRP programs focus on different types of wildlife habitat restoration including field buffers, bottomland hardwood forestland, pollinator habitat, restoring farmed wetlands, and riparian habitat (Riley 2004), some of which can increase the amount of tallgrass prairie and other grassland-cover types in agricultural landscapes. Greater prairie-chickens have been listed as one of the high priority species identified in the Back Forty Pheasant Habitat CRP-SAFE practice (USDA 2008). However, even programs that are not focused specifically on greater prairie-chickens may offer an important opportunity for habitat reconstruction as large contiguous tracts of land are enrolled and restored to grasslands (Riley 2004; Herkert 2009).

Although the protection and restoration of wildlife habitat is a stated objective of the CRP, the relationship between grassland CRP enrollments, landscape composition, and greater prairie-chicken populations at multiple spatial scales is not well understood. Merrill et al. (1999) reported that the CRP likely had a role in providing greater prairie-chicken habitat, based on observation of significantly larger amounts of CRP grassland in a 1.6-km radius area surrounding leks than random non-lek points in northwestern Minnesota. Merrill et al. (1999) also reported that smaller amounts of residential areas, farmsteads, and forests and greater amounts of CRP grassland were associated most strongly with presence of greater prairie-chicken leks. Additionally, Niemuth (2003) identified suitable landscapes for greater prairie-chicken translocation in Wisconsin and described landscapes surrounding lek sites as consisting of a larger amount of grassland and wetland-cover types and less forest and forage crops (e.g., alfalfa and hay) than landscapes surrounding random non-lek points within suitable cover and within 32 km of a known lek, the maximum distance observed between leks. However, Niemuth (2003) did not explicitly address grassland CRP composition, but rather included it as part of the grassland land-cover classification, so the specific impact of grassland CRP is unclear. Similar studies (i.e., Niemuth 2000; Larson and Bailey 2007; Hovick et al. 2015a) also link greater prairie-chicken presence, abundance, and persistence with the amount, types, and configuration of land-cover, but no other published studies specifically address specific relationships with CRP.

For a variety of reasons, area enrolled in the CRP has declined nationwide since its peak enrollment of approximately 149,000 $km^2$ in 2007 (Stubbs 2014). This decrease is scheduled to continue as the 2014 Farm Bill decreased the enrollment cap from approximately 130,000 $km^2$ to < 100,000 $km^2$ by 2018 (Stubbs 2014). In the greater prairie-chicken range in Minnesota, area enrolled in the CRP (all Conservation Practice codes) declined 16-52% across 17 established survey blocks in the last 11 years (Roy 2014), but how prairie-chicken populations have responded to loss of CRP grassland is not well documented or understood.

My objective was to quantify the relationship between greater prairie-chicken populations, CRP enrollments, and the resulting landscape structure in northwestern Minnesota at multiple spatial scales. Understanding this relationship at multiple spatial scales can provide insight into the role and importance of CRP for greater prairie-chicken habitat restoration and protection, and inform efforts to target CRP enrollments where they will be most effective for greater prairie-chicken conservation both at the landscape and lek scales. To address this objective, I modeled the relationship between population metrics of greater prairie-chickens (i.e., leks/$km^2$, males/lek, persistence, and stability) and landscape metrics (i.e., composition, contiguity, and fragmentation) at the landscape and lek scales. Based on previous studies, I expected that greater prairie-chicken abundance and lek persistence and stability would be associated with extent and distribution of CRP enrollments that result in grassland-cover types in an agricultural landscape in northwestern Minnesota.

## METHODS

### Study Area and Greater Prairie-Chicken Survey Data

I focused on greater prairie-chicken—habitat relations in the portion of northwestern Minnesota that currently supports greater prairie-chicken populations and where prairie-chickens have been surveyed annually using standardized protocols beginning in 2004 (Fig. 1, Minnesota Department of Natural Resources, unpublished data). As part of the standardized survey coordinated by the Minnesota Department of Natural Resources, 17 41-$km^2$ blocks were systematically surveyed for prairie-chicken leks from 2004-2016. These blocks provide a unique opportunity to analyze a diversity of habitat composition and land-management approaches as they were non-randomly selected to represent different grassland land ownerships that vary in management approaches across the greater prairie-chicken range (Guidice 2004) in Minnesota. Two of the 17 blocks were comprised of a majority of state and federally managed lands, 5 blocks were mostly under CRP contract in 1997, and 10 blocks had a mixture of CRP, state, federal, and The Nature Conservancy (TNC) lands.

Annual surveys of greater prairie-chickens were coordinated by the Minnesota Department of Natural Resources and executed in collaboration with the Minnesota Prairie-chicken Society, The Nature Conservancy, U. S. Fish and Wildlife Service, and other volunteers. Data from the greater prairie-chicken spring survey consisted of count and location information for leks from 2004-2016 within established survey blocks (Fig. 1). The survey protocol consisted of surveyors being assigned 4 Public Land Survey (PLS) sections within a survey block and attempting to observe mating display behavior repeatedly in these sections. Surveyors observed mating display behavior visually with the use of binoculars and counted the number of males, females, and prairie-chickens of unknown sex at each visit to each lek. Prairie-chickens displaying at leks were recorded as males; if no prairie-chickens displayed at the lek or the prairie-chickens on the lek were flushed before displaying was observed, individuals present at leks were recorded as unknown sex (Roy 2014). Location data were available for 58-114 leks per year within these survey blocks, typically recorded to the level of quarter-section or GPS coordinates. From these data, I derived 2 scales of analysis: survey-block and lek scale. The survey-block scale refers to the entirety of the 41-$km^2$ blocks; the lek scale considers a fixed buffer of 2 km around each recorded lek location to represent the breeding-cycle habitat radius of greater prairie-chickens (Merrill et al. 1999; Hovick et al. 2015a). Lek data from outside the survey blocks were also available, but survey effort outside of survey blocks was not consistent annually.

ArcGIS (ESRI 2015) shapefiles existed for lek locations during 2004-2009 and 2013-2016. I reconstructed shapefiles of existing survey data from 2010-2012 by converting public land survey (PLS) coordinates collected by survey volunteers into UTM point coordinates in ArcGIS and placing coordinates in the centers of quarter-sections and sections. I then derived population metrics at both survey-block and lek scales in ArcGIS. For these metrics, I considered a lek to be >1 displaying male for the survey location at ≥1 of the years surveyed (Schroeder and Braun 1993; Merrill et al. 1999). At the lek-scale I considered the number of males/lek as the dependent variable. At the survey-block scale I used the number of leks/$km^2$ in each of the 17 survey blocks. The metrics of males/lek and leks/$km^2$ have been previously used as indices of greater prairie-chicken population size and habitat quality (Hamerstrom and Hamerstrom 1973; Niemuth 2011).

I also examined lek stability by calculating the number of consecutive years that a lek had >1 displaying males (Schroeder and Braun 1993) and persistence of a lek by calculating the number of years that >1 male displayed throughout the study period (Merrill et al. 1999). Because the majority of the survey lek locations was accurate to the quarter-section level, I considered the measures of lek stability and persistence at that level and combined all recorded lek locations within a given quarter section (Merrill et al. 1999; Hovick et al. 2015a). If lek locations were only recorded to the accuracy of the section, I examined notes included with lek observations and surrounding lek locations in the current and previous and later years to more precisely estimate lek locations. If I could not estimate a more accurate lek location from the survey data or if the survey data indicated the lek was truly at the center of the section, I placed the lek location in the center of the section. This occurred in approximately 4% of the recorded leks. In addition, to reduce error due to drift of lek sites between years, I created a 250-m buffer around lek locations (Hovick et al. 2015a). If a lek site with high fidelity was not recorded in a particular year, I examined the distance to the nearest lek the following year. If the 250-m buffers of the 2 leks overlapped, I combined lek sites based on the assumption that the same group of birds used both leks between years.

**Land-Cover Data**

I obtained shapefiles for CRP enrollments and corresponding conservation practice codes within the survey blocks from Farm Service Agency (FSA) for 1997, 2006-2011, and 2013-2016. Shapefiles had data missing from the years 2004, 2005, and 2012 and for some locations in 2 counties (Polk and Otter Tail counties). I reconstructed the missing data for those years in ArcGIS by examining contract expiration dates provided in the available shapefiles and aerial photography. I also analyzed contract inconsistencies (e.g., different expiration dates recorded or a break in the enrollment in contract data but consistent aerial photography coverage) in years with provided shapefiles and reconstructed these inconsistences, as necessary. During June-August

2016, I visited and verified mapped areas of CRP enrollment reconstruction within survey blocks to insure that land-cover data were correct. Because the shapefiles obtained from FSA included all CRP practice codes within survey blocks, I distinguished the CRP practice codes that provide grassland-cover types used by greater prairie-chickens (Table 1) using classification categories of Nielson et al. (2008) and Drum et al. (2015).

Because CRP grasslands are not the only land-cover type that provides suitable greater prairie-chicken habitat in northwestern Minnesota, I also identified and quantified non-CRP grassland-cover within the study area during the period 2004-2016. To delineate other cover types, I examined infrared imagery; LiDAR data layers; the Minnesota Land-cover Classification (MLCC) and Impervious Surface Area by LANDSAT and LiDAR: 2013 Update; NASS Cropscape Cropland Data Layer (CDL) and National Land-cover Database (NLCD) land-cover in ArcGIS; and histories of state-, federal-, and TNC- managed areas within the study area. The MLCC layer is a raster-based land-cover data set for the state of Minnesota with 15-m accuracy (UMN-MLCC 2013). The CDL land-cover data layer is a raster-based, geo-referenced, crop-specific land-cover data layer with 30-m accuracy. The source of the CDL non-agricultural land-cover classes relies on the most recently released NLCD for that year (i.e., 2001, 2006, or 2011; USDA-NASS 2015). To determine the best land-cover classification to use for each year of my study period, I compared the accuracy of each land-cover data layer at classifying known areas of grassland (e.g., grassland CRP contracts or state-, federal-, and TNC-managed areas) by placing 200 random points within known areas of grassland and extracting the land-cover value at those points. I reclassified the land-cover data layers in each of the 17 survey blocks for each of the 13 years of my study period into 7 vegetation classes with 30-m accuracy (Appendix A). I also classified grassland and wetland-cover types into 3 more-specific categories of CRP; state-, federal-, and TNC-managed areas; and other sources (i.e., sources of grassland and wetland that didn't fall into the other 2 categories, e.g., CRP or state-, federal-, and TNC-managed areas), based on the histories of CRP contracts and state-, federal-, and TNC-managed areas.

I verified my reclassification of CRP and state-, federal-, and TNC-managed grassland and wetland and other known natural cover types (i.e., forest, shrubland, and open water) in state-, federal-, and TNC-managed areas by visiting 500 random points in the 17 survey blocks during June-August 2016. I placed 200 points randomly, stratified by CRP program type (e.g., CP 1, Establishment of Permanent Introduced Grasses & Legumes) and then placed the remaining 300 points by including ≥50 random points in each cover type placed within a 50-m buffer of a road in ArcGIS (Nelson 2010; Nelson and Andersen 2013). I then located and identified the cover type at each random point ≤ 50 m from a perpendicular distance from the road with the aid of a laser rangefinder (Nelson 2010; Nelson and Andersen 2013).). I did not evaluate classification accuracy for remaining cover classes (i.e., cropland, developed/barren land) because these land-cover types did not occur within the reclassification of CRP and state-, federal-, and TNC-managed areas, except that I confirmed the rare food plots in state-, federal, or TNC-managed areas by calling the managers of these properties. I calculated the accuracy of my reclassification of CRP and other cover types within state-, federal-, and TNC-managed areas by using error matrices and the Kappa statistic (Congalton and Green 1999). Because the 2016 CDL layer was released in January 2017 and I collected ground-truth data during June-August 2016, I used ground-truth data collected from a map created with the 2015 CDL layer. Nineteen of the original 500 data points were unusable because they were not within a 50-m buffer of a road in the updated map.

Following cover-type reclassification, I used FRAGSTATS spatial pattern analysis program (McGarigal et al. 2012) to calculate landscape metrics potentially related to abundance of greater prairie-chickens at both the survey-block and lek scales. Based on habitat—prairie-chicken relations from previous studies (e.g., Merrill et al. 1999; Niemuth 2000) and published information concerning greater prairie-chicken ecology (e.g., Stempel and Rodgers 1961; Niemuth 2011), I considered the following composition, contiguity, and fragmentation metrics (Table 3) of each land-cover class for each survey block or lek buffer:

<u>Composition:</u> Total area (ha) and percent landscape

I calculated the total area (ha) of each land-cover type in each survey block and the percent landscape of each land-cover type in each lek buffer (Table 3) using FRAGSTATS (McGarigal et al. 2012). I also considered transformations of the total area of grassland to allow for a non-linear response of greater prairie-chicken populations to amount of grassland at the survey-block or lek scale (Larson and Bailey 2007; Niemuth 2011). I also calculated the ratio of cropland to grassland at both scales to allow for a relationship where greater prairie-chickens may tolerate and benefit from some amount of conversion to cropland (similar to providing food plots), but then decline when cropland far exceeds grassland (Stempel and Rodgers 1961).

<u>Contiguity:</u> Contiguity Index

The contiguity index represents the size and connectivity of patches of a given land-cover type on a scale of 0 to 1. Large, contiguous patches result in contiguity index values closer to 1. I used the area-weighted mean of these patches of the same land-cover type at each scale to calculate the contiguity index for each land-cover type (McGarigal et al. 2012). I only considered the contiguity of land-cover types that were positively associated with greater prairie-chicken abundance (i.e., wetland and grassland-cover types, based on assessment of models only including composition covariates; see below).

Fragmentation: Number of patches

Number of patches sums the number of patches of a given land-cover type at the survey-block or lek scale. An increased number of patches represents an increase of fragmentation of a given land-cover type. I only considered the effect of fragmentation on land-cover types that were positively associated with greater prairie-chicken abundance (i.e., wetland and grassland-cover types, based on assessment of models only including composition covariates).

**Data Analysis**

I assessed models relating greater-prairie chicken population metrics (i.e., leks/km$^2$, males/lek, persistence and stability of leks) to landscape metrics using a layered approach in an information-theoretic framework (Burnham and Anderson 2002) based on Akaike's Information Criterion (AIC) values (Akaike 1973). I created multiple models of greater prairie-chicken metrics for each of 3 levels (composition, contiguity, and fragmentation; Table 3) and scale (survey-block and lek) *a priori* to evaluating models. I included covariates in models based on findings of previous studies and knowledge of greater-prairie chicken ecology. I evaluated the same set of mixed-effect models for the survey-block and lek scales, but used lek/km$^2$ as the response variable for the survey-block scale and the log transformation of males/lek and persistence and stability of each lek as the response variables at the lek scale. I derived values of composition, contiguity, and fragmentation covariates for each year during the period 2004-2016 and considered these to be fixed (Table 3). I considered each survey block (or lek, depending on analysis) and year as random effects in models because these are not the effects of primary interest.

I first evaluated models with covariates related to cover-type composition and identified the best-supported model (lowest AIC value) of greater prairie-chicken population metrics. I then used this model as the baseline model to assess covariates related to cover-type contiguity to again identify the best-supported model of greater prairie-chicken population metrics that included both composition and contiguity. I repeated this process using the best-supported model that considered both composition and contiguity covariates as the base model to evaluate fragmentation covariates, in a layered process similar to that used by Amundson and Arnold (2010) and Daly et al. (2015). I considered competing models as any model with $\Delta$AIC $\leq 2$ compared to the best-supported model. I considered composition, contiguity, and fragmentation metrics in that order based on published information regarding greater prairie-chicken ecology and results of previous studies of greater prairie-chicken--habitat relations (Table 4). I used $k$-fold cross validation ($k = 5$, iterations = 100) and the normalized root-mean-square error (NRMSE) of the best-supported models at the survey-block and lek scales to assess model accuracy. The *a priori* suite of models included 1 baseline model (random effects only), 11 composition models, 7 contiguity models, and 4 fragmentation models (Table 4).

## RESULTS

I created models at the survey-block and lek scales from 13 years of data collected in 17 survey blocks. At the survey-block scale, the number of leks/km$^2$ ranged from 0.02 to 0.32. At the lek scale, males/lek ranged from 2 to 67 at 311 different leks. Persistence and stability of leks ranged from 1 to 13.

### Land-Cover Classification Accuracy

I classified land-cover at 481 of 500 points placed randomly to assess cover–type classification accuracy (19 points were unusable after creation of a new land-cover map for 2016 after release of 2016 CDL layer in January 2017). Based on these points, I calculated the overall accuracy, the user's accuracy, and the producer's accuracy. The overall accuracy represents percentage of correctly classified points from all random points surveyed. Overall accuracy of known grassland-cover types in 2016 was 74% (Kappa-statistic = 0.64, Table 2). User's accuracy assesses the commission error, or the probability classifying a point in a category when it does not belong in that land-cover category. The user's accuracy of classification of the 5 land-cover types I assessed ranged from 50% (shrubland) to 84% (grassland). Producer's accuracy assesses the omission error or the probability of excluding a point from the classification to which it belongs. The producer's accuracy of classification of these 5 land-cover types ranged from 47% (forest) to 87% (wetland and open water).

### Survey-Block Scale Model

The best-supported composition model of leks/km$^2$ at the survey-block scale included area of CRP grassland; the area of state-, federal-, and TNC-managed grasslands; the area of CRP wetland; the area of state-, federal-, and TNC-managed wetlands; and the area of “other” wetlands (Table 4). One model was competitive ($\Delta$AIC= 0.38) with the best-supported model, and included the area of “other” grasslands as an additional covariate.

I used the best-supported model at the composition level as the baseline model to assess contiguity covariates. Two models at the contiguity level had a lower AIC than the best-supported (baseline) model from the composition level (Table 4); the best-supported model included grassland contiguity. One model was competitive ($\Delta$AIC= 1.04) with the best-supported model, and included contiguity of wetlands as an additional covariate.

I used the best-supported model at the contiguity level as a baseline model to assess fragmentation covariates. Two models at the fragmentation level had a lower AIC than the best-supported model from the contiguity level (Table 4); the best-supported model included the number of grassland patches and the number of wetland patches. One model was competitive ($\Delta$AIC= 1.16) with the best-supported model, and did not include the number of wetland patches as an additional covariate.

The best-supported model of leks/km$^2$ at the survey-block scale when considering all 3 levels (composition, contiguity, and fragmentation) included the area of CRP grassland; the area of state-, federal-, and TNC-managed grasslands; the area of CRP wetland; the area of state-, federal-, and TNC-managed wetland; the area of “other” wetlands; the contiguity of grasslands; and the number of patches of grasslands and wetlands in each survey block in each year (Table 4). Based on *k*-fold validation, this best-supported model had an average NRMSE of 13.15% (SD = 0.27%).

### Lek-Scale Model

At the lek scale [log(males/lek)], the best-supported model among those considered with composition metrics included the percent area CRP grassland; the percent area of state-, federal-, and TNC-managed grasslands; the percent area of CRP wetland; the percent area of state-, federal-, and TNC-managed wetlands; the percent area of “other” wetlands; the percent area of forest; the percent area of developed; and the percent area of shrub (Table 5). One model was competitive ($\Delta$AIC= 1.59) with the best-supported model, and included the percent area CRP grassland; the percent area of state-, federal-, and TNC-managed grasslands; the percent area of CRP wetland; the percent area of state-, federal-, and TNC-managed wetlands; and the percent area of “other” wetlands.

I used the best-supported model at the composition level as a baseline model to consider contiguity covariates. Three models at the contiguity level had a lower AIC than the best-supported model from the composition level (Table 5). The best-supported model at the contiguity level included the contiguity of CRP grassland. Two competing models were identified at the contiguity level. The first ($\Delta$AIC= 0.41) included the contiguity of CRP grassland; the contiguity of state-, federal-, and TNC-managed grasslands; and the contiguity of “other” grasslands. The second ($\Delta$AIC= 1.96) included the contiguity of CRP grassland and CRP wetland.

I used the best-supported model at the contiguity level as a baseline model to evaluate fragmentation covariates. No models at the fragmentation level had a lower AIC value than the best-supported model from the contiguity level (Table 5). Therefore, the best-supported model of males/lek (log transformed) at the lek scale included the percent area CRP grassland; the percent area of state-, federal-, and TNC-managed grasslands; the percent area of CRP wetland; the percent area of state-, federal-, and TNC-managed wetlands; the percent area of "other" wetlands; the percent area of forest; the percent area of developed; the percent area of shrub; and the contiguity of grassland CRP (Table 5). This model had an average NRMSE of 17.38% (SD= 0.11%). Finally, I constructed models at the lek scale of lek persistence and stability in the same layered approach as for males/lek. However, no models at the composition, contiguity, or fragmentation level had a lower AIC value than the model with only random effects (lek and year).

## DISCUSSION

The CRP and other land-conservation programs that commonly occur within an agriculture-dominated landscape have the potential to influence greater prairie-chicken ecology and abundance by dramatically influencing the amount and configuration of grassland (e.g., Merrill et al. 1999; Niemuth 2003). Results from my models suggest increased abundance of leks and the number of males per individual leks of greater prairie-chickens are related to the extent and configuration of CRP enrollments in the agricultural landscape of northwestern Minnesota. These results indicate that increasing the quantity of grassland and wetland CRP contracts throughout the existing range of greater prairie-chickens in northwestern Minnesota and specifically aggregating CRP grassland contracts in areas of known lek sites may increase greater prairie-chicken abundance. Additionally, my results suggest that grassland and wetland CRP play an important role in contributing to the contiguity and reducing fragmentation of grassland- and wetland-cover types at a larger landscape scale.

**Survey-Block Scale Model**

At the survey-block scale, the density of greater prairie-chicken leks (leks/$km^2$) over a 13-year period was related to the composition, contiguity, and fragmentation of land-cover types, particularly the amount and distribution of grassland and wetland-cover types. The amount of grassland- and wetland-cover types was an important predictor of lek density (leks/$km^2$). The importance of the amount of grassland cover is consistent with the majority of existing literature (Niemuth 2000; Niemuth 2003; Larson and Bailey 2007; Niemuth 2011; Hovick et al. 2015a), as the amount of grassland cover is typically thought of as the resource limiting greater prairie-chicken abundance. Although not generally thought of as high-quality habitat for greater prairie-chickens, my findings and several other studies (Niemuth 2000; Niemuth 2003) indicate that the amount of wetland cover may also be an important component of prairie-chicken habitat, at least in the landscapes of northwestern Minnesota.

At the composition level, the amount of grassland- and wetland-cover types in different ownership categories (i.e., CRP, state/federal/TNC, and "other") were important predictors of leks/$km^2$, likely because these different ownership categories varied in their management through the study period. For example, once state/federal/TNC areas are established, they were likely to have consistent management goals over the study period. Conversely, CRP areas may be established and then change to cropland as contracts expire after 10-15 years after particular contract enrollment. The direction of the relationship of these covariates with lek/$km^2$ were all positive with the exception of "other" wetlands (Table 6). Because all of these grassland and wetland ownership categories presumably provide suitable herbaceous land-cover for greater prairie-chickens, I did not expect the amount of "other" wetland to have a negative relationship with lek/km$^2$. However, management priorities differ among the 3 management categories (i.e., CRP, state/federal/TNC, and "other"). Whereas CRP contracts and state/federal/TNC managed properties have management plans to facilitate wildlife conservation, the "other" category is not necessarily managed with wildlife conservation as a priority; upon examination of aerial photography, these "other" wetland types were comprised primarily of wet areas within pasture and hay fields. The type and timing of management activities in these "other" areas may have an adverse effect on greater prairie-chicken lek density. For example, herbaceous cover in agricultural grassland sources may be subject to overgrazing or removed by haying multiple times throughout the year, but CRP contracts and state/ federal/TNC managed properties have management restrictions preventing the removal of cover during the nesting period (USDA 2008). The best-supported model at the composition level did not include "other" grasslands, which included agricultural grassland such as pasture and hay fields. Although greater prairie-chickens are grassland obligate birds, these grassland-cover types may not meet the habitat needs of greater prairie-chickens and may serve as sink habitat on the landscape (Niemuth 2003).

Both contiguity and fragmentation of suitable herbaceous-cover types (i.e., grasslands and wetlands) were related to prairie-chicken lek density, but ownership (or management goals) of grasslands and wetlands was not as important as they were for composition. Greater prairie-chickens are thought to be area sensitive, in that they require large patches of suitable habitat (Niemuth 2003; Niemuth 2011), and federal properties tended to be larger than other land ownerships within specific survey blocks. However, the relationship of wetland contiguity to lek/km$^2$ was negative, and the relationship of leks/km$^2$ to fragmentation or number of patches of wetland was positive. There are multiple explanations for these relationships: First, herbaceous wetlands may act as a supplementary source of suitable land cover whereas grasslands are acting as the primary source. Second, there is considerable ambiguity in remote sensing between grasslands and wetlands; 85% of the misclassified wetland points were grassland and 77% of the misclassified grassland points were wetland. The error caused by misclassification may exaggerate the extent of wetland fragmentation by creating a patchier herbaceous-land-cover matrix than what is actually occurring on the landscape. Because of this tendency to confound wetlands and grasslands in my cover-type classification, it may be that the apparent positive relationship between lek density and fragmentation is spurious. To explore this relationship further, it may be useful to combine wetland and grassland-land-cover classifications in a single “herbaceous cover” classification to decrease fragmentation caused by misclassification. Finally, these observed relationships may also be due to the type or size of wetland. Different types of wetlands (e.g., seasonally flooded wetland, wet meadows, marshes, swamps, bogs) have varying vegetation characteristics, amounts of water supported throughout the year, and in turn, differing contiguity. Additionally, these characteristics also make some wetlands more suitable as greater prairie-chicken habitat than others. Small wetlands with shallow water may be considered classified as less contiguous than large open-water wetlands but are much more suitable for greater prairie-chickens.

**Lek-Scale Model**

At the lek scale, the number of greater prairie-chicken males/lek over a 13-year period was related to the composition and contiguity, but not the fragmentation of land-cover types, with the amount of grassland- and wetland-cover types being important predictors of males/lek. Similar to the survey-block scale, this finding may result from the classification of grassland that included grassland-cover types associated with agriculture (i.e., hay and pasture), which may serve as sink habitat for greater prairie-chickens (Niemuth 2003). As is the case for similar associations at the survey-block scale, the amount of suitable habitat (i.e., grassland and wetland types) is also associated with lek-scale abundance of greater prairie-chickens (Niemuth 2000; Niemuth 2003; Larson and Bailey 2007; Niemuth 2011; Hovick et al. 2015a).

The relationships observed between grassland and wetland area were the same as at the survey-block scale and indicate that at both scales, different types of ownership of suitable cover (i.e., grassland and wetland types) do not have the same relationship with abundance of greater prairie-chickens. At both the survey-block and lek scales, greater amounts of grassland and wetland CRP and state/federal/ TNC managed areas had a positive relationship with abundance of greater prairie-chickens. This is similar to the conclusions of Merrill et al. (1999), who reported that leks were located in areas with greater amounts of CRP than found at randomly selected non-lek sites; however, Merrill et al. (1999) drew no conclusions specifically regarding publicly (e.g., state, federal, or TNC) managed grasslands or wetlands or abundance of leks. Additionally, at both the survey-block and lek scales, categories of grassland not enrolled in the CRP or publically managed (e.g., state, federal, or TNC) were not important predictors of lek abundance and sources of grassland not enrolled in the CRP did not have a positive relationship with abundance of greater prairie-chickens. This is likely because the category of "other" grassland and wetland indicated areas of herbaceous cover such as pasture and hay fields that may serve as sink habitat on the landscape (Niemuth 2003).

Negative relationships between males/lek and forest and developed areas, and positive relationships with shrublands, are consistent with other studies. (Merrill et al. 1999; Hovick et al. 2015a). Both reported that lower amounts of developed and forested areas were important predictors of presence of lek sites, but did not specifically report on abundance of greater prairie-chickens. However, Merrill et al. (1999) reported that the amount of grass-shrub land-cover was not a significant predictor of the presence of leks, and Hovick et al. (2015a) did not include shrubland land-cover in their analysis. Conversely, Niemuth (2000) reported that the proportion of shrubland was higher in areas around leks than random points and also found the proportion of forested area around leks was lower than around random points, but did not include a developed-land-cover class in his analysis. My findings are consistent with what are thought to be key ecological needs of greater prairie-chickens. Because greater prairie-chickens tend to remain near their natal areas, the lek scale represents the area in which all requirements of a greater prairie-chicken's life cycle must be met (Merrill et al. 1999; Niemuth 2011). Although greater prairie-chickens may not use shrubby areas for display sites, shrub-dominated-cover types are an important component of winter habitat, in that prairie-chickens use these cover types for winter roosting (Hamerstrom et al. 1957) and nesting (Niemuth 2000). Additionally, greater prairie-chickens select nesting and display sites that are generally treeless (Hovick et al. 2015a; Hovick et al. 2015b); therefore the presence of trees at the lek scale is an indicator of poor quality breeding habitat.

The relationship between the contiguity of all grassland-cover types and males/lek was positive, which is consistent with the well-accepted idea that greater prairie-chickens are area sensitive, or that they require large aggregations of appropriate cover types that together provide suitable habitat (Niemuth 2003; Niemuth 2011). However, the relationship between CRP wetland and the number of males at leks was negative in my assessment, with higher numbers of males associated with less connected CRP wetland surrounding leks. This negative relationship is likely because herbaceous wetlands serve as supplementary and not primary habitat for greater prairie-chickens, and occur as smaller, less connected patches within the herbaceous land-cover matrix. The best-supported model of males/lek included only the contiguity of CRP grassland, indicating that aggregating CRP grassland contracts in areas of known lek sites may increase greater prairie-chicken abundance. This highlights the importance of protecting existing and establishing new contiguous CRP grassland contracts in areas immediately surrounding known lek locations to maintain or increase the number of males/lek.

**Management Implications**

Greater prairie-chickens have been targeted by the FSA as a high-priority wildlife species in several conservation programs and by the Minnesota Department of Natural Resources as a Species of Special Concern. However, the relationship between CRP enrollments and other land-management programs and greater prairie-chicken populations has never been quantified and is not well understood. My research provides new insight into the importance of the type of ownership at both the survey-block and lek scales. At both scales, amount of CRP and state/federal/TNC managed grasslands and wetlands were positively related to both lek density (lek/km$^2$ at the survey-block scale) and the number of males at leks (males/lek at the lek scale). In addition, fewer, more contiguous patches of grassland were positively related to higher lek density. At the lek scale, the contiguity of grassland CRP was a significant predictor of lek size. Based on these results, management efforts that focus on enrolling contiguous grassland CRP contracts at the lek scale around known lek sites are likely to increase greater prairie-chicken abundance at both the survey-block (lek/km$^2$) and lek (males/lek) scales. At the lek scale, management efforts that protect known lek sites from encroachment of forested and developed areas are likely to increase or maintain the number of males at individual leks.

Table 1. All Conservation Reserve Program (CRP) practice codes in northwestern Minnesota greater prairie-chicken survey blocks provided by the Farm Service Agency classified into categories of CRP grassland, CRP forest, and CRP wetland.

| CRP Practice Code | CRP Practice Name |
|---|---|
| ***CRP Grassland*** | |
| CP1 | Establishment of Permanent Introduced Grasses & Legumes |
| CP10 | Vegetative Cover - Grasses Already Established |
| CP12 | Wildlife Food Plot |
| CP18 | Establishment of Permanent Vegetation to Reduce Salinity |
| CP18B | Establishment of Perm. Vegetation to Reduce Salinity, Non-easement |
| CP18C | Establishment of Perm. Salt Tolerant Vegetative Cover, Non-easement |
| CP2 | Establishment of Permanent Native Grasses |
| CP21 | Filter Strips |
| CP25 | Restoration of Rare & Declining Habitat |
| CP38E | SAFE – Grass |
| CP42 | Pollinator Habitat |
| CP4D | Permanent Wildlife Habitat, Non-easement |
| CP8A | Grass Waterways, Non-easement |
| ***CRP Forest*** | |
| CP11 | Vegetative Cover - Trees Already Established |
| CP16 | Shelterbelt Establishment |
| CP16A | Shelterbelt Establishment, Non-easement |
| CP17 | Living Snow Fence |
| CP22 | Riparian Forest Buffer |
| CP35E | Emergency Forestry – Bottomland Hardwood, New |
| CP3A | Hardwood Tree Planting |
| CP5 | Field windbreak Establishment |
| CP5A | Field windbreak Establishment, Non-easement |
| ***CRP Wetland*** | |
| CP23 | Wetland Restoration |
| CP23A | Wetland Restoration, Non-flood Plain |
| CP27 | Farmable Wetland |
| CP28 | Farmable Wetland Associated Buffer |
| CP30 | Marginal Pastureland Wetland Buffer |

Table 2. Land-cover classification error matrix in known categories of grassland within the northwestern Minnesota study area in 2016. Rows are classification of points from the derived land-cover map and columns indicate classification of a random point based on a visit to that point during June-August 2016. Total accuracy indicates the total proportion of map points correctly classified based on visits to random points. User's accuracy is the proportion of map points of each cover type correctly classified of the total number claimed to be in that map class (e.g., GIS-identified wetland points deemed to be classified correctly in visits/total points wetland-cover type identified in GIS). Producer's accuracy is the proportion of map points correctly classified of the total number observed in that class (e.g., GIS-based points correctly classified as wetland-cover type in visits/total points wetland-cover type identified in GIS and visited).

| | Ground Truth Land-cover | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Land-Cover Classification** | **Wetland** | **Shrubland** | **Open Water** | **Forest** | **Grassland** | **User's Accuracy By Class (%)** | **Producer's Accuracy By Class (%)** | **Total Accuracy of All Classes (%)** |
| Wetland | 132 | 8 | 3 | 12 | 24 | 73.7 | 86.8 | |
| Shrubland | 0 | 31 | 0 | 31 | 0 | 50.0 | 59.6 | |
| Open Water | 1 | 2 | 45 | 6 | 0 | 83.3 | 88.2 | |
| Forest | 2 | 8 | 3 | 43 | 7 | 68.3 | 46.7 | |
| Grassland | 17 | 3 | 0 | 0 | 107 | 84.3 | 77.5 | |
| | | | | | | | | 74.4 |

Table 3. Land-cover covariates at each level of model development of greater prairie-chicken (GRPC) abundance in northwestern Minnesota and their hypothesized relationship and rationale.

| Acronym | | Hypothesized Relationship to GRPC Metrics | Rationale |
|---|---|---|---|
| **Composition:** Area or percent area within each survey block or lek buffer | | | |
| CGA | Categorized as grassland CRP | Higher density associated with higher area | Merrill et al. 1999; Niemuth 2003 |
| PGA | Categorized as state, federal, TNC grassland | Higher density associated with higher area | Niemuth 2000; Niemuth 2003; Hovick et al. 2015a |
| OGA | Categorized as "other" grassland (e.g., hay and pasture) | Lower density associated with higher area | Niemuth 2003 |
| CWA | Categorized as wetland CRP | Higher density associated with higher area | Merrill et al. 1999 |
| PWA | Categorized as state, federal, TNC wetland | Higher density associated with higher area | Niemuth 2000; Niemuth 2003 |
| OWA | Categorized as "other" wetland (e.g., wet areas in pasture or hay fields) | Higher density associated with higher area | Niemuth 2000; Niemuth 2003 |
| FA | Categorized as forest | Lower density associated with higher area | Merrill et al. 1999; Niemuth 2000; Hovick et al. 2015a |
| DA | Categorized as developed | Lower density associated with higher area | Merrill et al. 1999; Larson and Bailey 2007; Hovick et al. 2015a |
| SA | Categorized as shrubland | Higher density associated with higher area | Niemuth 2000 |
| CA | Categorized as cropland | Lower density associated with higher area | Niemuth 2000 |
| OA | Categorized as open water | Lower density associated with higher area | non-habitat |
| GA | Categorized as all types of grassland | Higher density associated with higher area, relationship may not be linear | Niemuth 2000; Niemuth 2003; Larson and Bailey 2007; Niemuth 2011; Hovick et al. 2015a |
| WA | Categorized as all types of wetland | Higher density associated with higher area | Niemuth 2000; Niemuth 2003 |
| Ratio | Ratio of area of cropland to area of all types of grassland within each survey block or lek buffer | | Stempel and Rodgers 1961 |
| **Contiguity:** Contiguity index within each survey block or lek buffer | | | |
| GC | All types of categorized grassland | Higher density associated with higher connectivity | Niemuth 2011 |
| WC | All types of categorized wetland | Higher density associated with higher connectivity | Niemuth 2011 |
| CGC | Categorized grassland CRP | Higher density associated with higher connectivity | Niemuth 2011 |

| | | | |
|---|---|---|---|
| CWC | Categorized wetland | Higher density associated with higher connectivity | Niemuth 2011 |
| PGC | Categorized state, federal, TNC grassland | Higher density associated with higher connectivity | Niemuth 2011 |
| PWC | Categorized state, federal, TNC wetland | Higher density associated with higher connectivity | Niemuth 2011 |
| OGC | Categorized "other" grassland (i.e., not CRP or state, federal TNC managed grassland) | Lower density associated with higher connectivity | Niemuth 2011 |
| OWC | Categorized "other" wetland (i.e., not CRP or state, federal TNC managed wetland) | Higher density associated with higher connectivity | Niemuth 2011 |
| **Fragmentation:** Number of patches within each survey block or lek buffer | | | |
| GN | All types of categorized grassland | Higher density associated with lower number of patches | Niemuth 2003 |
| WN | All types of categorized wetland | Higher density associated with lower number of patches | Niemuth 2003 |
| CGN | Categorized grassland CRP | Higher density associated with lower number of patches | Niemuth 2003 |
| CWN | Categorized wetland CRP | Higher density associated with lower number of patches | Niemuth 2003 |

Table 4. Number of parameters (*K*), Akaike's Information Criterion (AIC) value, and model comparisons for composition, contiguity, and fragmentation levels at the survey-block scale of greater prairie-chicken lek density in northwestern Minnesota. ΔAIC compares models at each level of model development whereas $\Delta AIC^{i}$ compares models to the best-supported model of the previous level; negative values indicate a decrease in AIC. Covariate acronyms are presented in Table 3.

<table>
<tr><th rowspan="3">Model</th><th colspan="11">Layer</th></tr>
<tr><th colspan="3">Composition</th><th colspan="4">Contiguity</th><th colspan="4">Fragmentation</th></tr>
<tr><th>K</th><th>AIC value</th><th>Δ AIC</th><th>K</th><th>AIC value</th><th>Δ AIC</th><th>Δ AIC[a]</th><th>K</th><th>AIC value</th><th>Δ AIC</th><th>Δ AIC[b]</th></tr>
<tr><td>CGA+PGA+CWA+PWA+OWA+GC+WN+GN+(1|SB)+(1|YEAR)</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>12</td><td>-785.86</td><td>0</td><td>-2.66</td></tr>
<tr><td>CGA+PGA+CWA+PWA+OWA+GC+GN+(1|SB)+(1|YEAR)</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>11</td><td>-784.70</td><td>1.16</td><td>-1.50</td></tr>
<tr><td>CGA+PGA+CWA+PWA+OWA+GC+CGN+(1|SB)+(1|YEAR)</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>11</td><td>-782.20</td><td>3.66</td><td>1.00</td></tr>
<tr><td>CGA+PGA+CWA+PWA+OWA+GC+CGN+CWN+(1|SB)+(1|YEAR)</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>12</td><td>-780.62</td><td>5.24</td><td>2.58</td></tr>
<tr><td>CGA+PGA+CWA+PWA+OWA+GC+(1|SB)+(1|YEAR)[b]</td><td></td><td></td><td></td><td>10</td><td>-783.21</td><td>0.00</td><td>-2.54</td><td></td><td></td><td></td><td></td></tr>
<tr><td>CGA+PGA+CWA+PWA+OWA+GC+WC+(1|SB)+(1|YEAR)</td><td></td><td></td><td></td><td>11</td><td>-782.17</td><td>1.04</td><td>-1.50</td><td></td><td></td><td></td><td></td></tr>
<tr><td>CGA+PGA+CWA+PWA+OWA+CGC+(1|SB)+(1|YEAR)</td><td></td><td></td><td></td><td>10</td><td>-780.29</td><td>2.92</td><td>0.38</td><td></td><td></td><td></td><td></td></tr>
<tr><td>CGA+PGA+CWA+PWA+OWA+CWC+(1|SB)+(1|YEAR)</td><td></td><td></td><td></td><td>10</td><td>-779.23</td><td>3.98</td><td>1.44</td><td></td><td></td><td></td><td></td></tr>
<tr><td>CGA+PGA+CWA+PWA+OWA+CWC+CGC+(1|SB)+(1|YEAR)</td><td></td><td></td><td></td><td>11</td><td>-778.62</td><td>4.58</td><td>2.05</td><td></td><td></td><td></td><td></td></tr>
<tr><td>CGA+PGA+CWA+PWA+OWA+OGC+PGC+CGC+(1|SB)+(1|YEAR)</td><td></td><td></td><td></td><td>12</td><td>-778.01</td><td>5.20</td><td>2.66</td><td></td><td></td><td></td><td></td></tr>
<tr><td>CGA+PGA+CWA+PWA+OWA+OGC+PGC+CGC+OWC+PWC+CWC +(1|SB)+(1|YEAR)</td><td></td><td></td><td></td><td>15</td><td>-774.39</td><td>8.81</td><td>6.28</td><td></td><td></td><td></td><td></td></tr>
<tr><td>CGA+PGA+CWA+PWA+OWA+(1|SB)+(1|YEAR)[a]</td><td>9</td><td>-780.67</td><td>0.00</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>CGA+OGA+PGA+CWA+OWA+PWA+(1|SB)+(1|YEAR)</td><td>10</td><td>-780.29</td><td>0.38</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>CGA+PGA+CWA+PWA+OWA+FA+DA+SA+(1|SB)+(1|YEAR)</td><td>12</td><td>-778.32</td><td>2.35</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>CA+DA+FA+OA+SA+GA+WA+(1|SB)+(1|YEAR)</td><td>11</td><td>-758.43</td><td>22.24</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>WA+GA+(1|SB)+(1|YEAR)</td><td>6</td><td>-757.50</td><td>23.17</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>GA+(1|SB)+(1|YEAR)</td><td>5</td><td>-757.11</td><td>23.56</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>CGA+OGA+PGA+(1|SB)+(1|YEAR)</td><td>7</td><td>-755.23</td><td>25.44</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>log(GA)+(1|SB)+(1|YEAR)</td><td>5</td><td>-753.15</td><td>27.52</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>$GA^4$+(1|SB)+(1|YEAR)</td><td>8</td><td>-753.03</td><td>27.64</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>WA+(1|SB)+(1|YEAR)</td><td>5</td><td>-746.88</td><td>33.79</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>(CA:GA)+(1|SB)+(1|YEAR)</td><td>5</td><td>-743.54</td><td>37.13</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>(1|SB)+(1|YEAR)</td><td>4</td><td>-743.91</td><td>36.76</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
</table>

[a]Best-supported model at the composition level, [b]Best-supported model at the contiguity level

Table 5. Number of parameters (*K*), Akaike's Information Criterion (AIC) value, and model comparisons for composition, contiguity, and fragmentation model levels of the number of greater prairie-chickens at leks in northwestern Minnesota. ΔAIC compares models at each level of model development whereas ΔAIC[i] compares models to the best-supported model of the previous level; negative values indicate a decrease in AIC. Covariate acronyms are presented in Table 3.

| Model | Layer | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Composition | | | Contiguity | | | | Fragmentation | | | |
| | K | AIC value | Δ AIC | K | AIC value | Δ AIC | Δ AIC[a] | K | AIC value | Δ AIC | Δ AIC[b] |
| CGA+PGA+CWA+PWA+OWA+FA+DA+SA+CGC+CGN+(1\|LEK) +(1\|YEAR) | | | | | | | | 14 | 253.10 | 0.00 | 1.80 |
| CGA+PGA+CWA+PWA+OWA+FA+DA+SA+CGC+GN+(1\|LEK) +(1\|YEAR) | | | | | | | | 14 | 253.26 | 0.16 | 1.97 |
| CGA+PGA+CWA+PWA+OWA+FA+DA+SA+CGC+CGN+CWN +(1\|LEK)+(1\|YEAR) | | | | | | | | 15 | 254.80 | 1.70 | 3.51 |
| CGA+PGA+CWA+PWA+OWA+FA+DA+SA+CGC+WN+GN+(1\|LEK) +(1\|YEAR) | | | | | | | | 15 | 254.81 | 1.72 | 3.52 |
| CGA+PGA+CWA+PWA+OWA+FA+DA+SA+CGC+(1\|LEK)+(1\|YEAR)[b] | | | | 13 | 251.29 | 0.00 | -3.36 | | | | |
| CGA+PGA+CWA+PWA+OWA+FA+DA+SA+OGC+PGC+CGC + (1\|LEK)+(1\|YEAR) | | | | 15 | 251.70 | 0.41 | -2.95 | | | | |
| CGA+PGA+CWA+PWA+OWA+FA+DA+SA+CWC+CGC+(1\|LEK) +(1\|YEAR) | | | | 14 | 253.25 | 1.96 | -1.40 | | | | |
| CGA+PGA+CWA+PWA+OWA+FA+DA+SA+GC+(1\|LEK)+(1\|YEAR) | | | | 13 | 256.32 | 5.02 | 1.66 | | | | |
| CGA+PGA+CWA+PWA+OWA+FA+DA+SA+CWC+(1\|LEK)+(1\|YEAR) | | | | 13 | 256.64 | 5.35 | 1.99 | | | | |
| CGA+PGA+CWA+PWA+OWA+FA+DA+SA+GC+WC+(1\|LEK) +(1\|YEAR) | | | | 14 | 257.30 | 6.01 | 2.64 | | | | |
| CGA+PGA+CWA+PWA+OWA+FA+DA+SA+OWC+PWC+CWC +(1\|LEK)+(1\|YEAR) | | | | 15 | 260.60 | 9.31 | 5.94 | | | | |
| CGA+PGA+CWA+PWA+OWA+FA+DA+SA+(1\|LEK)+(1\|YEAR)[a] | 12 | 254.65 | 0.00 | | | | | | | | |
| CGA+PGA+CWA+PWA+OWA+(1\|LEK)+(1\|YEAR) | 9 | 256.24 | 1.59 | | | | | | | | |
| CGA+OGA+PGA+CWA+OWA+PWA+(1\|LEK)+(1\|YEAR) | 10 | 257.76 | 3.11 | | | | | | | | |
| log(GA)+(1\|LEK)+(1\|YEAR) | 5 | 258.35 | 3.69 | | | | | | | | |
| CGA+OGA+PGA+(1\|LEK)+(1\|YEAR) | 7 | 258.49 | 3.83 | | | | | | | | |
| CA+DA+FA+OA+SA+GA+WA+(1\|LEK)+(1\|YEAR) | 11 | 258.96 | 4.30 | | | | | | | | |
| $GA^4$+(1\|LEK)+(1\|YEAR) | 8 | 259.30 | 4.65 | | | | | | | | |
| GA+(1\|LEK)+(1\|YEAR) | 5 | 259.86 | 5.21 | | | | | | | | |
| WA+GA+(1\|LEK)+(1\|YEAR) | 6 | 260.86 | 6.21 | | | | | | | | |
| (1\|LEK)+(1\|YEAR) | 4 | 263.13 | 8.48 | | | | | | | | |
| WA+(1\|LEK)+(1\|YEAR) | 5 | 264.79 | 10.14 | | | | | | | | |
| (CA:GA)+(1\|LEK)+(1\|YEAR) | 5 | 265.13 | 10.48 | | | | | | | | |

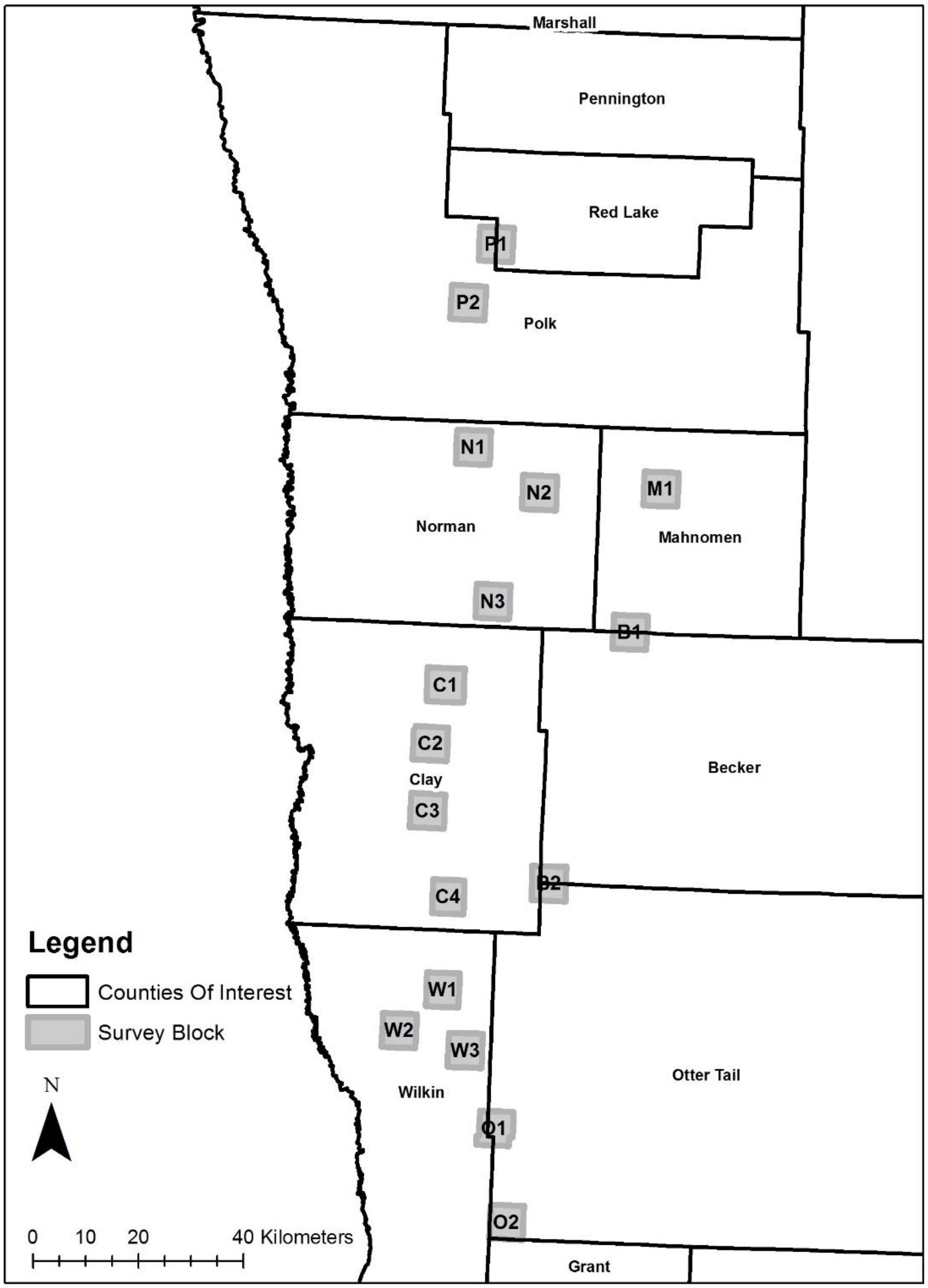
**a** Best-supported model at the composition level, **b** Best-supported model at the contiguity level

Table 6. Parameter estimates for best-supported models of greater prairie-chicken abundance in northwestern Minnesota at each scale of analysis and each layer of model building with their associated standard errors, and *P*-value of the test of whether 95% confidence intervals around those estimates include zero. Covariate acronyms are presented in Table 3.

| **Model Level** | **Parameter** | **Estimate of Coefficient** | **Standard Error** | ***P*-value** |
|---|---|---|---|---|
| *Survey Block Composition* | | | | |
| | CGA | 5.50E-05 | 1.28E-05 | 3.33E-05 |
| | PGA | 7.54E-05 | 1.92E-05 | 5.55E-04 |
| | CWA | 9.87E-05 | 2.27E-05 | 2.58E-05 |
| | PWA | 5.23E-05 | 1.94E-05 | 1.26E-02 |
| | OWA | -4.25E-05 | 1.53E-05 | 6.06E-03 |
| *Survey Block Contiguity* | | | | |
| | CGA | 4.67E-05 | 1.33E-05 | 5.48E-04 |
| | PGA | 7.00E-05 | 1.86E-05 | 8.19E-04 |
| | CWA | 1.18E-04 | 2.39E-05 | 2.69E-06 |
| | PWA | 5.75E-05 | 1.88E-05 | 5.35E-03 |
| | OWA | -2.87E-05 | 1.61E-05 | 7.65E-02 |
| | GC | 1.16E-02 | 1.16E-02 | 3.96E-02 |
| *Survey Block Fragmentation* | | | | |
| | CGA | 4.95E-05 | 1.33E-05 | 2.75E-04 |
| | PGA | 6.24E-05 | 1.91E-05 | 2.85E-03 |
| | CWA | 1.41E-04 | 2.49E-05 | 1.16E-07 |
| | PWA | 7.57E-05 | 2.03E-05 | 8.41E-04 |
| | OWA | -1.66E-05 | 1.67E-05 | 3.22E-01 |

| | | | | |
|---|---|---|---|---|
| | GC | 6.44E-03 | 5.90E-03 | 2.76E-01 |
| | WN | 4.18E-05 | 2.38E-05 | 8.12E-02 |
| | GN | -9.42E-05 | 3.69E-05 | 1.16E-02 |
| *Lek Composition* | | | | |
| | CGA | 2.22E-02 | 1.32E-02 | 9.20E-02 |
| | PGA | 3.66E-02 | 1.32E-02 | 5.85E-03 |
| | CWA | 1.89E-02 | 1.06E-02 | 7.38E-02 |
| | PWA | 3.99E-03 | 1.37E-02 | 7.71E-01 |
| | OWA | -1.19E-02 | 1.22E-02 | 3.31E-01 |
| | FA | -1.79E-02 | 1.40E-02 | 2.04E-01 |
| | DA | -3.46E-02 | 1.46E-02 | 1.84E-02 |
| | SA | 7.21E-03 | 1.20E-02 | 5.47E-01 |
| *Lek Contiguity* | | | | |
| | CGA | 1.16E-02 | 1.40E-02 | 4.05E-01 |
| | PGA | 3.21E-02 | 1.34E-02 | 1.67E-02 |
| | CWA | 2.13E-02 | 1.06E-02 | 4.40E-02 |
| | PWA | 9.05E-03 | 1.39E-02 | 5.15E-01 |
| | OWA | -5.66E-03 | 1.25E-02 | 6.51E-01 |
| | FA | -1.94E-02 | 1.40E-02 | 1.67E-01 |
| | DA | -3.25E-02 | 1.46E-02 | 2.63E-02 |
| | SA | 4.36E-03 | 1.20E-02 | 7.16E-01 |
| | CGC | 3.14E-02 | 1.37E-02 | 2.18E-02 |

Figure 1. Location of the 17 greater prairie-chicken survey blocks (gray labeled squares, 41 km$^2$) in northwestern Minnesota. Survey blocks are labeled with the first letter of the respective county (black border) and corresponding number (from north to south).



Appendix A: Land-cover reclassification categories used in models of greater prairie-chicken abundance in northwestern Minnesota, 2004-2016.

| **Assigned Land-Cover Classification** | **MLCC & NLCD Classification** | **CDL Classification** | **Other Classification Sources** |
|---|---|---|---|
| Cropland | row crops | corn, cotton, rice, sorghum, soybeans, sunflower, peanuts, tobacco, sweet corn, popcorn corn, mint, winter wheat/soybeans, canola, flaxseed, safflower, rapeseed, mustard, camelina, sugar beets, dry beans, potatoes, other crops, sugar cane, sweet potatoes, misc. fruits and veg, watermelons, onions, cucumbers, chickpeas, lentils, peas, tomatoes, caneberries, hops, honeydew melons, broccoli, peppers, greens, strawberries, squash, vetch, winter wheat/corn, oats/corn, lettuce, pumpkins, lettuce/durum, lettuce/cantaloupe, lettuce/cotton, lettuce/barley, wheat/cotton, soybeans/cotton, soybeans/oats, corn/soybeans, blueberries, cabbage, cauliflower, celery, radishes, turnips, eggplants, gourds, cranberries, barley/soybeans, oats, millet, barley, durum wheat, spring wheat, winter wheat, other small grains, rye, spelt, buckwheat | NA |
| Developed/ Barren | impervious (1-100%), extraction | developed, developed/open space, developed/low intensity, developed/med intensity, developed/high intensity, barren | NA |

| | | | |
|---|---|---|---|
| Grassland | managed grass/natural grass, hay, and pasture | sod/grass seed, switchgrass, grassland herbaceous, fallow/idle crop land, alfalfa, clover/wildflowers, triticale, other hay/non alfalfa, pasture/hay | Conservation Reserve Program (CRP) grassland (from Farm Service Agency (FSA)shapefiles & data reconstruction), state/federal/privately managed wildlands (from shapefiles obtained including Wildlife Management Areas (WMA; including Pheasants Forever (PF) acquisitions), (Wetlands Preservation Areas (WPA); including PF acquisitions), Walk-In Access (WIA), Scientific and Natural Areas (SNA), Nature Conservancy, Prairie Bank easements, MNDNR native prairies, Reinvest in Minnesota (RIM), Wildlife refuges) |
| Shrubland | forested and shrub wetlands | shrubland, grapes, woody wetlands | State/federal/privately managed wildlands (from various shapefiles obtained including WMA (including PF acquisitions), WPA(including PF acquisitions), WIA, SNA, Nature Conservancy, Prairie Bank easements, DNR native prairies, RIM, Wildlife refuges) |

| | | | |
|---|---|---|---|
| Forest | conifer forest, deciduous forest, mixed forest | forest, Christmas trees, deciduous forest, evergreen forest, mixed forest, tree crops (including: cherries, peaches, apples, citrus, pecans, almonds, walnuts, pears, pistachios, prunes, olives, oranges, pomegranates, nectarines, plums, apricots and other tree crops) | CRP tree practice codes from FSA shapefiles & data reconstruction, state/federal/privately managed wildlands (from various shapefiles obtained including WMA (including PF acquisitions), WPA (including PF acquisitions), WIA, SNA, Nature Conservancy, Prairie Bank easements, DNR native prairies, RIM, Wildlife refuges) |
| Open Water | lakes, ponds, and rivers | water, aquaculture, open water | NA |
| Wetland | emergent wetlands | herbaceous wetlands, wetlands | CRP wetlands (from FSA shapefiles & data reconstruction), state/federal/privately managed wildlands (from various shapefiles obtained including WMA (including PF acquisitions), WPA (including PF acquisitions), WIA, SNA, Nature Conservancy, Prairie Bank easements, DNR native prairies, RIM, Wildlife refuges) |
| No Data | NA | clouds/no data, non ag/undefined, perennial ice/snow | NA |

## Chapter 2

## Predicting the Effects of Grassland Conservation Reserve Program Enrollments and Expirations on Greater Prairie-Chickens in Northwestern Minnesota

***Overview**:* The Conservation Reserve Program (CRP) has the potential to influence the abundance of greater prairie-chickens (*Tympanuchus cupido pinnatus),* a species of special concern in Minnesota, by altering the amount and configuration of grassland and wetland in agriculturally dominated landscapes. However, the CRP has experienced recent declines in enrollments in northwestern Minnesota, and these declines are expected to continue following the reduced enrollment cap in the 2014 Farm Bill. These declines increase the need to prioritize CRP reenrollments or new enrollments that are likely to have the most positive impact on greater prairie-chicken populations. To predict changes in greater prairie-chicken abundance caused by expirations of CRP contracts and target CRP enrollments at both the landscape and lek scale, I used models relating lek density and the number of males at leks to CRP enrollments and the resulting landscape structure. I simulated different land-cover scenarios of CRP contract expirations, and results indicated that the abundance of greater prairie-chickens would be reduced. Simulations of targeted CRP contract enrollment suggested mixed effects on greater prairie-chicken abundance if adding grassland cover did not increase existing grassland contiguity. Landscapes with a large proportion of existing CRP grasslands and wetlands were most likely to continue to support high prairie-chicken abundance through reenrollment and enrollment of new contracts that are large and contiguous with existing grassland- and wetland-cover types. These findings highlight the importance of maintaining existing

CRP grasslands and wetlands in landscapes that currently have low levels of grassland and wetland cover.

***Key Words****:* Greater prairie-chicken, *Tympanuchus cupido pinnatus,* landscape, grassland, Conservation Reserve Program, Minnesota

## INTRODUCTION

The Conservation Reserve Program (CRP) is the largest federal private land retirement program in the United States (Stubbs 2014). Established in 1985, the CRP is authorized to remove land from crop production with the objectives to reduce soil erosion, improve water quality, and restore and protect wildlife habitats by providing financial incentives to reseed agricultural land to sod-forming or native vegetation for a period of 10 to 15 years. A variety of CRP programs focus on different types of wildlife habitat restoration including field buffers, bottomland hardwood forestland, pollinator habitat, restoring farmed wetlands, and riparian habitat (Riley 2004), some of which can increase the amount of tallgrass prairie and other grassland-cover types in agricultural landscapes. Even programs that are not focused specifically at wildlife species may offer an opportunity for grassland habitat restoration as large contiguous tracts of land are enrolled (Riley 2004; Herkert 2009).

The opportunity that the CRP offers for habitat reconstruction could be vital for grassland bird species that have been extirpated from historically occupied ranges due to land-use conversion to agriculture. Shirk et al. (2017) created habitat models and differing management scenarios to understand why specific greater sage-grouse (*Centrocercus urophasianus*) populations in Washington, USA persisted despite extensive land-use modifications and a high probability of extirpation. Their study concluded that the CRP integrated within native sagebrush-steppe was an essential component of sage-grouse conservation in this region. They predicted that without the CRP, 66% of predicted sage-grouse habitat would be reduced and strategic concentration of CRP enrollment could increase area of habitat by 63% relative to the existing levels

(Shirk et al. 2017). Greater prairie-chickens (*Tympanuchus cupido pinnatus)* are another grouse species that has experienced population declines and local extirpations resulting from landscape-scale conversion of grassland to agriculture and are targeted by the CRP for conservation. Greater prairie-chickens are obligate grassland birds (Robel et al. 1970a), a Species of Special Concern in Minnesota, and the CRP has developed practices and programs to protect and restore their habitat. For example, greater prairie-chickens have been listed as one of the high priority species identified in the Back Forty Pheasant Habitat CRP-SAFE practice (USDA 2008).

For a variety of reasons, area enrolled in the CRP has declined nationwide since its peak enrollment of approximately 149,000 $km^2$ in 2007 (Stubbs 2014). This decrease is scheduled to continue as the 2014 Farm Bill decreased the enrollment cap from approximately 130,000 $km^2$ to < 100,000 $km^2$ by 2018 (Stubbs 2014). In the greater prairie-chicken range in northwestern Minnesota, area enrolled in the CRP (all Conservation Practice codes) within 17 established greater prairie-chicken survey blocks declined 16-52% from peak enrollment to 2016. To better understand the relationship between CRP enrollments and greater prairie-chicken populations, I previously quantified the association between greater-prairie chicken lek density and CRP enrollments in the context of landscape structure and composition at multiple spatial scales in northwestern Minnesota during the period 2004-2016 (Adkins Chapter I). That assessment found that the amount of CRP grassland and wetland, the contiguity of grasslands, and the number of patches of grasslands and wetlands, including CRP grassland and wetland contracts, were the best-supported covariates in models of lek density (leks/$km^2$) at the landscape scale. Similarly, at the lek scale, the amount of CRP grassland and wetland and the contiguity of CRP grassland were the best-supported covariates in models of the number of males at leks. These models provide insight into the landscape features that potentially influence greater prairie-chicken abundance, but also can be used to predict how greater prairie-chicken populations might respond to future landscape conditions, especially in light of projected losses of CRP grassland through contract expiration.

Herein, I use these models to predict the potential impact of grassland CRP enrollments and expirations on greater prairie-chicken populations in northwestern Minnesota at both the survey block and lek scale. As the amount of CRP continues to decline in landscapes that currently support greater prairie-chickens, understanding the impact of CRP contracts at the survey block and lek scale will inform efforts to target CRP enrollments where they will be most effective for greater prairie-chicken conservation. Based on previous studies, I expected that greater prairie-chicken lek density and the number of males at leks would decline with continued scheduled grassland and wetland CRP expirations and consequential conversion to agricultural production, and that losses would be greatest when all CRP contracts were allowed to expire. I also expected that lek density and the number of males at leks would increase with strategic enrollments that increase the amount and contiguity of grassland and wetland CRP on the landscape.

## METHODS

### Study Area and Greater Prairie-Chicken Survey Data

I evaluated greater prairie-chicken—habitat relations in the portion of northwestern Minnesota that currently supports greater prairie-chicken populations and where prairie-chickens have been surveyed annually since 2004 [Fig. 1, Minnesota

Department of Natural Resources (MNDNR), unpublished data]. As part of the standardized survey protocol developed by the MNDNR, 17 41-km$^2$ blocks were systematically surveyed for prairie-chicken leks from 2004-2016. Data from the greater prairie-chicken spring survey consisted of count and location information for leks from 2004-2016 within established survey blocks (Fig. 1).

Annual surveys of greater prairie-chickens were coordinated by the MNDNR and executed in collaboration with the Minnesota Prairie-Chicken Society, The Nature Conservancy (TNC), U. S. Fish and Wildlife Service, and other volunteers. The survey protocol consisted of surveyors being assigned 4 Public Land Survey (PLS) sections within a survey block and attempting to observe greater prairie-chicken mating display behavior repeatedly in these sections. Surveyors observed mating display behavior visually with the use of binoculars and counted the number of males, females, and prairie-chickens of unknown sex at each visit to each lek. Prairie-chickens displaying at leks were recorded as males; if no prairie-chickens displayed at the lek or prairie-chickens on the lek were flushed before displaying was observed, individuals present at leks were recorded as unknown sex (Roy 2014). Location data were available for 58-114 leks per year within these survey blocks recorded to the level of quarter-section or GPS coordinates (Roy et al. 2015). Occasionally, lek locations were only recorded to the accuracy of the section. When this occurred, I examined notes included with lek observations and surrounding lek locations in the current, previous, and later years to more precisely estimate lek locations. If I could not estimate a more accurate lek location from the survey data or if the survey data indicated the lek was truly at the center of the section, I placed the lek location in the center of the section. This occurred in approximately 4% of recorded leks.

Based on survey data from 2004-2016, I derived 2 scales of analysis: survey-block and lek scales. The survey-block scale refers to the entirety of 41-$km^2$ blocks; the lek scale considers a fixed buffer of 2 km around each recorded lek location to represent the breeding-cycle habitat radius of greater prairie-chickens (Merrill et al. 1999; Hovick et al. 2015a). At the survey-block scale I used the number of leks/$km^2$ in each of the 17 survey blocks. At the lek scale I considered the number of males/lek. The metrics of leks/$km^2$ and males/lek have been previously used as indices of greater prairie-chicken population size and habitat quality (Hamerstrom and Hamerstrom 1973; Niemuth 2011). For both of these metrics, I considered a lek to be indicated by >1 displaying male at the same location during ≥1 of the years surveyed (Schroeder and Braun 1993; Merrill et al. 1999). For a complete description of greater prairie-chicken data used to develop models of lek density and number of males at leks, see Chapter I.

**Land-cover Data**

I created a historical record of CRP enrollments using Farm Service Agency (FSA) shapefiles for CRP enrollments and corresponding conservation practice codes within survey blocks for 1997, 2006-2011, and 2013-2016. I reconstructed data for missing years in ArcGIS (ERSI 2015) to derive a complete history of CRP land-cover for the period 2004-2016 (see Chapter I for details). During June-August 2016, I visited and verified mapped areas of CRP enrollment reconstruction within survey blocks to ensure that land-cover data were correct. Because the shapefiles obtained from FSA included all CRP practice codes within survey blocks, I distinguished the CRP practice codes that provide grassland-cover types used by greater prairie-chickens (Table 1) using classification categories of Nielson et al. (2008) and Drum et al. (2015).I also identified and quantified non-CRP grassland-cover within the study area to create a 2016 land-cover raster map. To delineate other cover types, I examined infrared imagery; LiDAR data layers; the Minnesota Land-cover Classification (MLCC) and Impervious Surface Area by LANDSAT and LiDAR: 2013 Update; NASS Cropscape Cropland Data Layer (CDL) and National Land-cover Database (NLCD) land-cover in ArcGIS; and histories of state-, federal-, and TNC-managed areas within the study area (Merrill et al. 1999; Niemuth 2000; Poiani et al. 2001; Nielson et al. 2008; ESRI 2015; Evans and Potts 2015; Drum et al. 2015).

I reclassified the land-cover data layers in each of the 17 survey blocks into 7 vegetation classes (i.e., developed, cropland, open water, wetland, forest, shrubland, and grassland) with 30-m accuracy (Appendix A). I further classified grassland and wetland-cover types into 3 more-specific, mutually exclusive management categories of (1) CRP, (2) state-, federal-, and TNC-managed areas, and (3) other areas (i.e., sources of grassland and wetland that didn't fall into the other 2 categories, e.g., CRP or state-, federal-, and TNC-managed areas), based on the histories of CRP contracts and state-, federal-, and TNC-managed areas. I verified and calculated the accuracy of my classification categories by visiting 500 random points in the survey blocks during June-August 2016. Based on ground-truthing, the accuracy of classification of the land-cover types was adequate for my intended use. For a complete description of land-cover reclassification accuracy assessment methodology, see Chapter I.

## Predictive Model Development

I used models relating lek density and number of males/lek to landscape metrics described in Chapter 1 using a layered approach in an information-theoretic framework (Burnham and Anderson 2002). The best supported model of lek/km$^2$ at the survey-block scale included the area of CRP grassland; the area of state-, federal-, and TNC-managed grasslands; the area of CRP wetland, the area of state-, federal-, and TNC-managed wetlands; the area of "other" wetlands; the contiguity of grasslands; and the number of patches of grasslands and wetlands in each survey block in each year (Adkins Chapter I). Based on *k*-fold validation, this best-supported model had an average normalized root mean square error (NRMSE) of 13.15% (SD = 0.27%). The best-supported model of males/lek (log-transformed) at the lek scale included the percent area CRP grassland; the percent area of state-, federal-, and TNC-managed grasslands; the percent area of CRP wetland; the percent area of state-, federal-, and TNC-managed wetlands; the percent area of "other" wetlands; the percent area of forest; the percent area of developed; the percent area of shrub; and the contiguity of grassland CRP (Adkins Chapter I:Table 5). This model had an average NRMSE of 17.38% (SD = 0.11%). I used the best-supported models at both the survey-block and lek scales to predict the density of lek/km$^2$ and males/lek based on different land-cover scenarios. I used the NRMSE from both the survey-block- and lek-scale models to calculate the error in prediction associated with the model.

## Land-Cover Scenarios

To predict greater prairie-chicken lek density and number of males/lek under different potential future landscape conditions, I developed different land-cover scenarios simulating both CRP grassland loss and gain within the study area. This is similar to the approach used by Princè et al. (2015) to model grassland bird abundance and Shirk et al. (2017) to evaluate the influence of changes in CRP enrollments on greater sage-grouse. My scenarios included (1) no change in CRP enrollment, (2) CRP expiration scenarios based on the yearly scheduled CRP expirations from contracts enrolled as of 2016 until all scheduled expirations are complete in 2030, and (3) CRP enrollment scenarios based on 100 random simulations of adding CRP grassland and wetland to the survey blocks as prescribed in the core and corridor goals of Minnesota Prairie Conservation Plan (Minnesota Prairie Plan Working Group 2011).

**Scenarios of CRP Expirations**

The 16 management scenarios represented (1) no change in CRP enrollment, and (2) 15 years of cumulative scheduled CRP expirations beginning in 2016 until 2030. Except for the management scenario with no change in CRP enrollment, I modified the 2016 land-cover map by reclassifying CRP contract areas to cropland. I then used FRAGSTATS (McGarigal et al. 2012) to calculate area of CRP grassland, the area of CRP wetland, the contiguity of grasslands, and the number of patches of grasslands and wetlands in each survey block for the survey-block scale model. For the lek-scale model I calculated the percent area CRP grassland, the percent area of CRP wetland, and the contiguity of grassland CRP within a fixed buffer of 2 km around traditional leks that had $\geq$1 displaying male recorded in 2016. I used Merrill et al.'s (1999) definition of traditional lek locations, where displaying males occurred >50% of the period studied ($\geq$7 of 13 years, $n$ = 26) to identify leks that were active in the most recent survey and used most frequently throughout my study period to include in my analysis.

**Scenarios of CRP Enrollments**

I simulated adding grassland and wetland to survey blocks as prescribed in the core and corridor goals of Minnesota Prairie Conservation Plan (MPCP, Minnesota Prairie Plan Working Group 2011), through the addition of area in the CRP. This 25-year plan was developed in 2011 by various conservation organizations in Minnesota, using guidance of existing resource plans (e.g., pheasant, duck, and wildlife area management plans), and includes distinct goals for core and corridor areas to create a connected landscape within Minnesota's prairie region from Canada to Iowa. Core areas were identified as areas with a high concentration of native prairie, other grassland, wetlands, or shallow lakes that maintain a minimum of 40% grassland and 20% wetland. Corridors connecting core areas were also designed to include core complexes ~23.3 $km^2$ (9 $mi^2$) in size at ~9.7-km (6-mi) intervals. These core complexes also had a goal of a minimum of 40% grassland and 20% wetland. For the remainder of corridors, a minimum of 10% of each ~2.6 $km^2$ (1-$mi^2$) is grassland (Minnesota Prairie Plan Working Group 2011).

To simulate the potential influence of meeting the landscape prescriptions of the MPCP, I first identified the intersection of survey blocks and core, corridor complexes, and corridor areas. Portions of 15 of the 17 survey blocks were included in ≥1of the core, corridor complexes, and corridor areas. I then clipped the 2016 land-cover raster with the intersection areas and calculated the existing percentages of each land-cover type of interest (i.e., cropland, grassland, and wetland), and how much cropland needed to be converted to grassland or wetland CRP to meet each goal defined above. I then randomly simulated 100 different iterations for each of the 15 survey blocks to meet the core, corridor complexes, and corridor areas goals defined above by converting the cropland areas in the 2016 land-cover raster map to polygons and then dividing these polygons into $4.04 \times 10^{-3}$ $km^2$ (1-acre) areas using the *fishnet* tool and the *intersect* tool in ArcGIS (ESRI 2015). I then randomly selected the area needed to meet each goal, reclassified this area to grassland or wetland CRP, and integrated them back into the 2016 land-cover raster map using the *is null* and *con* tool in ArcGIS (ESRI 2015). After creating 100 different iterations for each of the 15 survey blocks to meet the core, corridor complexes, and corridor areas goals, I used FRAGSTATS (McGarigal et al. 2012) to recalculate area of CRP grassland, the area of CRP wetland, the contiguity of grasslands, and the number of patches of grasslands and wetlands in each of the 100 scenarios for the survey-block scale model. For the lek-scale model I recalculated the percent area CRP grassland, the percent area of CRP wetland, and the contiguity of grassland CRP in a 2-km fixed buffer around traditional leks ($n$ = 25) recorded in 2016 within the 15 survey blocks included the MPCP goals (Merrill et al. 1999). I calculated the average number of lek/$km^2$ or males/lek and associated 95% confidence intervals from the 100 simulated iterations for each of the 15 survey blocks or 25 leks included in the Minnesota Prairie Plan core, corridor complexes, and corridor goals.

Additionally, I created another scenario for each of the 15 survey blocks to simulate converting existing cropland to grassland or wetland CRP to meet the landscape prescriptions of the MPCP in larger patches with maximum contiguity. I created larger patches by combining the previously created $4.04 \times 10^{-3}$-$km^2$ (1-acre) polygons into contiguous 0.08-$km^2$ (20-acre) areas using the *dissolve* tool in ArcGIS (ESRI 2015). I used 0.08 $km^2$ (20-acre) areas because this was the calculated average area of the current grassland and wetland CRP contracts within the survey blocks. I calculated the number of

0.08-$km^2$ (20-acre) cropland areas needed to be converted to grassland or wetland CRP to meet each goal defined above and used the *near* tool to calculate the distance of each 0.08 $km^2$ (20-acre) area to an existing grassland or wetland patch on the landscape. I selected the 0.08-$km^2$ (20-acre) areas with the shortest distance to the nearest existing patch of grassland or wetland to simulate converting into grassland or wetland to meet the landscape prescriptions of the MPCP. I then reclassified these selected 0.08-$km^2$ (20-acre) areas to grassland or wetland CRP, and integrated them back into 2016 land-cover raster map using the *is null* and *con* tool in ArcGIS (ESRI 2015). The result was a scenario to meet the core, corridor complexes, and corridor areas goals using 0.08-$km^2$ (20-acre) areas with maximum contiguity to existing grassland and wetland patches on the landscape for each of the 15 survey blocks. I then used FRAGSTATS (McGarigal et al. 2012) to recalculate area of CRP grassland, the area of CRP wetland, the contiguity of grasslands, and the number of patches of grasslands and wetlands for each of the 15 survey blocks to predict prairie-chicken abundance with the survey-block-scale model. For the lek-scale model I recalculated the percent area CRP grassland, the percent area of CRP wetland, and the contiguity of grassland CRP in the new scenario in a 2-km fixed buffer around traditional leks ($n$ = 25) recorded in 2016 within the 15 survey blocks included the MPCP goals (Merrill et al. 1999).

## RESULTS

### CRP Expiration Scenarios at the Survey-Block Scale

All 17 survey blocks had predicted declines in lek density as the area of CRP enrollments declined (i.e., contracts expired). Total changes predicted with the loss of all CRP ranged from 1.73% (error: $\pm$ 0.23%) to 80.18% (error: $\pm$ 10.54%) decline in the number of leks/km$^2$ (Fig. 2). The average total change in the number of leks/km$^2$ resulting from expiration of all CRP (2016 – 2030) in all survey blocks was -22.12% (error: $\pm$ 2.91%), and 9 of the 17 blocks had predicted declines in lek density >20% (Fig. 2). On average across all survey blocks, the largest percent decline in number of leks/km$^2$ from the landscape configuration the previous year followed CRP contract expirations scheduled in 2018. In several years in all survey blocks, the predicted change in number of leks/km$^2$ from the following year was zero because no CRP contracts were set to expire in the survey block and therefore no changes in landscape configuration were predicted from the previous year. The largest percent decline in number of leks/km$^2$ in any survey block from predictions the previous year was -42.7% (error: $\pm$5.62) following expirations scheduled in 2021 (survey block N1, Appendix A).

### CRP Expiration Scenarios at the Lek Scale

Using the lek-scale model and 16 future predicted landscape configurations based on scheduled CRP expirations from contracts enrolled in 2016 until all CRP enrollments were projected to expire in 2030, I predicted the number of males/lek in each of the 26 traditional leks for each predicted future landscape configuration. Twenty-five of 26 had predicted declines in the number of males/lek (Fig. 3). One lek (lek 6 in C3, Appendix A) had no change in the predicted number of males/lek because there were no CRP contracts within the 2-km buffer around the recorded lek location. Total changes predicted in the number of males/lek with the loss of all CRP (i.e., by 2030) ranged from -0.03% (lek 21 in C1, Appendix A; error = ±0.01%) to -19.16% (lek 1 in P1, Appendix A; error = ±3.32%). The average predicted total change in the number of males/lek by 2030 in all survey blocks was -7.15% (error =±1.24%). Across all traditional leks, the largest average predicted percent decline in number of males/lek from the previous landscape configuration was following expirations scheduled in 2023 (Fig. 3). For all traditional leks, years occurred when the predicted change in number of males/lek from the landscape configuration in the previous year was zero because no CRP contracts were set to expire in the survey block where the lek was located and therefore there were no predicted landscape configuration changes from the previous year. The largest predicted percent decline in number of males/lek from the landscape configuration the previous year was -12.9% following expirations scheduled in 2019 (lek 12 in C4, Appendix A).

**CRP Enrollment Scenarios at the Survey-Block Scale**

Ten of 15 survey blocks (N2 and W2 were outside of the area included in the MPCP; see Appendix A) had predicted increases in the number of leks/km$^2$ associated with small, random CRP enrollment scenarios. Thirteen of the same 15 survey blocks had predicted increases in the number of leks/km$^2$ associated with large, non-random CRP enrollment scenarios selected to increase contiguity with existing grassland and wetland patches on the landscape. Of the 10 blocks where both CRP enrollment scenarios resulted in increases in the predicted number of leks/km$^2$, 1 (B2; Appendix A) had the larger increase associated with small, random CRP enrollment scenarios, and 9 had the larger increase associated with large, non-random CRP enrollment scenarios selected to increase contiguity with existing grassland and wetland patches on the landscape. However, 5 blocks (C1, C2, C3, C4 and N1; Appendix A) had declines of the predicted number of leks/$km^2$ associated with small, random CRP enrollment scenarios, and 2 blocks (C1 and C3; Appendix A) had declines of the predicted number of leks/$km^2$ associated with large, non-random CRP enrollment scenarios to reach MPCP landscape configuration objectives. The largest predicted increase in lek density associated with meeting MPCP landscape configuration objectives with small, random CRP enrollment scenarios was 59.6% (error: $\pm$7.84; O2, Appendix A) and the largest predicted decrease in lek density was -18.6% (error: $\pm$2.44; N1, Appendix A). The largest predicted increase in lek density associated with large, non-random CRP enrollment scenarios selected to increase contiguity with existing grassland and wetland patches on the landscape to meet MPCP landscape configuration objectives was 107.9% (error: $\pm$14.19; O2, Appendix A) and the largest predicted decrease in lek density was -0.73% (error: $\pm$0.10; C3, Appendix A).

**CRP Enrollment Scenarios at the Lek Scale**

Twenty-one of the 25 survey blocks had predicted increases in the number of males/leks associated with small, random CRP enrollment scenarios (Fig. 5). Twenty-four of the same 25 survey blocks had predicted increases in the number of males/leks associated with large, non-random CRP enrollment scenarios selected to increase contiguity with existing grassland and wetland patches in the survey blocks (Fig. 5). Of the 21 blocks where both CRP enrollment scenarios resulted in increases in the predicted number of males/lek, 3 leks (lek 6 in C3, lek 15 in W3, and lek 17 in W3; Appendix A) had the larger increase associated with small, random CRP enrollment scenarios, and 17 had the larger increase associated with large, non-random CRP enrollment scenarios selected to increase contiguity with existing grassland and wetland patches on the landscape. However, 4 leks (lek 9 in C3, lek 11 in C4, lek 20 in C1, and lek 26 in W1; Appendix A) had decreases in the predicted number of males/lek associated with small, random CRP enrollment scenarios. The only lek predicted to have declines in the number of males/lek associated with large, non-random CRP enrollment scenarios selected to increase contiguity with existing grassland and wetland patches in the survey blocks was lek 26 in W1. The largest predicted increase in the number of males/lek associated with meeting MPCP landscape configuration objectives with small, random CRP enrollment scenarios was 9.04% (error: ±1.57; Lek 14 in survey block M1, Appendix A) and the largest predicted decrease in lek density was -1.47% (error: ±0.25; lek 20 in survey block C1, Appendix A). The largest predicted increase in lek density associated with large, non-random CRP enrollment scenarios selected to increase contiguity with existing grassland and wetland patches on the landscape to meet MPCP landscape configuration objectives was 12.87% (error: ±2.24; Lek 14 in survey block B2, Appendix A) and the only predicted decrease in lek density was -0.34% (error: ±0.06; lek 26 in survey block W1, Appendix A).

## DISCUSSION

The manner in which grassland and wetland is added to the existing landscape can alter lek density and the number of males per/lek of greater prairie-chickens in northwestern Minnesota. My simulations suggested increased lek density and the number of males per/lek of greater prairie-chickens where larger amounts and increased contiguity of grassland CRP occur on the landscape. Furthermore, I found that adding larger patches of grassland and wetland that increased contiguity between existing grassland and wetland patches on the landscape generally increased lek density and the number of males per/lek of greater prairie-chickens more than random addition of the same amount of grassland and wetland in smaller parcels to the existing landscape. Even though all simulated management scenarios added CRP grassland or wetland to the landscape, declines of the number of leks/$km^2$ were predicted in a third of the survey blocks potentially affected if the prescriptions in the Minnesota Prairie Plan were implemented by randomly adding small patches of grassland and wetland. However, when larger patches were non-randomly added to the landscape to increase contiguity, not only the number of survey blocks where declines of the number of leks/$km^2$ were predicted, but also the magnitude of the predicted declines were reduced. In some cases randomly adding CRP grassland and wetland to the landscape to meet the MPCP goals increased fragmentation and reduced contiguity of grassland within some of the survey blocks, therefore lowering the predicted number of leks/$km^2$ (Adkins Chapter 1). Survey blocks where increases in the number of leks/$km^2$ were predicted through random additions of CRP grassland and wetland enrollments were those that had increased grassland contiguity in addition to more patches of grassland and wetland. Although almost all of the scenarios with large patches of grassland and wetland CRP non-randomly added to increase contiguity with existing grassland and wetland patches on the landscape resulted in increases in the number of leks/$km^2$, the largest increases in the number of leks/$km^2$ occurred where the largest increases in contiguity and decreases in fragmentation occurred. This indicates that randomly adding grassland or wetland CRP to the landscape may not be sufficient to meet MPCP goals, and to get the best outcome these additions need to be implemented strategically. My results indicate that CRP enrollments ≥0.08-$km^2$ (20 ac) in size or contiguous with other CRP grassland contracts or other grassland-cover types are likely to have the greatest positive effect on greater prairie-chicken conservation. Specifically, the P2, M1, N3, B2, and W3 survey blocks exhibited increases in predicted greater prairie-chicken abundance in either scenario of addition of grassland and wetland CRP to meet prescriptions in the Minnesota Prairie Plan. The survey blocks of P1, N1, B1, C2, C4, W1, O1, and O2 had much larger increases (~50%) in the predicted number of leks/$km^2$ associated with non-random additions of grassland and wetland CRP to meet prescriptions in the Minnesota Prairie Plan, with N1, C2, and C4 transitioning from predicted declines in lek/$km^2$ with random addition to predicted increases with non-random additions. To maximize increases in greater prairie-chicken abundance, all new enrollments of grassland and wetland CRP would occur in close proximity to existing sources of grassland and wetland. However in the areas highlighted above that had a large increase associated with non-random additions of grassland and wetland CRP, new enrollments that increase contiguity would have the greatest impact on greater prairie-chicken conservation. Conversely, survey blocks C1 and C3 had predicted declines in the number of leks/$km^2$ whether grassland and wetland CRP were added randomly or non-randomly. This suggests that suitable habitat within these areas is so sparse that even concentrated efforts to increase contiguity does not have a positive impact, which suggests that such areas might not be priorities for locating CRP enrollments to benefit greater prairie-chickens.

Similar to the survey-block scale, my simulated management scenarios resulted in predicted declines in the number of males/lek associated with randomly adding CRP enrollments to the landscape surrounding about 1/5 of traditional leks. However, only 1 lek was predicted to decline in number of males when grassland and wetland CRP was non-randomly added. Predicted declines in the number of males occurred at leks with high existing grassland CRP contiguity within 2 km that was lowered by randomly adding small patches of CRP grassland or wetland. Similarly, the only decline predicted with targeted addition of CRP grassland or wetland occurred when grassland contiguity in the 2-km buffer around the lek declined by >1%, although overall grassland contiguity was increased in the survey block. Leks with the highest increase in the number of males with both random and targeted addition of grassland and wetland CRP occurred in areas with low levels of existing CRP grassland and low contiguity and these additions increased contiguity by >100%. The difference in random versus targeted addition of grassland and wetland CRP seems to be less pronounced at the lek scale than the survey-block scale, likely because lek location was not taken into consideration when grassland and wetland was added non-randomly to the existing landscape to meet MCPC goals and increase contiguity. Future studies could investigate simulations that non-randomly add grassland and wetland area within a 2-km breeding-cycle buffer around leks.

The simulated landscape resulting from loss of all CRP enrollments represents what might exist in the absence of land-conservation programs in this agricultural landscape. Predicted landscape configurations prior to 2030 represent conditions intermediate between current conditions and those in landscapes in the absence of federal farm land-retirement programs simulated to assess the effects of adding individual CRP enrollments on landscape composition, configuration, and fragmentation.

Results of my simulations of CRP contract expirations in northwestern Minnesota over the next 14-year period (through the expiration of all existing CRP contracts) suggest both reduced lek density and the number of males per/lek of greater prairie-chickens across most of this landscape following the expiration of all CRP contracts by 2030. The largest predicted declines in lek density across this landscape following loss of all existing CRP contracts were those where CRP enrollments make up a large percentage of the available herbaceous cover (e.g., grassland and wetland). Additionally, survey blocks with the highest predicted decline in lek density also resulted from increased fragmentation of grassland cover following loss of all existing CRP contracts. At the lek scale, traditional leks with the highest predicted decline in the number of males following loss of all existing CRP contracts were those where CRP enrollments make up a large percentage of the 2-km buffer around leks. Furthermore, traditional leks that began with a low percentage of CRP contracts and contiguity between existing contracts within the 2-km breeding-cycle habitat radius (i.e., starting condition in 2016) also had the lowest predicted declines associated with loss of all existing CRP contracts because the landscape was not altered as dramatically. Results of my simulations at both the survey-block and lek scale are consistent with current understanding of greater prairie-chicken ecology; that greater prairie-chickens are area sensitive, in that they require large patches of suitable habitat (Niemuth 2003; Niemuth 2011). My results suggest that if grassland or wetland CRP enrollments currently make up a large percentage of the habitat available to greater prairie-chickens, then declines in prairie-chicken abundance will be greater than if there are other categories (i.e., non-CRP) of grassland or wetland cover available. At the survey-block scale, the areas that seem to be most affected by loss of CRP include the northern part of the current prairie-chicken range in Polk and northern Norman and Mahnomen counties and the south-central part of the range including southern Clay and Becker and northern Otter Tail and Wilkin counties. Losses of over a third of the density of leks are predicted for these areas, and it is not known whether greater prairie-chickens would persist under these conditions. This trend is also evident at the lek scale, with the greatest predicted decreases in males/lek occurring in traditional leks in northern Polk and Wilkin and southern Clay counties.

As with all studies that project population response based on habitat relations, my study has several limitations. First, all my scenarios only altered the amount of CRP grassland or wetland on the landscape; no other land-cover types were altered. Yet, the amount, contiguity, and fragmentation of land-cover types other than grassland and CRP wetland may influence abundance of greater prairie-chickens (Adkins Chapter I). Moreover, although the expiration scenarios I simulated are identified by year of the expiration date of selected contracts, the predictions associated with these scenarios are not estimates of greater prairie-chicken abundance for that year. Instead these predictions are of greater prairie-chicken abundance in the context of the projected landscape conditions and help elucidate the potential effect of specific contract expirations with reference to the current landscape.

However, my simulations do provide a means of evaluating how potential changes in northwestern Minnesota landscapes related to cover types and how land-retirement programs might influence greater prairie-chicken populations, and provide some guidance about how and where to target conservation efforts. The areas predicted to be most vulnerable to loss of CRP are the northern and south-central parts of the current prairie-chicken range. Specifically, existing CRP contracts in northern Polk, Norman, Mahnomen, Otter Tail and Wilkin and southern Clay and Becker counties are high priority areas for enrolling or reenrolling CRP contracts. Contracts within these areas that are large and contiguous with other grassland sources are likely to have the highest conservation value.

The ability to target specific survey blocks, greater prairie-chicken breeding-cycle habitat radii, and CRP contract expirations that may have the greatest effect on prairie-chicken populations becomes more necessary as the cap on CRP enrollments is lowered. My results suggest that conserving CRP contracts in landscapes that currently have low levels of non-CRP grassland and wetland cover, and targeting new enrollments that are contiguous with existing grassland and wetland are likely to have the most positive influence on greater prairie-chicken conservation. To better understand these relationships in a more complex context, a better understanding of how cover types other than grassland and wetland might influence prairie-chicken population ecology (e.g., juxtaposition of crops used as food by prairie chickens related to grassland and wetland-cover) may be useful. And, as with all predictive models, validating predictions with empirical information would help identify which factors influence greater prairie-chicken—habitat relations most consistently and to the greatest extent.

**Management Implications**

My study extends previous work by evaluating how configuration and fragmentation of grassland-cover types, especially CRP grasslands, are related to greater prairie-chicken abundance. In the context of CRP contract expirations and a lower cap on enrollments, how grassland-cover types occur in this and other agricultural landscapes becomes more important. My results suggest that maintaining existing CRP grasslands and wetlands in landscapes that currently have low levels of non-CRP grassland and wetland cover, both within landscapes with current high lek density and around traditional leks with high numbers of males, is likely to have the most positive influence on greater prairie-chicken conservation. Furthermore, my simulations suggest that achieving the goals of the MPCP may have mixed effects on greater prairie-chicken abundance if new grassland cover is not added in a manner to increase existing grassland contiguity. Therefore, as the extent of CRP grassland decreases in this, and likely other landscapes, new enrollments that are contiguous with existing grassland- and wetland-cover types and add to or create larger patches are most likely to benefit greater prairie-chickens.

Table 1. All Conservation Reserve Program (CRP) practice codes in northwestern Minnesota greater prairie-chicken survey blocks provided by the Farm Service Agency classified into categories of CRP grassland, CRP forest, and CRP wetland.

| **CRP Practice Code** | **CRP Practice Name** |
|---|---|
| ***CRP Grassland*** | |
| CP1 | Establishment of Permanent Introduced Grasses & Legumes |
| CP10 | Vegetative Cover - Grasses Already Established |
| CP12 | Wildlife Food Plot |
| CP18 | Establishment of Permanent Vegetation to Reduce Salinity |
| CP18B | Establishment of Perm. Vegetation to Reduce Salinity, Non-easement |
| CP18C | Establishment of Perm. Salt Tolerant Vegetative Cover, Non-easement |
| CP2 | Establishment of Permanent Native Grasses |
| CP21 | Filter Strips |
| CP25 | Restoration of Rare & Declining Habitat |
| CP38E | SAFE – Grass |
| CP42 | Pollinator Habitat |
| CP4D | Permanent Wildlife Habitat, Non-easement |
| CP8A | Grass Waterways, Non-easement |
| ***CRP Forest*** | |
| CP11 | Vegetative Cover - Trees Already Established |
| CP16 | Shelterbelt Establishment |
| CP16A | Shelterbelt Establishment, Non-easement |

| | |
|---|---|
| CP17 | Living Snow Fence |
| CP22 | Riparian Forest Buffer |
| CP35E | Emergency Forestry – Bottomland Hardwood, New |
| CP3A | Hardwood Tree Planting |
| CP5 | Field windbreak Establishment |
| CP5A | Field windbreak Establishment, Non-easement |

***CRP Wetland***

| | |
|---|---|
| CP23 | Wetland Restoration |
| CP23A | Wetland Restoration, Non-flood Plain |
| CP27 | Farmable Wetland |
| CP28 | Farmable Wetland Associated Buffer |
| CP30 | Marginal Pastureland Wetland Buffer |

Figure 1. Location of the 17 greater prairie-chicken survey blocks (black bordered squares, 41 $km^2$) and Minnesota Prairie Conservation Plan (MPCP) core (gray fill), corridor (hatch fill), and corridor complex (stipple fill) areas in northwestern Minnesota. Survey blocks are labeled with the first letter of the respective county (black border) and corresponding number (from north to south).

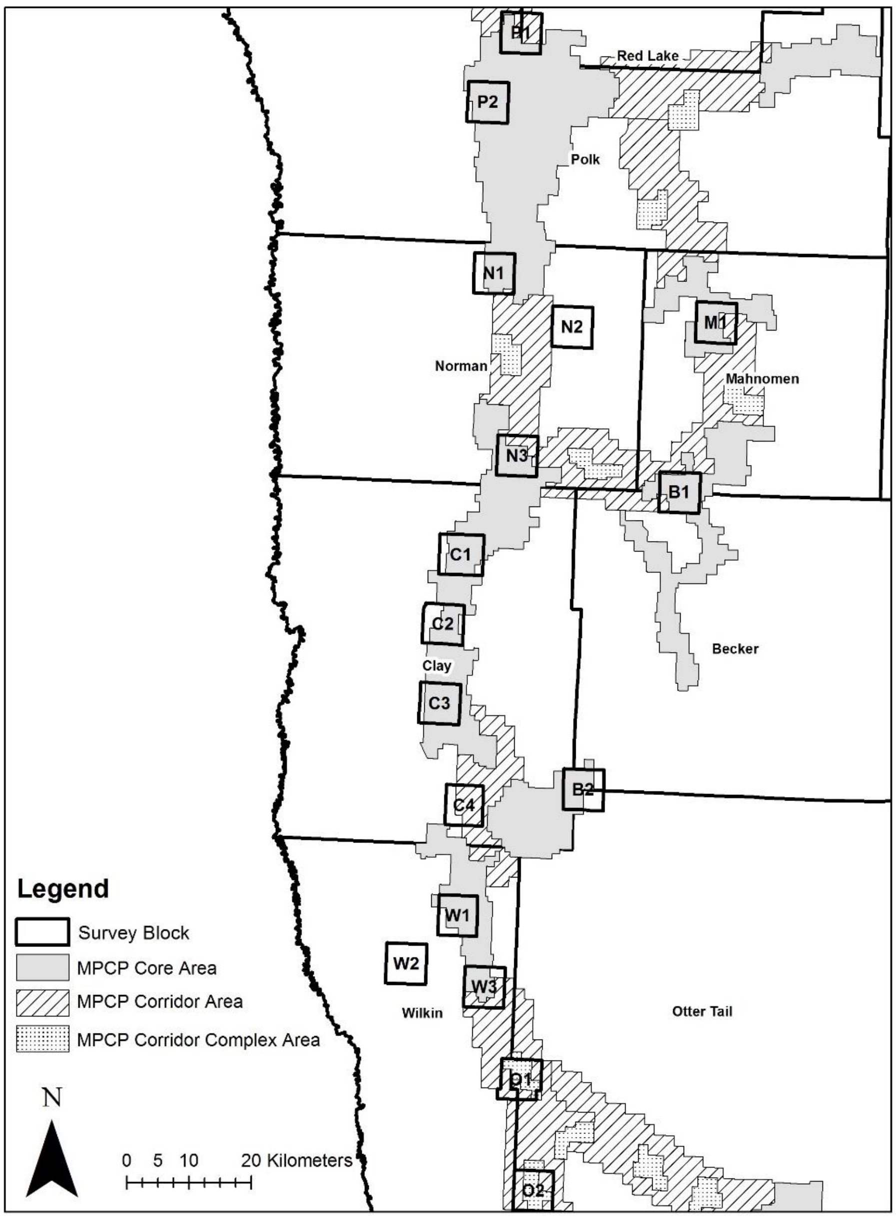


Figure 2. Predicted percent change in the number of greater prairie-chicken leks/km$^2$ using the survey-block-scale model and 17 predicted future landscape configurations for each of the 17 survey blocks and the average of all survey blocks in northwestern Minnesota. Landscape configurations include the 2016 mapped land-cover with all Conservation Reserve Program (CRP) enrollments as of 2016; 2016 mapped land-cover with CRP expirations scheduled from 2016 to 2029; and 2016 mapped land-cover with no CRP enrollments in 2030. Error bars are derived from the normalized root-mean-square error (13.15%) calculated from the survey-block-scale model.

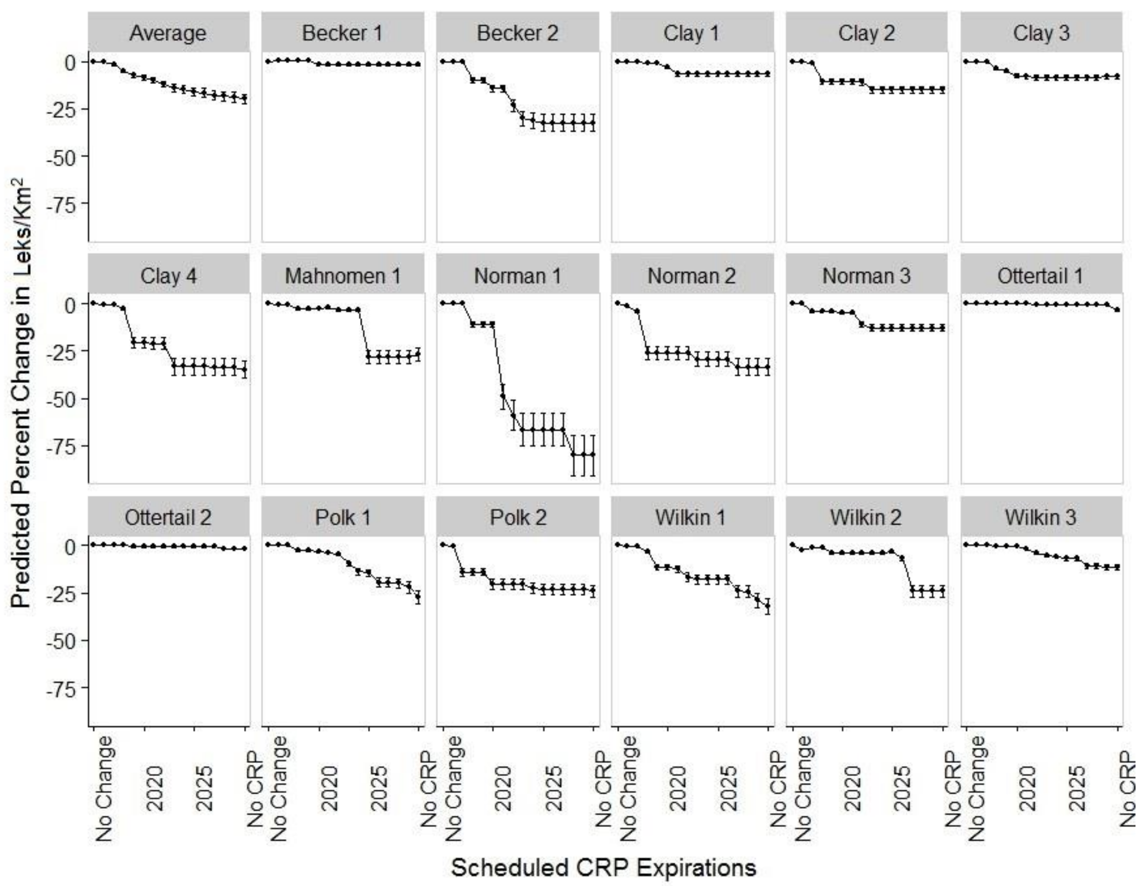


Figure 3. Predicted percent change in the number of male greater prairie-chickens [log (males/lek)] using the lek-scale model and 17 predicted landscape configurations for each of the 26 traditional leks in the study area and the average of all traditional leks in northwestern Minnesota. Landscape configurations include the 2016 mapped land-cover with all Conservation Reserve Program (CRP) enrollments as of 2016; 2016 mapped land-cover with CRP expirations scheduled from 2016 to 2029; and 2016 mapped land-cover with no CRP enrollments in 2030. Error bars are derived from the normalized root-mean-square error (17.38%) calculated from the lek-block scale model.

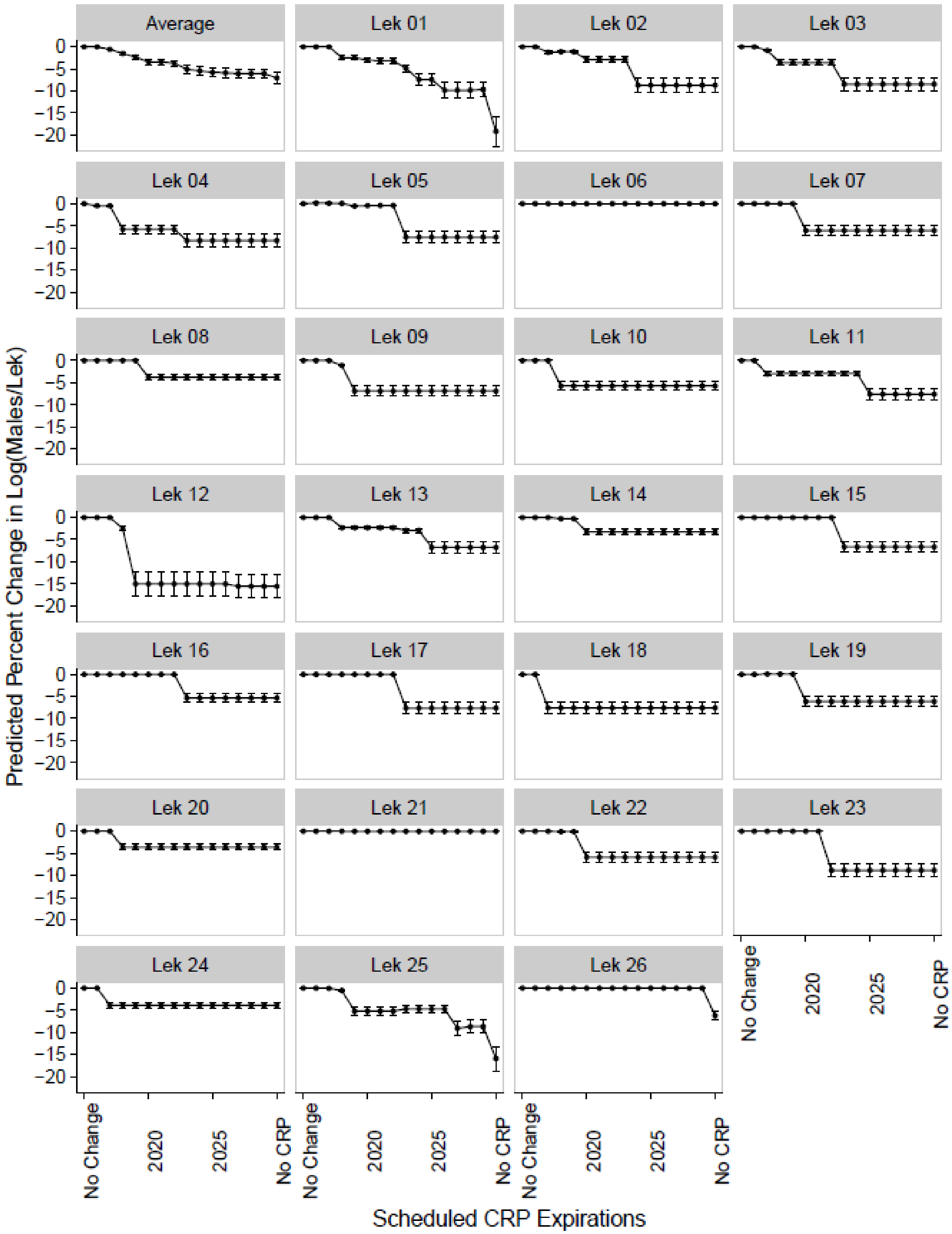
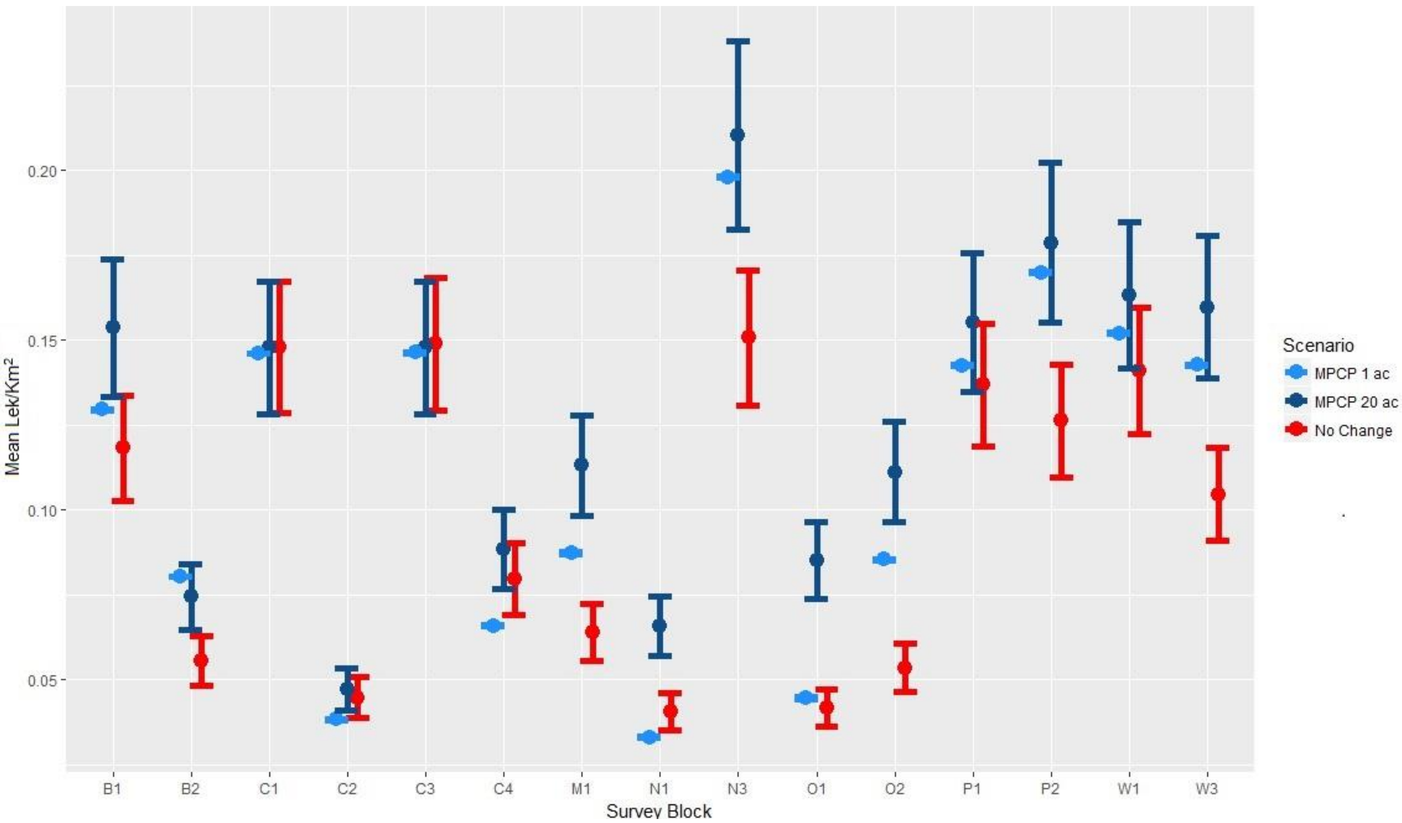
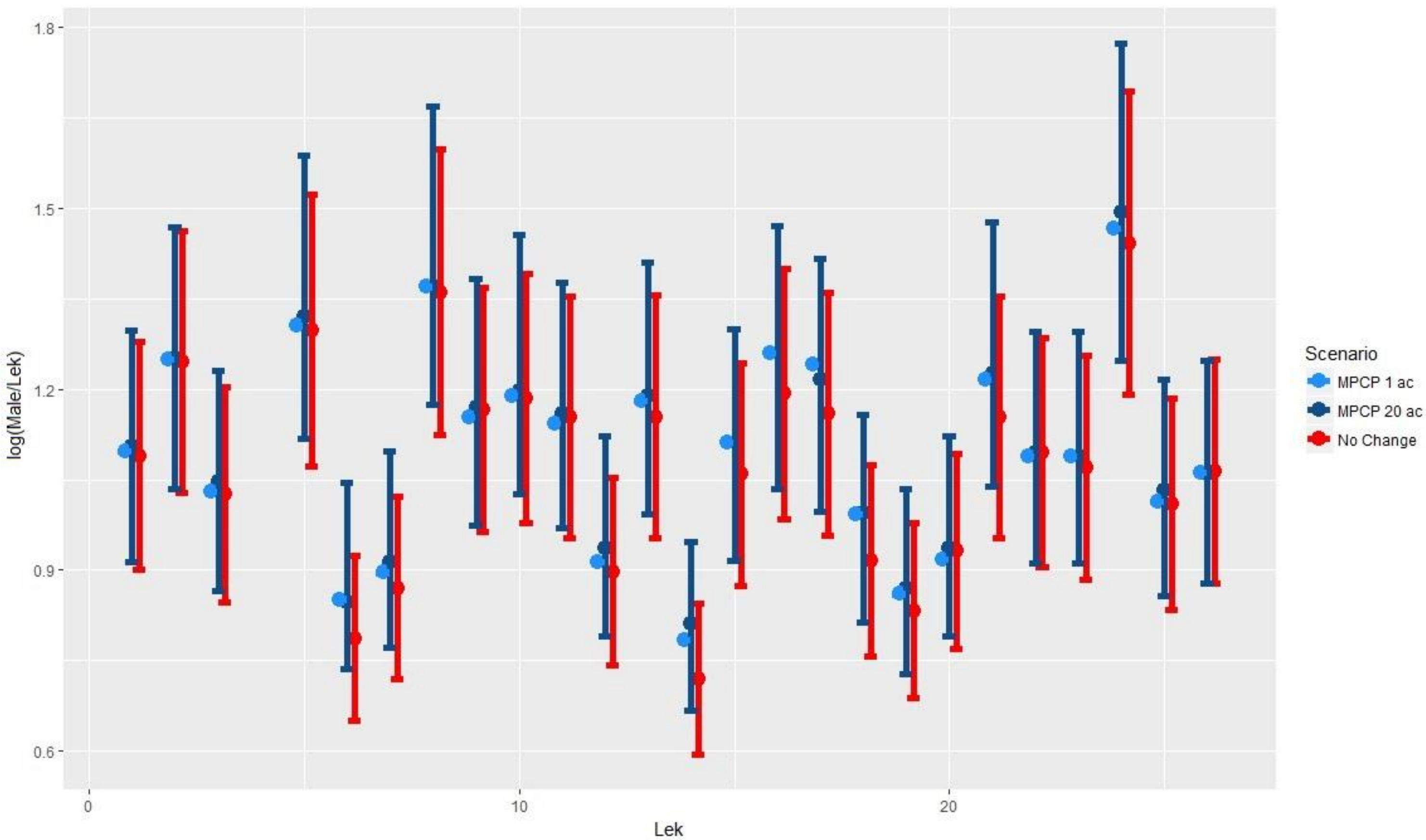

Average
Lek 01
Lek 02
Lek 03
Lek 04
Lek 05
Lek 06
Lek 07
Lek 08
Lek 09
Lek 10
Lek 11
Lek 12
Lek 13
Lek 14
Lek 15
Lek 16
Lek 17
Lek 18
Lek 19
Lek 20
Lek 21
Lek 22
Lek 23
Lek 24
Lek 25
Lek 26
0
−5
−10
−15
−20
No Change
2020
2025
No CRP
Predicted Percent Change in Log(Males/Lek)
Scheduled CRP Expirations

Figure 4. Predicted number of greater prairie-chicken leks/km$^2$ using the survey-block-scale model and 3 management scenarios for 15 of 17 survey blocks (N2 and W2 are not within the Minnesota Prairie Conservation Plan [MPCP] boundary; Appendix A) in northwestern Minnesota. Management scenarios include the 2016 mapped land-cover with all Conservation Reserve Program (CRP) enrollments as of 2016 (No Change); 100 simulations of randomly added grassland and wetland CRP to meet the MPCP core, corridor complexes, and corridor areas goals of each block added to the 2016 mapped land-cover with all CRP enrollments as of 2016 (MPCP 1 ac); and non-randomly added grassland and wetland CRP to meet the MPCP core, corridor complexes, and corridor areas goals of each block added to the 2016 mapped land-cover with all CRP enrollments as of 2016 (MPCP 20 ac). The predicted number of leks/km$^2$ under the MPCP $4.04 \times 10^{-3}$-km$^2$ (1-ac) scenario is the mean of 100 simulations and the associated error bars are the 95% confidence intervals. No change and MPCP 0.08-km$^2$ (20-ac) prediction error bars are associated with the normalized root-mean-square error (13.15%) calculated from the survey-block-scale model.



0.20
0.15
0.10
0.05
Mean Lek/Km²
B1
B2
C1
C2
C3
C4
M1
N1
N3
O1
O2
P1
P2
W1
W3
Survey Block
Scenario
MPCP 1 ac
MPCP 20 ac
No Change

Figure 5. Predicted number of male greater prairie-chickens [log(males/lek)] using the lek-scale model and 3 management scenarios for 25 traditional leks (1 lek analyzed was in survey block N2, which is not within the Minnesota Prairie Conservation Plan [MPCP] boundary) in northwestern Minnesota. Management scenarios include the 2016 mapped land-cover with all Conservation Reserve Program (CRP) enrollments as of 2016 (No Change); 100 simulations of randomly added grassland and wetland CRP to meet the MPCP core, corridor complexes, and corridor areas goals of each block added to the 2016 mapped land-cover with all CRP enrollments as of 2016 (MPCP 1 ac); and non-randomly added grassland and wetland CRP to meet the MPCP core, corridor complexes, and corridor areas goals of each block added to the 2016 mapped land-cover with all CRP enrollments as of 2016 (MPCP 20 ac). The predicted number of log(males/lek) under the MPCP $4.04 \times 10^{-3}$-$km^2$ (1-ac) scenario is the mean of 100 simulations and the associated error bars are the 95% confidence intervals. No change and MPCP 0.08-$km^2$ (20-ac) prediction error bars are derived from the normalized root-mean-square error (17.38%) calculated from the lek-scale model.


1.8
1.5
1.2
0.9
0.6
log(Male/Lek)
0
10
20
Lek
Scenario
MPCP 1 ac
MPCP 20 ac
No Change

Appendix A: Summary of predicted changes in the density of greater prairie-chicken leks (lek/km$^2$), the number of males/lek, and land-cover metrics at the survey-block and lek scales associated with expiration scenarios and Minnesota Prairie Conservation Plan (MPCP) enrollment scenarios. Calculation of relevant 2016 land-cover metrics including percent Grassland Conservation Reserve Program (CRP) and Wetland CRP at the survey-block level and percent combined grassland and wetland CRP and contiguity index of Grassland CRP at the lek scale in northwestern Minnesota. Error at the survey-block scale is derived from the normalized root-mean-square error (NRMSE; 13.15%) calculated from the survey-block-scale model. Error at the lek scale is derived from the NRMSE (17.38%) calculated from the lek-scale model. Number of Patches (NP) were not calculated for the lek scale because that model did not include that metric for predictions.

| | Expiration Scenarios | | | | 2016 Land-cover | |
|---|---|---|---|---|---|---|
| Survey Block | Total % Δ Lek/km$^2$ | Error | Year with Largest Δ Lek/km$^2$ | % Δ NP Following All Expirations | % Grassland CRP | % Wetland CRP |
| B1 | -1.83 | ±0.24 | 2020 | 9.76 | 7.20 | 2.01 |
| B2 | -32.41 | ±4.26 | 2022 | -22.38 | 11.43 | 3.20 |
| C1 | -6.64 | ±0.87 | 2021 | -2.02 | 7.19 | 2.01 |
| C2 | -15.03 | ±1.98 | 2018 | 8.13 | 5.02 | 7.48 |
| C3 | -7.90 | ±1.04 | 2018 | 4.94 | 7.00 | 4.04 |
| C4 | -34.93 | ±4.59 | 2019 | 19.61 | 21.29 | 28.38 |
| M1 | -26.83 | ±3.53 | 2025 | 20.59 | 63.44 | 5.64 |

| | | | | | | |
|---|---|---|---|---|---|---|
| N1 | -80.18 | ±10.54 | 2021 | 20.22 | 49.10 | 34.74 |
| N2 | -33.53 | ±4.41 | 2018 | 20.49 | 24.99 | 44.48 |
| N3 | -12.74 | ±1.68 | 2022 | 9.94 | 29.47 | 7.24 |
| O1 | -3.75 | ±0.49 | 2030 | 1.24 | 6.90 | 1.78 |
| O2 | -1.73 | ±0.23 | 2028 | 1.70 | 0.36 | 1.06 |
| P1 | -27.10 | ±3.56 | 2030 | 4.92 | 34.58 | 29.43 |
| P2 | -24.03 | ±3.16 | 2017 | -5.71 | 31.54 | 13.46 |
| W1 | -32.09 | ±4.22 | 2019 | 18.13 | 20.96 | 17.42 |
| W2 | -24.02 | ±3.16 | 2027 | 8.13 | 33.46 | 1.56 |
| W3 | -11.25 | ±1.48 | 2027 | 3.67 | 23.14 | 4.26 |

| Lek | Survey Block | Total % Δ Males/ Lek | Error | Year with Largest Δ Males/ Lek | % CRP | Contiguity of Grassland CRP |
|---|---|---|---|---|---|---|
| 1 | P1 | -19.16 | ±3.32 | 2030 | 40.81 | 0.79 |
| 2 | P2 | -8.72 | ±1.51 | 2024 | 13.77 | 0.78 |
| 3 | P2 | -8.47 | ±1.47 | 2023 | 6.52 | 0.86 |
| 4 | N2 | -8.34 | ±1.45 | 2018 | 9.24 | 0.42 |
| 5 | C2 | -7.60 | ±1.32 | 2023 | 6.51 | 0.43 |
| 6 | C3 | 0.00 | 0.00 | NA | 0.00 | 0.00 |
| 7 | C3 | -6.08 | ±1.06 | 2020 | 0.26 | 0.33 |
| 8 | C3 | -3.77 | ±0.65 | 2020 | 2.59 | 0.36 |
| 9 | C3 | -6.90 | ±1.20 | 2019 | 3.29 | 0.78 |
| 10 | C3 | -5.77 | ±1.00 | 2018 | 3.49 | 0.40 |
| 11 | C4 | -7.63 | ±1.32 | 2025 | 6.56 | 0.72 |
| 12 | C4 | -15.57 | ±2.7 | 2019 | 13.72 | 0.42 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 13 | B2 | -6.79 | ±1.18 | 2025 | 3.64 | 0.75 |
| 14 | M1 | -3.27 | ±0.57 | 2020 | 1.11 | 0.31 |
| 15 | W3 | -6.68 | ±1.6 | 2023 | 2.71 | 0.56 |
| 16 | W3 | -5.38 | ±0.93 | 2023 | 1.85 | 0.54 |
| 17 | N3 | -7.68 | ±1.33 | 2023 | 3.19 | 0.82 |
| 18 | N3 | -7.64 | ±1.33 | 2017 | 4.87 | 0.43 |
| 19 | B1 | -6.15 | ±1.07 | 2020 | 3.12 | 0.52 |
| 20 | C1 | -3.59 | ±0.62 | 2018 | 0.28 | 0.67 |
| 21 | C1 | -0.03 | ±0.01 | 2019 | 0.08 | 0.00 |
| 22 | C1 | -5.89 | ±1.02 | 2020 | 2.47 | 0.79 |
| 23 | N3 | -8.87 | ±1.54 | 2022 | 3.81 | 0.63 |
| 24 | C2 | -3.89 | ±0.67 | 2017 | 0.18 | 0.31 |
| 25 | W1 | -15.95 | ±2.77 | 2030 | 21.07 | 0.72 |
| 26 | W1 | -6.21 | ±1.08 | 2030 | 4.11 | 0.88 |

## Chapter 3

## Greater Prairie-Chicken Habitat Quality in CRP Contracts and Predicted Greater Prairie-Chicken Density in Northwestern Minnesota

***Overview**:* Although greater prairie-chickens (*Tympanuchus cupido pinnatus)* are identified as grassland obligate birds, not all grassland-cover types meet their habitat requirements of a diverse mosaic of vegetation composition and structural components. The Conservation Reserve Program (CRP) has the potential to make millions of ha of grassland in CRP enrollments available nationwide, but many are not high-quality habitat for greater prairie-chickens because the seeding mix planted or subsequent management plan for the planting does not result in high-quality habitat conditions for greater prairie-chickens. Because the CRP has experienced recent declines in northwestern Minnesota that are expected to continue, the ability to understand which CRP programs provide high-quality habitat conditions for greater prairie-chickens can allow for prioritization of these programs. To understand the program types and conditions that create optimal greater prairie-chicken habitat conditions, I modeled the relationships between remotely measured characteristics of CRP enrollments and vegetation characteristics associated with high-quality greater prairie-chicken breeding habitat. I then used models based on these relationships to predict existing extent and distribution of CRP enrollments that provide high-quality greater prairie-chicken breeding habitat across their northwestern Minnesota distribution. My results suggest that there are many combinations of CRP contract type, age of planting, and soil type that can provide appropriate vegetation structure and composition for greater prairie-chickens, and that high-quality greater prairie-chicken breeding habitat is not restricted to high diversity native-seed plantings.

Additionally, my results suggest that a higher amount of high-quality breeding habitat in northwestern Minnesota is positively associated with greater prairie-chicken abundance (leks/$km^2$) although there are many other landscape factors that also contribute to greater prairie-chicken abundance.

***Key Words***: Greater prairie-chicken, *Tympanuchus cupido pinnatus*, landscape, grassland, Conservation Reserve Program, Minnesota

## INTRODUCTION

Greater prairie-chickens (*Tympanuchus cupido pinnatus)* are obligate grassland birds that were once considered the leading game bird in central North America (Robel et al. 1970a; McNew et al. 2015). Declines in greater prairie-chicken abundance are strongly associated with decreases in the extent of the tallgrass prairie ecosystem, which once spanned over 380,000 $km^2$ in the Midwestern United States but has since experienced alteration and losses between 83 and >99% of its area due to conversion to row-crop agriculture and invasion of exotic grass (Noss et al. 1995; Herkert et al. 1996; Steiner and Collins 1996; Ryan 2000; Burger et al. 2006). Similarly, greater prairie-chicken abundance has declined over much of their distribution since the early 20$^{th}$ Century, resulting in heightened conservation concern and focused management efforts to increase and re-establish sustainable populations. In Minnesota, prairie-chicken hunting was closed in 1942 (Svedarsky et al. 1997), prairie-chickens were designated as a Species of Special Concern in 1984, and a limited-participation hunting season was reinitiated in 2003 (Roy 2014).

Greater prairie-chicken conservation in Minnesota and elsewhere has focused on maintaining and re-establishing grassland-cover types within large landscapes. Federal and state agricultural policy and programs provide opportunities to dramatically influence the amount of grassland in an agriculture-dominated landscape, and the largest private land retirement program in the United States is the Conservation Reserve Program (CRP; Stubbs 2014). Established in 1985, the CRP is authorized to remove land from crop production with the objectives to reduce soil erosion, improve water quality, and restore and protect wildlife habitats by providing financial incentives to reseed agricultural land to sod-forming or ecologically native vegetation for a period of 10 to 15 years. A variety of CRP contract types focus on different types of wildlife habitat restoration including field buffers, bottomland hardwood forestland, pollinator habitat, restoring farmed wetlands, and riparian habitat (Riley 2004), some of which can increase the amount of tallgrass prairie and other grassland-cover types in agricultural landscapes. Specific to greater prairie-chickens, the Back Forty Pheasant Habitat CRP-SAFE practice (USDA 2008) focuses on establishing or enhancing grasslands to provide high-quality greater prairie-chicken habitat within their distribution in northwestern Minnesota. However, even contract types that are not focused specifically on greater prairie-chickens may offer an important opportunity for habitat reconstruction as large contiguous tracts of land are enrolled and restored to grasslands (Riley 2004; Herkert 2009).

Grassland and wetland CRP enrollments can provide essential components of greater prairie-chicken habitat in northwestern Minnesota. The density (i.e., leks/$km^2$ and males/lek) of greater prairie-chickens in northwestern Minnesota is positively related to the amount of CRP grassland and wetland at the landscape and lek scales and the contiguity of CRP grassland at the landscape scale (Adkins, Chapter I). Additionally, simulations of targeted grassland and wetland CRP enrollments resulted in projected increases of greater prairie-chicken abundance by 59.6% (error: $\pm$7.84) at the landscape scale and 9.04% (error: $\pm$1.57) at the lek scale (Adkins, Chapter II). However, area enrolled in the CRP has declined nationwide since its peak enrollment of approximately 149,000 $km^2$ in 2007 (Stubbs 2014). This decrease is scheduled to continue as the 2014 Farm Bill decreased the enrollment cap from approximately 130,000 $km^2$ to < 100,000 $km^2$ by 2018 (Stubbs 2014). In the greater prairie-chicken range in Minnesota, area enrolled in the CRP (all Conservation Practice codes) declined 16-52% from 2007 to 2016.

As the area enrolled in the CRP continues to decline, it becomes vital to understand if differences in the vegetation structure and composition created by CRP contract types exist for greater prairie-chicken conservation. Intuitively, if conversion of grasslands and intensification of agriculture is the leading threat to greater prairie-chickens, then establishment of all grassland CRP should contribute to their conservation. However, although greater prairie-chickens are identified as grassland obligate birds, not all grassland-cover types provided by different CRP contract types meet their habitat requirements (Jones 1963; Niemuth 2000; McNew et al. 2015). Habitat requirements of greater prairie-chickens include areas for day resting, night roosting, courtship, nesting, and brood rearing that all require a different mosaic of vegetation composition and structural components (Jones 1963; McNew et al. 2015). Nationwide, millions of ha of land in CRP enrollments may be available, but many are not high-quality habitat for greater prairie-chickens because the seeding mix planted or subsequent management plan for the planting does not result in high-quality habitat conditions for greater prairie-chickens (Niemuth 2003; Burger et al. 2006; McNew et al. 2015).

My objective was to predict habitat quality of existing CRP grassland in greater prairie-chicken range in northwestern Minnesota and assess whether the amount of predicted high-quality CRP grassland available is related to greater prairie-chicken abundance range-wide at the landscape scale. Understanding the suitability of different types of CRP cover for greater prairie-chickens during the breeding season can provide important insight regarding which CRP contract types to prioritize within greater prairie-chicken range in northwestern Minnesota. Prioritizing where and what kind of practices to employ in the CRP to benefit species of high conservation concern becomes increasingly important as the cap on CRP enrollment decreases. To address this objective, I modeled the relationships between remotely measured characteristics of CRP enrollments under different practice codes, on different soil types, and age since enrollment and vegetation characteristics associated with high-quality greater prairie-chicken breeding habitat (maximum height of vegetation, visual obstruction of vegetation, and percent cover of forbs). I then used models based on these relationships to predict existing extent and distribution of CRP enrollments that provide high-quality greater prairie-chicken breeding habitat. I expected CRP contract types that are specified with the main objective of wildlife conservation to be the most likely to have vegetation characteristics within the ranges considered to be high-quality greater prairie-chicken breeding habitat. I also expected a positive relationship between the predicted abundance of greater prairie-chickens and the predicted abundance of high-quality greater prairie-chicken breeding habitat provided by the CRP across the entire greater prairie-chicken breeding distribution in northwestern Minnesota.

## METHODS

### Study Area and Greater Prairie-Chicken Survey Data

I assessed relationships between CRP enrollment type, soil type, and time since enrollment and greater prairie-chicken breeding habitat characteristics in the portion of northwestern Minnesota that currently supports greater prairie-chicken populations and where prairie-chickens have been surveyed annually using standardized protocols beginning in 2004 (Fig. 1, Minnesota Department of Natural Resources, unpublished data). As part of the standardized survey coordinated by the Minnesota Department of Natural Resources, 17 41-$km^2$ blocks were systematically surveyed for prairie-chicken leks from 2004-2016. Data from the greater prairie-chicken spring survey consisted of count and location information for leks from 2004-2016 within established survey blocks (Fig. 1).

Annual surveys of greater prairie-chickens were coordinated by the MNDNR and executed in collaboration with the Minnesota Prairie-Chicken Society, The Nature Conservancy (TNC), U. S. Fish and Wildlife Service, and other volunteers. The survey protocol consisted of surveyors being assigned 4 Public Land Survey (PLS) sections within a survey block and attempting to observe greater prairie-chicken mating display behavior repeatedly in these sections. Surveyors observed mating display behavior visually and counted the number of males, females, and prairie-chickens of unknown sex at each visit to each lek. Prairie-chickens displaying at leks were recorded as males and individuals not displaying during display bouts as females; if prairie-chickens at a lek were flushed without prior determination of sex, individuals present at leks were recorded as unknown sex (Roy 2014). Location data were available for 58-114 leks per year within these survey blocks recorded to the level of quarter-section or GPS coordinates (Roy et al. 2015). Occasionally, lek locations were only recorded to the accuracy of the section. When this occurred, I examined notes included with lek observations and surrounding lek locations in the current, previous, and later years to more precisely estimate lek locations. If I could not estimate a more accurate lek location from the survey data or if the survey data indicated the lek was at the center of the section, I placed the lek location in the center of the section. This occurred in approximately 4% of recorded leks.

**Vegetation Survey Data**

I randomly selected 200 survey points stratified by grassland CRP program type, soil type, and time since planting across the study area. These variables are most likely to influence composition and structural diversity of vegetation and are of primary interest in the context of assessing how different cover types resulting from CRP enrollments are related to greater prairie-chicken abundance. Type of CRP program gives a range of different grassland-cover types of differing habitat quality and composition due to program standards and seeding requirements, soil characteristics are commonly used as predictors in land-use and cover-type models (Stoebner and Lant 2014), and time since planting is related to how long the cover type has been available and the structure of vegetation.

I considered types of CRP enrollments to include in my analysis that comprised ≥2% of each survey block during the 2016 field season. If no types of CRP enrollments comprised ≥2% of a survey block, I conducted no vegetation surveys in that survey block. I included CRP grassland and wetland categories CP1, CP2, CP10, CP23, CP25, and CP4D (Table 1). I determined CRP enrollment and expiration dates by referring to CRP contract information and by corresponding with private landowners. I included 4 categories of time since planting-A: 0-4, B: 5-9, C: 10-14, D: ≥15 years. I identified soil type from the Soils Survey Geographic database (SSURGO) soils data set (Soil Survey Staff 2011a), and I used the descriptions of taxonomic classes of soil provided by the National Cooperative Soil Survey to categorize soil type into sand, loam, clay, muck, and silt (Soil Survey Staff 2011b).

I allocated 200 survey points across combinations of these remotely measured characteristics (i.e., CRP conservation code, time since planting, and soil type) that represented >0.5% of the total survey area, which resulted in 34 categories. However, because all survey locations fell on private property (i.e., areas in CRP contracts), sampling at individual locations required landowner permission. Landowners denied access to survey points in 2 categories and I therefore sampled a total of 32 categories. I allocated a minimum of 5 survey points to each of these 32 categories and allocated the remaining survey points proportionally across categories resulting in a range of 5 – 8 survey points per category. I assigned 1 survey point to a single CRP contract until each contract in a category was assigned a survey point before assigning a second survey point to an individual contract. If there were more contracts within a category than survey points to assign to that category, I allocated survey points to the contracts with the greatest area.

**Vegetation Measurement**

I conducted vegetation surveys from June to August in 2016. Each survey point served as the center of 2 intersecting transects extending 12-m in each cardinal direction, and each transect arm was restricted to lie entirely within the same patch of grassland cover. At the center of the 2 transects and at 6-m intervals along each 12-m arm of each transect, I measured vegetation in 1-$m^2$ plots, for a total of 9 1-$m^2$ plots per pair of intersecting transects (Daubenmire 1959; McNew et al. 2015). I estimated the percent cover of vegetation categories using an 80-$cm^2$ grid nested within the 1-$m^2$ plots, dividing the plot into 16 cells of 20-$cm^2$ (Nack and Andersen 2006). I categorized cover as grass, forbs, woody vegetation, bare ground, or duff and estimated the percent cover of each cover type by determining the most dominant cover type within each cell, tallying totals for each cover type per transect, and dividing by 144 (the number of available cells at each transect; Nack and Andersen 2006). In addition, I took photographic images from 2 m above ground level at each of the 1-$m^2$ plots (Booth et al. 2008). These photographs served as a source of data verification for vegetation measurements. I described vegetation structural composition by taking maximum height measurements and 2 visual obstruction readings (VOR) at opposite directions along the contour at a distance of 2 m and height of 0.5 m in the center plot and the plots at the end of the 4 12-m transect arms of each pair of intersecting transects to determine vegetation vertical density (Robel et al. 1970b; McNew et al. 2015). I used the mean of the 10 measurements from each pair of intersecting transects to assign vegetation density and height for that sample location.

**Data Analysis**

I used remotely measured characteristics (i.e., soil type, CRP contract type, age of planting) to predict maximum vegetation height, VOR, and percent cover of forbs in different CRP contract types with linear regression based on vegetation measurements made in 2016. I considered models that included the main effects of remotely measured characteristics and potential interactions between the characteristics identified with interaction plots. I assessed models relating remotely measured characteristics and maximum vegetation height, VOR, and percent cover of forbs at different CRP contract types by comparing Akaike Information Criterion (AIC) values (Akaike 1973; Burnham and Anderson 2002). I then evaluated whether predicted vegetation conditions in different CRP contract types using the best-supported model for maximum vegetation height, VOR, and percent cover of forbs were within the range of conditions associated with high-quality greater prairie-chicken breeding habitat (e.g., nesting, brood rearing, escape), based on descriptions in the peer-reviewed literature. I considered high-quality breeding habitat to have maximum vegetation height between 12-90 cm (Jones 1963; Svedarsky 1979; Prose 1985), VOR between 2.0-3.0 dm (Prose 1985), and percent cover of forbs >20% (Jones 1963; Robel 1970a). I considered CRP contracts to be high-quality greater prairie-chicken breeding habitat if all 3 of the predicted structural and composition metrics (i.e., maximum vegetation height, VOR, and percent cover of forbs) were within the ranges of values reported in the literature associated with high-quality greater prairie-chicken breeding habitat. I therefore only considered CRP contracts that met these criteria to provide high-quality greater prairie-chicken breeding habitat.

I then created a 41-$km^2$ moving window to predict lek density (lek/$km^2$) across the entire breeding distribution of greater prairie-chickens in northwestern Minnesota using a previously created 2016 land-cover map and survey-block-scale model relating greater prairie-chicken abundance to landscape characteristics of cover-type composition, contiguity, and fragmentation (Adkins, Chapter I). I calculated the amount of high-quality greater prairie-chicken breeding habitat on CRP contracts within each 41-$km^2$ block using 2016 CRP contract data provided by Farm Service Agency (FSA) and SSURGO soils data set. Finally, I assessed the relationship between predicted lek density and amount of predicted high-quality greater prairie-chicken breeding habitat on CRP contracts using linear regression.

## RESULTS

### Models of High-Quality Greater Prairie-Chicken Breeding Habitat

The best-supported model of maximum vegetation height included the main effects of CRP contract type, soil type, and age of planting and the interaction between CRP contract type and age of planting (Table 2). Interaction plots indicated significant pairwise interactions between all main effects and I therefore included all pairwise interactions in the model set. No competitive models were within 2 AIC units of the best-supported model (Table 2). I therefore used the best-supported model to predict maximum vegetation height at each of the 120 possible combinations (i.e., 6 CRP contract types*4 age categories*5 soil types) of the 3 remotely measured characteristics. Of these 120 possible combinations, 69 were within the range considered to be high-quality greater prairie-chicken breeding habitat (12-90 cm: Jones 1963; Svedarsky 1979; Prose 1985). Eighty percent of predictions of maximum vegetation height for the possible CP25 combinations; 60% of the possible CP1, CP2, and CP23 combinations; 50% of the possible CP10 combinations; and 35% of the possible CP4D combinations were within the range considered to be high-quality breeding habitat.

The best-supported model of VOR included the main effects of CRP contract type, soil type, and age of planting and the interaction between soil type and age of planting (Table 3). Interaction plots indicated significant pairwise interactions between all main effects and I therefore included them in the model set. Two additional models were competitive; the first ($\Delta$AIC= 0.06) included the main effects of CRP contract type, soil type, and age of planting and the interaction between CRP contract type and age of planting (Table 3) and the second ($\Delta$AIC= 0.31) included only the main effects of CRP contract type, soil type, and age of planting. I therefore used the predicted values from each of these 3 models to predict VOR for each of the 120 possible combinations of CRP contract type, soil type, and age of planting. Of these 120 possible combinations, predictions of VOR for 37 were within the range considered to be high-quality greater prairie-chicken breeding habitat (2.0- 3.0 dm; Prose 1985). Thirty-five percent of the predictions of VOR for possible CP1, CP10, and CP23 combinations; 30% of the possible CP25 and CP4D combinations; and 20% of the possible CP2 combinations were within the range considered to be high-quality greater prairie-chicken breeding habitat.

The best-supported model of percent cover of forbs included only the main effects of CRP contract type, soil type, and age of planting. I included interactions between CRP contract type and soil type and between soil type and age of planting, but not between CRP contract type and age of planting in models based on assessment of interaction plots. No models were competitive with the best-supported model (all $\Delta AIC > 2$) in the suite of models I considered. I used the best-supported model to predict the percent cover of forbs at each of the 120 possible combinations of CRP contract type, soil type, and age of planting. Of these 120 possible combinations, none were predicted to be high-quality greater prairie-chicken breeding habitat based on percent cover of forbs (>20%: Jones 1963; Robel 1970a). I therefore redefined high-quality greater prairie-chicken breeding habitat based on percent cover of forbs greater than the average forb cover (4.8%), based on the assumption that forb cover is an important component of breeding habitat (Jones 1963; Robel 1970a). Under this assumption, predictions of percent cover of forbs for the 120 possible combinations of CRP contract type, soil type, and age of planting included 49 that were high-quality breeding habitat. One hundred percent of the possible CP1 combinations; 45% of the possible CP23 combinations; 30% of the possible CP10, CP25, and CP4D combinations; and 10% of the possible CP2 combinations were predicted to have high-quality greater prairie-chicken breeding habitat (i.e., percent forb cover > average percent forb cover).

Eleven combinations of CRP contract type, soil type, and age of planting with predicted values of maximum vegetation height, VOR, and percent forb cover were in the respective ranges associated with high-quality greater prairie-chicken breeding habitat. The combinations of CRP contract type, soil type, and age of planting resulting in predicted high-quality greater prairie-chicken breeding habitat included CP1 codes with sandy soils of all ages, with loam soils > 15 years, or with clay soils in the upper intermediate age (10-14 years); CP2, CP23, CP25, and CP4D codes with clay soils in the lower intermediate ages (5-9 years); and CP23 codes with clay soils in the upper intermediate age.

**Relationship between Predicted High-Quality Breeding Habitat and Lek Density**

I calculated the predicted amount of high-quality greater prairie-chicken breeding habitat, based on the models described above in 41-km$^2$ blocks (the size of standardized survey blocks, see Adkins, Chapter I) across the northwestern Minnesota greater prairie-chicken breeding distribution (Fig. 2). Of the 653 41-km$^2$ blocks across the study area, 482 had no CRP enrollments predicted to be high-quality breeding habitat and 71 had no grassland or wetland CRP contracts. The highest amount of predicted high-quality breeding habitat within a 41-km$^2$ block was 1.5 km$^2$. Five blocks had predicted high-quality breeding habitat totaling >1 km$^2$ in CRP; these blocks were all within Polk, Red

Lake, and Norman counties, which are in the northern part of the study area and historically have or have had a high amount of CRP contracts.

I also predicted the density of leks/km$^2$ across the same grid of 41-km$^2$ blocks (Fig. 3), and predictions ranged from 0.02 to 0.24 leks/km$^2$. The amount of predicted high-quality greater prairie-chicken breeding habitat in CRP was positively associated with the predicted lek density (predicted lek density increased 0.05 leks/km$^2$ with an increase in amount of predicted high-quality breeding habitat of 1 km$^2$; Fig. 4). However, only about 12% ($R^2$=0.12) of the variation in the predicted density of leks/km$^2$ was explained by the amount of predicted high-quality breeding habitat in CRP. To further evaluate this relationship, I excluded 41-km$^2$ blocks with no predicted high-quality breeding habitat in CRP, but the resulting association between predicted high-quality breeding habitat and predicted lek density (predicted lek density increased 0.04 leks/km$^2$ with an increase in amount of predicted high-quality breeding habitat of 1 km$^2$; $R^2$=0.12) was similar (Fig. 5).

## DISCUSSION

### High-Quality Greater Prairie-Chicken Breeding Habitat

Based on CRP contract requirements, I expected contract types and programs targeted at wildlife conservation to result in a higher percent of forbs and warm-season grasses and provide high-quality greater prairie-chicken breeding habitat. Although soil and age of planting conditions on CRP programs CP25 (Restoration of Rare & Declining Habitat; Table 1) and CP4D (Permanent Wildlife Habitat, Non-easement; Table 1) are intended to provide high-quality greater prairie-chicken habitat, I found that the CRP contract type in over half of the 11 categories predicted to provide high-quality breeding habitat was CP1 (Introduced Grasses and Legumes; Table 1). That contract type requires a minimum of 2 introduced grass species (USDA 2017a). Although introduced cool-season grasses commonly used in this program (e.g., smooth brome [*Bromus inermis*], timothy [*Phleum pretense*], and Kentucky bluegrass [*Poa pratensis*]) are not commonly used for native prairie restorations and can degrade existing remnant prairies through invasion, early green up and structural composition may provide high-quality greater prairie-chicken habitat (Svedarsky et al. 2003). In fact, Svedarsky (1979) found that greater prairie-chickens in northwestern Minnesota exhibited a strong preference for smooth brome for nesting.

Additionally, even though no native forbs are required in the specifications of CP1, I found all of the possible CP1 combinations of soil type and age of planting were predicted to have above average percent forb cover. Although this seems like a contradiction, it is likely due to the increased presence of "weedy" or introduced forbs on this contract type. I did not consider whether forbs were indigenous or introduced in my predictions of percent forb cover, because although introduced forbs are not thought to be as desirable in a tallgrass prairie restoration as indigenous forbs, introduced forbs likely still attract insects, which are an essential part of chick diet during brood rearing (Jones 1963). It is not clear whether more diverse forb plantings associated with different CRP contract types result in more diverse species composition. However, plant species composition is not as important as structural requirements for greater prairie-chickens (Svedarsky et al. 2003).

Of the 11 combinations of CRP contract type, soil type, and age of planting that resulted in predicted high-quality greater prairie-chicken breeding habitat, 8 were in intermediate age-of-planting categories (i.e., B:5-9 and C:10-14 years). Mid-contract management of CRP contracts (e.g., disk, spray, burn or interseed) typically occurs between years 5-6 of a 10-year contract and years 8-10 of a 15-year contract (USDA 2017b). Predicted high-quality habitat conditions seem to align with the occurrence of this management, because management is conducted to increase plant community species and structural diversity (USDA 2017a). Furthermore, mid-contract management may be increasingly important in contract types and conservation programs where native forbs are required to be planted (i.e., CP2, CP23, CP25, and CP4D). All predicted high-quality breeding habitat conditions on these contract types with specified forb plantings were during the 2 intermediate age-of-planting categories (i.e., B:5-9 and C:10-14). Notably, 4 of the 6 CP1 soil and age-of-planting combinations predicted to provide high-quality greater prairie-chicken breeding habitat were on sandy soils in all ages of planting. This suggests that age of planting, and the related management that occurs over time, is less important for greater prairie-chickens on plantings without forbs on sandy soils.

All of the soil-type and age-of-planting combinations of CRP contract types that had predicted high-quality greater prairie-chicken breeding habitat and that require native forbs to be planted (i.e., CP2, CP23, CP25, and CP4D) were found on clay soil types. Highly productive soils tend to have higher clay content (Whisler et al. 2016). Possibly, these more diverse seeding mixes require highly productive soils and a management regime to result in the vegetation composition and structural diversity that comprises high-quality greater prairie-chicken habitat. However, this rich soil type is most commonly converted to agriculture (Whisler et al. 2016) and therefore likely does not contribute substantively to greater prairie-chicken breeding habitat. Conversely, the majority of CP1 contracts were found on sandy soils that are typically less productive.

**Range-Wide Breeding Habitat and Lek Density Predictions**

Predicted lek density and the amount of high-quality greater prairie-chicken breeding habitat in CRP enrollments were positively related in the same 41-$km^2$ blocks across the greater prairie-chicken distribution in northwestern Minnesota. However, this relationship left considerable variation in lek density unexplained, so other factors likely influence lek density beyond the amount of high-quality breeding habitat provided by CRP contracts. In Chapter I I constructed models to predict the number of leks/$km^2$ in the survey blocks used in this analysis, and these models indicated that landscape composition, contiguity, and fragmentation were all related to lek density. Additionally, several other complications occurred in the analysis of the relationship between the amounts of high-quality greater prairie-chicken breeding habitat provided by CRP contracts and the predicted leks/$km^2$. The models I developed provide a means of identifying areas at a distribution-wide scale that have a landscape suitable to support greater prairie-chickens. However, greater prairie-chickens usually settle near their natal areas; for example, greater prairie-chickens have been found to occur within a ~2-km radius surrounding leks (Merrill et al. 1999; Niemuth 2011) throughout their breeding cycle. The model I used to predict the number of leks/$km^2$ at a distribution-wide scale did not account for whether greater prairie-chickens occurred within a particular 41-$km^2$ block. Although land-cover conditions may be highly suitable for greater prairie-chickens, they will be unlikely to occur in an area isolated from other leks. Finally, although greater prairie-chickens use grassland for all portions of their life history (e.g., winter roosting, mating rituals, foraging; Merrill et al. 1999, Niemuth 2000), my models only focused on attributes of greater prairie-chicken breeding habitat as defined in the literature. Different vegetation composition and structural conditions are required by greater prairie-chickens at each stage of their life history, and these conditions do not necessarily fall within the range of conditions associated with high-quality greater prairie-chicken breeding habitat that I used. Additionally, "breeding season" captures a variety of different stages during the greater prairie-chicken life-cycle (i.e., nesting and brood rearing) and spans from early spring to summer. However, my vegetation measurements were conducted in the summer (June-August) and may have more heavily captured brood-rearing conditions compared to conditions in the literature regarding nesting. To understand how different types of CRP contribute to the entire life cycle of greater prairie-chickens, CRP grassland vegetation measurements would need to be made from CRP grasslands throughout the year and compared to habitat needs at specific, corresponding times of year.

**Management Implications**

As the extent of CRP grassland continues to decrease due to CRP contract expirations and a lower cap on enrollments, it becomes increasingly important to understand the relationship between CRP grassland and greater prairie-chickens, including where to target CRP enrollments and how to provide high-quality greater prairie-chicken habitat within CRP contracts. CRP grassland contract types encompass a wide variety of standards and specifications for vegetative cover, and this cover may differ based on the age of planting and soil type. My results suggest that many combinations of CRP contract type, age of planting, and soil type can provide appropriate vegetation structure and composition for breeding greater prairie-chickens, and that high-quality greater prairie-chicken breeding habitat is not restricted to high-diversity native-seed plantings. CRP contract types that have a more diverse seeding specification, including native forbs and grasses, meet high-quality habitat conditions when they are seeded in highly productive soil and undergo mid-contract management. Conversely, CRP contract types that only include introduced grasses can provide appropriate vegetation on a diversity of soils and ages of planting. My results suggest that more high-quality breeding habitat at a distribution-wide scale in northwestern Minnesota is positively associated with greater prairie-chicken abundance (leks/$km^2$), but that many other landscape factors are also related to greater prairie-chicken abundance. Finally, my analyses did not consider vital rates (e.g., nesting success, brood survival) of greater prairie-chickens, which may relate differently to habitat characteristics than measures of abundance.

Table 1. All Conservation Reserve Program (CRP) practice codes in northwestern Minnesota greater prairie-chicken survey blocks provided by the Farm Service Agency classified into categories of CRP grassland, CRP forest, and CRP wetland.

| **CRP Practice Code** | **CRP Practice Name** |
|---|---|
| ***CRP Grassland*** | |
| CP1 | Establishment of Permanent Introduced Grasses & Legumes |
| CP10 | Vegetative Cover - Grasses Already Established |
| CP12 | Wildlife Food Plot |
| CP18 | Establishment of Permanent Vegetation to Reduce Salinity |
| CP18B | Establishment of Perm. Vegetation to Reduce Salinity, Non-easement |
| CP18C | Establishment of Perm. Salt Tolerant Vegetative Cover, Non-easement |
| CP2 | Establishment of Permanent Native Grasses |
| CP21 | Filter Strips |
| CP25 | Restoration of Rare & Declining Habitat |
| CP38E | SAFE (State Acres for wildlife Enhancement)– Grass |
| CP42 | Pollinator Habitat |
| CP4D | Permanent Wildlife Habitat, Non-easement |
| CP8A | Grass Waterways, Non-easement |
| ***CRP Forest*** | |
| CP11 | Vegetative Cover - Trees Already Established |
| CP16 | Shelterbelt Establishment |
| CP16A | Shelterbelt Establishment, Non-easement |
| CP17 | Living Snow Fence |

| | |
|---|---|
| CP22 | Riparian Forest Buffer |
| CP35E | Emergency Forestry – Bottomland Hardwood, New |
| CP3A | Hardwood Tree Planting |
| CP5 | Field Windbreak Establishment |
| CP5A | Field Windbreak Establishment, Non-easement |

***CRP Wetland***

| | |
|---|---|
| CP23 | Wetland Restoration |
| CP23A | Wetland Restoration, Non-floodplain |
| CP27 | Farmable Wetland |
| CP28 | Farmable Wetland Associated Buffer |
| CP30 | Marginal Pastureland Wetland Buffer |

Table 2. Number of parameters (*K*), Akaike's Information Criterion (AIC) value, model comparisons, and weights for competing models (ω) for maximum height of vegetation on Conservation Reserve Program (CRP) contracts in the greater prairie-chicken distribution in northwestern Minnesota. Covariates considered were CRP contract type (CRP), soil type (Soil), and age of planting (Age). Interactions between covariates were considered when indicated by interaction plots.

| Model | *K* | AIC Value | Δ AIC | ω |
|---|---|---|---|---|
| CRP+Soil+Age+CRP:Age | 19 | 1238.77 | 0.00 | 0.70 |
| CRP+Soil+Age+CRP:Age+Soil:Age | 24 | 1240.99 | 2.22 | 0.23 |
| CRP+Soil+Age+CRP:Soil+CRP:Age+Soil:Age | 29 | 1244.88 | 6.11 | 0.03 |
| CRP+Soil+Age+CRP:Age+Soil:CRP | 25 | 1245.84 | 7.07 | 0.02 |
| CRP+Soil+Age+CRP:Soil+Soil:Age | 25 | 1249.08 | 10.31 | 0 |
| CRP+Soil+Age+Soil:Age | 19 | 1249.12 | 10.34 | 0 |
| CRP+Soil+Age | 14 | 1249.71 | 10.93 | 0 |
| CRP+Soil+Age+CRP:Soil | 21 | 1250.02 | 11.25 | 0 |

Table 3. Number of parameters ($K$), Akaike's Information Criterion (AIC) value, model comparisons, and weights for competing models (ω) for visual obstruction reading (VOR) on Conservation Reserve Program (CRP) contracts in the greater prairie-chicken distribution in northwestern Minnesota. Covariates considered were CRP contract type (CRP), soil type (Soil), and age of planting (Age). Interactions between covariates were considered when indicated by interaction plots.

| Model | $K$ | AIC Value | Δ AIC | ω |
|---|---|---|---|---|
| CRP+Soil+Age+Soil:Age | 19 | 200.22 | 0.00 | 0.35 |
| CRP+Soil+Age+CRP:Age | 19 | 200.29 | 0.06 | 0.34 |
| CRP+Soil+Age | 14 | 200.54 | 0.31 | 0.30 |
| CRP+Soil+Age+CRP:Age+Soil:Age | 24 | 202.59 | 2.37 | 0 |
| CRP+Soil+Age+CRP:Soil+Soil:Age | 25 | 204.32 | 4.09 | 0 |
| CRP+Soil+Age+CRP:Age+Soil:CRP | 15 | 204.79 | 4.57 | 0 |
| CRP+Soil+Age+CRP:Soil+CRP:Age+Soil:Age | 29 | 204.86 | 4.64 | 0 |
| CRP+Soil+Age+CRP:Soil | 21 | 205.13 | 4.90 | 0 |

Table 4. Number of parameters (*K*), Akaike's Information Criterion (AIC) value, model comparisons, and weights for competing models (ω) for percent cover of forbs on Conservation Reserve Program (CRP) contracts in the greater prairie-chicken distribution in northwestern Minnesota. Covariates considered were CRP program (CRP), soil type (Soil), and age of planting (Age). Interactions between covariates were considered when indicated by interaction plots.

| Model | *K* | AIC Value | Δ AIC | ω |
|---|---|---|---|---|
| CRP+Soil+Age | 14 | -1140.90 | 0.00 | 0.78 |
| CRP+Soil+Age+Soil:Age | 19 | -1137.82 | 3.07 | 0.27 |
| CRP+Soil+Age+CRP:Soil | 21 | -1135.07 | 5.83 | 0.04 |
| CRP+Soil+Age+CRP:Soil+Soil:Age | 25 | -1133.12 | 7.78 | 0.02 |
| CRP+Soil+Age+CRP:Age+Soil:CRP | 25 | -1128.69 | 12.20 | 0 |

Figure 1. Location of the 17 greater prairie-chicken survey blocks (gray labeled squares, 41 $km^2$) in northwestern Minnesota. Survey blocks are labeled with the first letter of the respective county (black border) and corresponding number (from north to south).

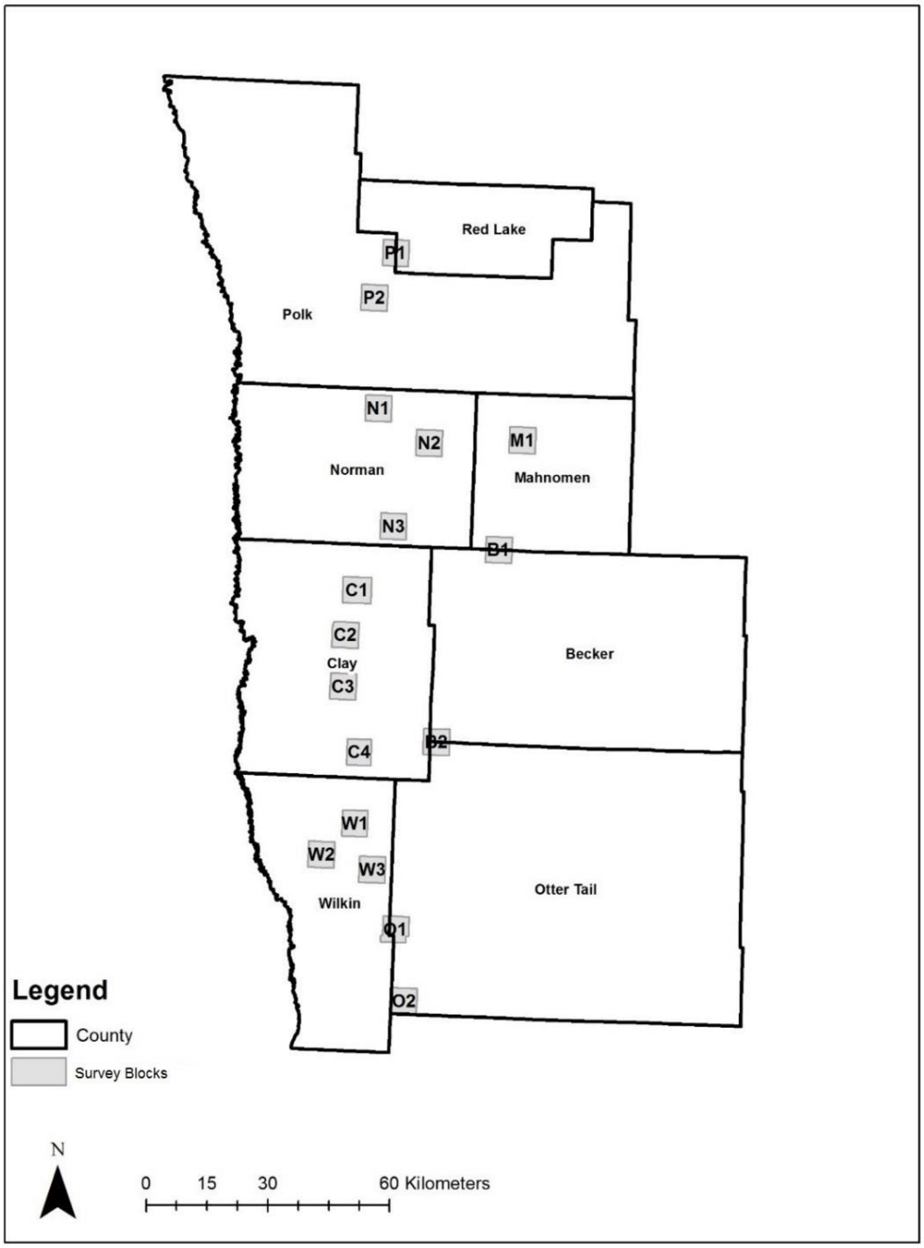


Figure 2. Amount of predicted high-quality greater prairie-chicken breeding habitat in Conservation Reserve Program (CRP) per 41 $km^2$ in the 8-county (black border) study area that encompasses the breeding distribution in northwestern Minnesota. Highest density is dark red and lowest is dark blue.

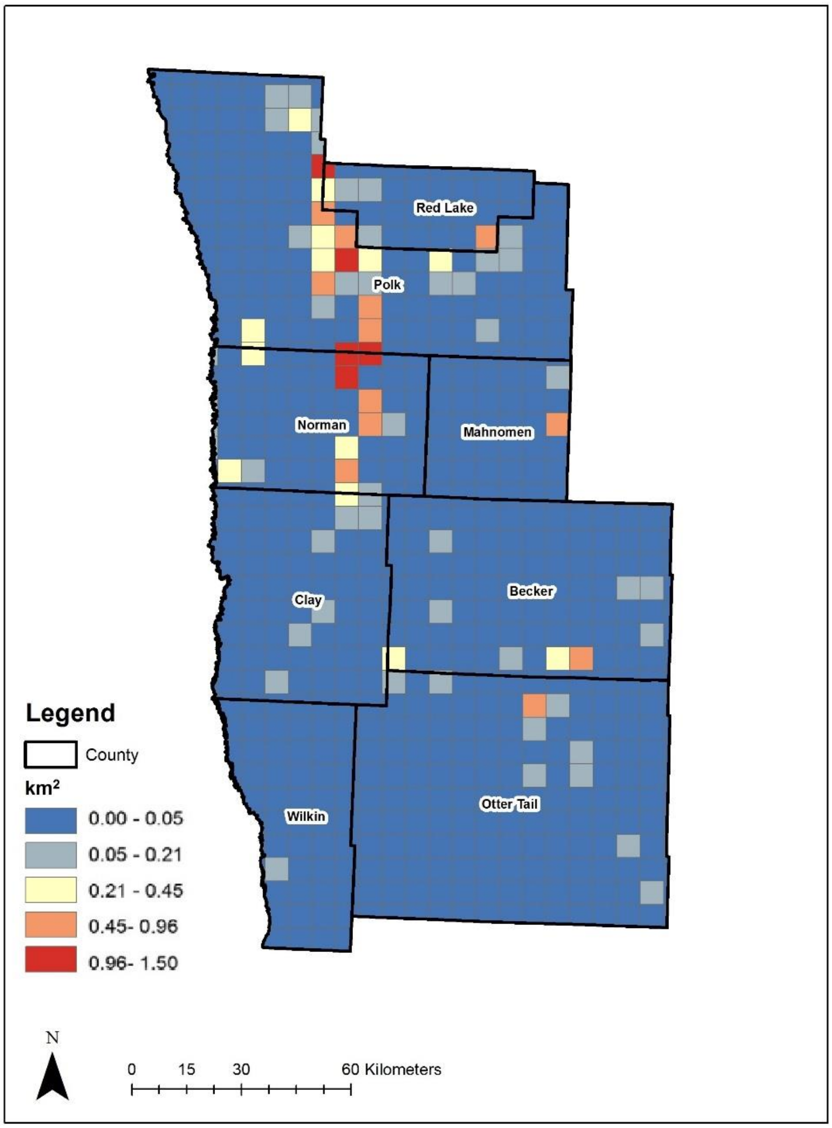


Figure 3. Predicted greater prairie-chicken density (lek/km$^2$) in a 41-km$^2$ grid in the 8-county (black border) study area in northwestern Minnesota. Highest density is dark red and lowest is dark blue.

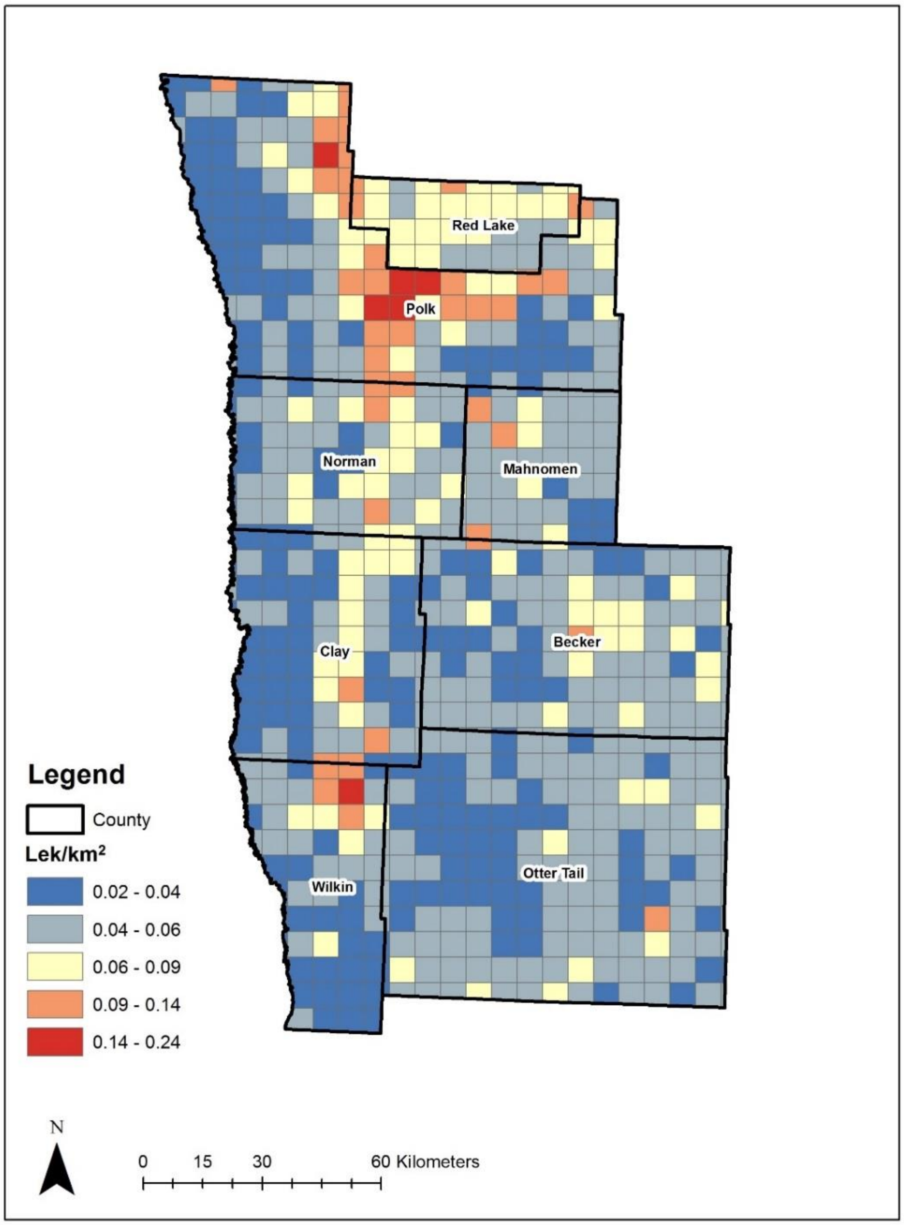


Figure 4. Scatterplot of the relationship between the predicted leks/km$^2$ and the amount of high-quality greater prairie-chicken breeding habitat in Conservation Reserve Program (CRP) contracts in 653 41-km$^2$ blocks across the 8-county study area in northwestern Minnesota with the regression line and associated 95% confidence region.

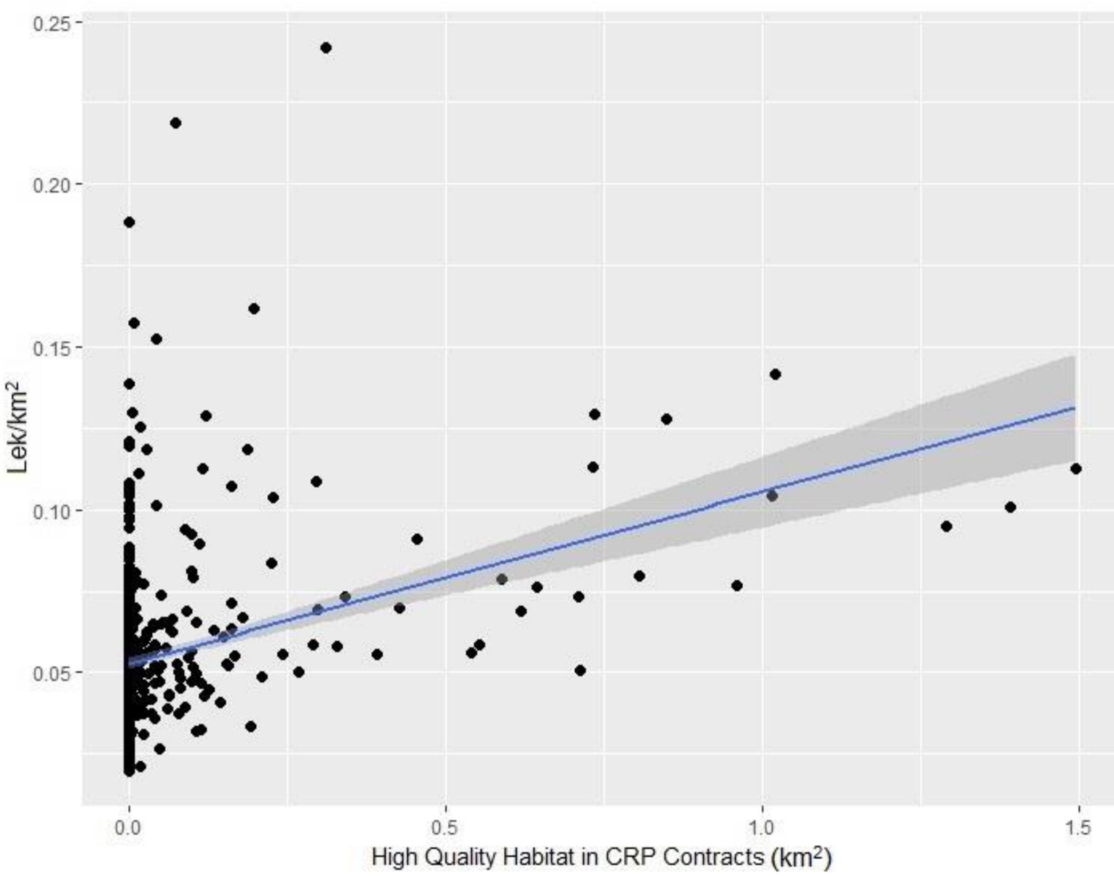
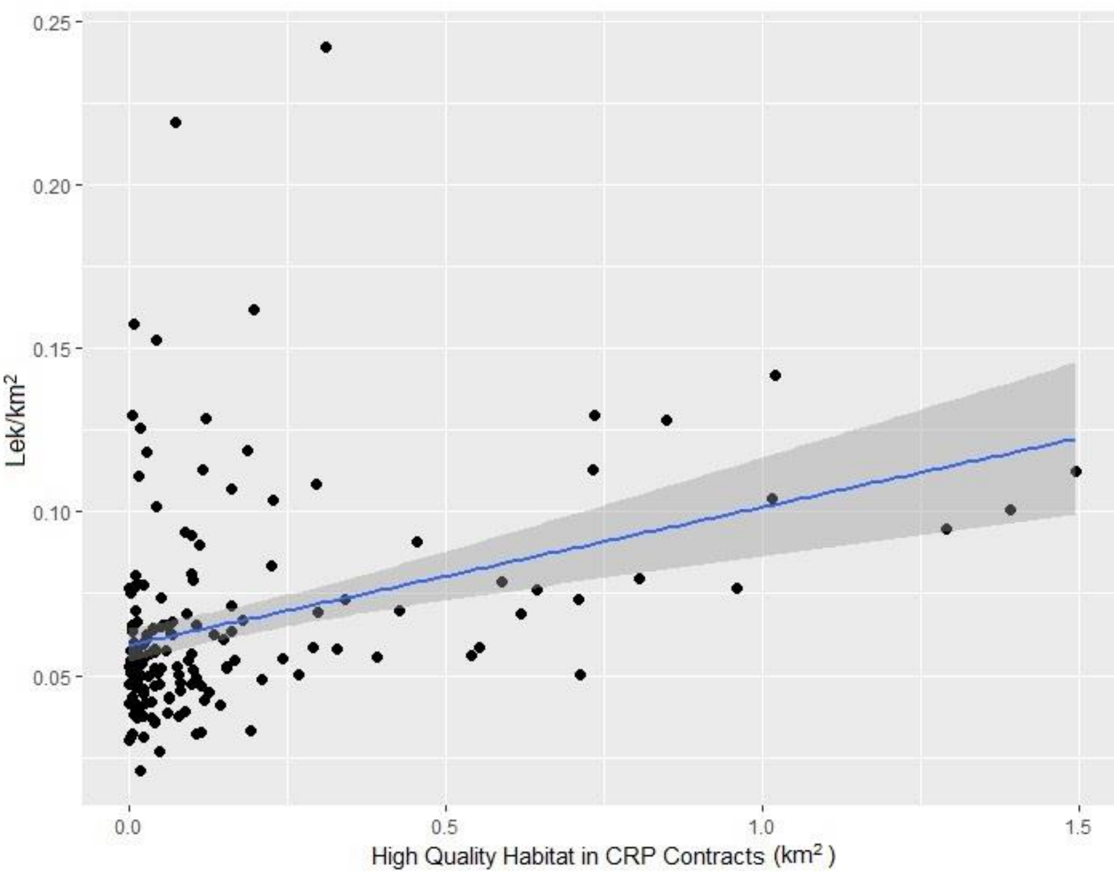


Figure 5. Scatterplot of the relationship between the predicted leks/$km^2$ and the amount of high-quality greater prairie-chicken breeding habitat in Conservation Reserve Program (CRP) contracts in 171 41-$km^2$ blocks where there was any high-quality breeding habitat across the 8-county study area with the regression line and associated 95% confidence region.



Appendix A. Summary of vegetation measurements [i.e., Visual Obstruction Reading (VOR), Maximum Height, and Forb Cover] by different considered combinations of remotely measured characteristics [i.e., Conservation Reserve Program (CRP) conservation code, time since planting, and soil type].

| Class | Sample Size | Unique Contracts | Average VOR | Standard Deviation VOR | Average Max Height | Standard Deviation Max Height | Average Forb Cover | Standard Deviation Forb Cover |
|---|---|---|---|---|---|---|---|---|
| CP10loamD | 6 | 4 | 2.39 | 0.50 | 74.88 | 12.82 | 0.002 | 0.005 |
| CP10sandyD | 7 | 5 | 2.27 | 0.56 | 68.44 | 5.29 | 0.000 | 0.002 |
| CP1loamD | 5 | 1 | 3.41 | 0.68 | 74.04 | 10.76 | 0.015 | 0.039 |
| CP1sandyD | 6 | 1 | 2.31 | 0.90 | 59.41 | 16.53 | 0.009 | 0.030 |
| CP23clayA | 5 | 1 | 0.59 | 0.34 | 36.19 | 8.02 | 0.015 | 0.041 |
| CP23clayC | 5 | 1 | 2.92 | 0.26 | 68.91 | 2.95 | 0.011 | 0.032 |
| CP23loamA | 7 | 7 | 1.82 | 3.08 | 49.90 | 44.34 | 0.009 | 0.021 |
| CP23loamB | 6 | 5 | 3.51 | 1.38 | 84.84 | 31.90 | 0.006 | 0.009 |
| CP23loamC | 6 | 6 | 4.63 | 3.49 | 89.05 | 44.50 | 0.001 | 0.005 |
| CP23loamD | 8 | 2 | 3.48 | 1.54 | 93.92 | 22.14 | 0.003 | 0.009 |
| CP23muckD | 5 | 2 | 6.26 | 1.28 | 117.73 | 16.14 | 0.011 | 0.034 |
| CP23sandyA | 8 | 6 | 1.06 | 1.08 | 42.20 | 18.35 | 0.007 | 0.033 |
| CP23sandyB | 7 | 7 | 2.52 | 0.49 | 70.15 | 9.01 | 0.009 | 0.019 |
| CP23sandyC | 6 | 3 | 1.04 | 1.31 | 36.48 | 24.33 | 0.008 | 0.031 |
| CP23sandyD | 6 | 1 | 3.87 | 0.83 | 102.07 | 7.38 | 0.003 | 0.009 |
| CP23siltB | 5 | 5 | 3.08 | 0.55 | 69.56 | 5.71 | 0.013 | 0.026 |
| CP25loamA | 7 | 5 | 3.46 | 0.85 | 78.65 | 9.57 | 0.001 | 0.007 |
| CP25loamC | 6 | 6 | 2.88 | 1.40 | 74.32 | 25.67 | 0.001 | 0.003 |
| CP25sandyA | 7 | 4 | 2.97 | 0.76 | 76.16 | 11.47 | 0.001 | 0.003 |
| CP25sandyC | 6 | 5 | 2.33 | 0.55 | 64.12 | 16.01 | 0.001 | 0.003 |
| CP25siltA | 5 | 2 | 3.52 | 0.70 | 81.96 | 10.92 | 0.001 | 0.004 |
| CP2loamB | 5 | 4 | 3.73 | 1.92 | 81.26 | 22.31 | 0.005 | 0.011 |
| CP2loamD | 6 | 3 | 3.37 | 1.12 | 77.48 | 12.89 | 0.003 | 0.008 |
| CP2sandyA | 6 | 4 | 3.15 | 1.72 | 77.61 | 26.17 | 0.001 | 0.003 |
| CP2sandyB | 6 | 4 | 3.07 | 0.68 | 81.71 | 9.12 | 0.001 | 0.005 |
| CP2sandyD | 6 | 3 | 3.35 | 0.95 | 77.04 | 4.74 | 0.001 | 0.002 |
| CP4DclayD | 6 | 2 | 2.23 | 0.43 | 69.11 | 6.92 | 0.005 | 0.013 |
| CP4DloamB | 5 | 1 | 3.07 | 0.51 | 79.17 | 5.01 | 0.001 | 0.003 |
| CP4DloamD | 7 | 7 | 3.00 | 1.54 | 87.86 | 23.83 | 0.001 | 0.002 |
| CP4DsandyB | 6 | 1 | 3.71 | 1.46 | 88.27 | 17.44 | 0.006 | 0.015 |
| CP4DsandyD | 7 | 7 | 3.46 | 0.50 | 79.00 | 9.30 | 0.001 | 0.002 |
| CP4DsiltD | 5 | 1 | 4.17 | 0.70 | 105.17 | 9.65 | 0.000 | 0.002 |

Appendix B. Summary of vegetation measurements [i.e., Visual Obstruction Reading (VOR), Maximum Height, and Forb Cover] by different considered Conservation Reserve Program (CRP) programs.

| CRP Program Code | Sample Size | Unique Contracts | Average VOR | Standard Deviation VOR | Average Max Height | Standard Deviation Max Height | Average Forb Cover | Standard Deviation Forb Cover |
|---|---|---|---|---|---|---|---|---|
| CP1 | 11 | 2 | 2.83 | 0.97 | 66.32 | 15.86 | 0.011 | 0.034 |
| CP10 | 13 | 9 | 2.33 | 0.53 | 71.81 | 10.45 | 0.001 | 0.004 |
| CP2 | 29 | 18 | 3.33 | 1.37 | 79.23 | 16.96 | 0.002 | 0.007 |
| CP23 | 74 | 46 | 2.92 | 2.24 | 73.20 | 35.37 | 0.007 | 0.025 |
| CP25 | 31 | 22 | 3.06 | 0.97 | 75.48 | 15.92 | 0.001 | 0.004 |
| CP4D | 36 | 19 | 3.27 | 1.15 | 84.29 | 17.63 | 0.002 | 0.008 |

Appendix C. Summary of vegetation measurements [i.e., Visual Obstruction Reading (VOR), Maximum Height, and Forb Cover] by different considered soil types.

| Soil Type | Sample Size | Unique Contracts | Average VOR | Standard Deviation VOR | Average Max Height | Standard Deviation Max Height | Average Forb Cover | Standard Deviation Forb Cover |
|---|---|---|---|---|---|---|---|---|
| Clay | 16 | 4 | 1.82 | 1.04 | 56.85 | 17.18 | 0.010 | 0.032 |
| Loam | 74 | 51 | 3.22 | 1.81 | 79.34 | 26.83 | 0.004 | 0.014 |
| Muck | 5 | 2 | 6.26 | 1.28 | 117.73 | 16.14 | 0.011 | 0.034 |
| Sandy | 84 | 51 | 2.71 | 1.27 | 71.24 | 22.21 | 0.003 | 0.017 |
| Silt | 15 | 8 | 3.56 | 0.77 | 84.36 | 16.47 | 0.004 | 0.015 |

Appendix D. Summary of vegetation measurements [i.e., Visual Obstruction Reading (VOR), Maximum Height, and Forb Cover] in considered age categories of time since planting (A: 0-4, B: 5-9, C: 10-14, D: ≥15 years).

| Age Category | Sample Size | Unique Contracts | Average VOR | Standard Deviation VOR | Average Max Height | Standard Deviation Max Height | Average Forb Cover | Standard Deviation Forb Cover |
|---|---|---|---|---|---|---|---|---|
| A | 46 | 29 | 2.51 | 1.75 | 65.71 | 26.86 | 0.004 | 0.020 |
| B | 34 | 26 | 3.16 | 1.16 | 78.05 | 18.15 | 0.005 | 0.014 |
| C | 29 | 21 | 2.70 | 2.14 | 65.90 | 32.03 | 0.003 | 0.018 |
| D | 85 | 40 | 3.35 | 1.41 | 83.81 | 20.96 | 0.004 | 0.018 |

## Literature Cited


Akaike, H. 1973. Information theory and an extension of the maximum likelihood principle. Pages 267-281 *in* B.N. Petrov and P. Czaki, editors. Proceedings of the 2nd International Symposium on Information Theory. Akademiai Kaido, Budapest, Hungary.

Amundson, C.L. and T.W. Arnold. 2010. Effects of radiotransmitters and placticine bands on Mallard duckling survival. *Journal of Field Ornithology* 81:310-316.

Booth, D.T., Cox, S.E., Meikle, T., and H.R. Zuuring. 2008. Ground-cover measurements: assessing correlation among aerial and ground-based methods. *Environmental Management* 42:1091–1100.

Burger, L.W., McKenzie, D., Thackston, R., and S.J. Demaso. 2006. The role of farm policy in achieving large-scale conservation: bobwhite and buffers. *Wildlife Society Bulletin* 34:986–993.

Burnham, K.P. and D.R. Anderson. 2002. Model selection and multimodel inference: a practical information-theoretic approach. Second edition. Springer, New York, New York, USA.

Congalton, R.G. and K. Green. 1999. Assessing the accuracy of remotely sensed data: principles and practices. Lewis Publishers, New York, New York, USA.

Daly, K.O., Andersen, D.E., Brininger, W.L., and T.R. Cooper. 2015. Radio-transmitters have no impact on survival of pre-fledged American woodcocks. *Journal of Field Ornithology* 86:345-351.

Daubenmire, R.F. 1959. Canopy coverage method of vegetation analysis. *Northwest Science* 33:43-64.

Drum, R.G., Loesch, C.R., Carrison, K.M., Doherty, K.E., and B.C. Fedy. 2015. Assessing the biological benefits of the USDA-Conservation Reserve Program (CRP) for waterfowl and grassland passerines in the Prairie Pothole Region of the United States: spatial analyses for targeting CRP to maximize benefits for migratory birds. Final Report for USDA-FSA Agreement. Prairie Pothole Joint Venture. 98pp.

ESRI 2015. ArcGIS Desktop: Release 10.3. Environmental Systems Research Institute. Redlands, California, USA.

Evans, S.G. and M.D. Potts. 2014. Effect of agricultural commodity prices on species abundance of US grassland birds. *Environmental and Resource Economics*

62:549–565.

Guidice, J.H. 2004. Minnesota Prairie-chicken Survey: 2004 Annual Report. Minnesota Department of Natural Resources.

Giudice, J.H. and K.J. Haroldson. 2007. Using regional wildlife surveys to assess the CRP: scale and data-quality issues. *Journal of Field Ornithology* 78:140–151.

Hamerstrom, F.N., Jr., Mattson, O.H., and F. Hamerstrom. 1957. A guide to prairie chicken management. Wisconsin Conserv. Dept. Tech. Bull. 15. Madison, Wisconsin, USA. 128 pp.

Hamerstrom, F.N., Jr. and F. Hamerstrom. 1973. The prairie-chicken in Wisconsin: highlights of a 22 year study of counts, behavior, movements, turnover, and habitat. Wisconsin DNR Tech. Bull. 6, Madison, Wisconsin, USA.

Herkert, J.R. 2009. Response of bird populations to farmland set-aside programs. *Conservation Biology* 23:1036–1040.

Herkert, J.R., Sample, D.W., and R.E. Warner. 1996. Management of Midwestern grassland landscapes for the conservation of migratory birds. Pages 89-116 *in* F.R. Thompson III, editor. Management of Midwestern landscapes for the conservation of migratory birds. U.S. Department of Agriculture, Forest Service, General Technical Report NC-187.

Hovick, T.J., Allred, B.W., Elmore, R.D., Fuhlendorf, S.D., Hamilton, R.G., and A. Breland. 2015b. Dynamic disturbance processes create dynamic lek site selection in a prairie grouse. *PLoS ONE* 10:1-14.

Hovick, T.J., Dahlgren, D.K., Papeş, M., Elmore, R.D., and J.C. Pitman. 2015a. Predicting greater prairie-chicken lek site suitability to inform conservation actions. *PLoS ONE* 10:1-11.

Jones, R.E. 1963. Identification and analysis of lesser and greater prairie chicken habitat. *Journal of Wildlife Management* 27:757–778.

Kobriger, D. 1965. Status, movements, habitats, and foods of prairie grouse on a Sandhills refuge. *Journal of Wildlife Management* 29:788-800.

Larson, M.A. and W. Bailey. 2007. Identifying plots for surveys of prairie-chickens in Minnesota. Summaries of Wildlife Research Findings, Minnesota Department of Natural Resources, St. Paul, Minnesota, USA.

McGarigal, K., Cushman, S.A., and E. Ene. 2012. FRAGSTATS v4: spatial pattern analysis program for categorical and continuous maps. University of

Massachusetts, Amherst, Massachusetts, USA. http://www/umass.edu/landeco/research/fragstats/fragstats.html

McNew, L.B., Winder, V.L., Pitman, J.C., and B.K. Sandercock. 2015. Alternative rangeland management strategies and the nesting ecology of greater prairie-chickens. *Rangeland Ecology & Management* 68:298–304.

Merrill, M.D., Chapman, K.A., Poiani, K.A., and B. Winter. 1999. Land-use patterns surrounding greater prairie-chicken leks in northwestern Minnesota. *Journal of Wildlife Management* 63:189–198.

Minnesota Prairie Plan Working Group. 2011. Minnesota Prairie Conservation Plan 2010. Minnesota Prairie Plan Working Group, Minneapolis, Minnesota, USA. 55pp.

Nack, R.R. and D.E. Andersen. 2006. Brood movements of Eastern Prairie Population Canada geese: potential influence of light goose abundance. *Journal of Wildlife Management* 70:435–442.

Nelson, M. 2010. American woodcock singing-ground surveys in the western Great Lakes region: assessment of woodcock counts, forest cover types along survey routes, and landscape cover type composition. M.S. Thesis, University of Minnesota, Minneapolis, Minnesota, USA.

Nelson, M. and D.E. Andersen. 2013. Do singing-ground surveys reflect American woodcock abundance in western Great Lakes region? *Wildlife Society Bulletin* 37:585-595.

Nielson, R.M., McDonald, L.L., Sullivan, J.P., Burgess, C., Johnson, D.S., Johnson, D.H., Bucholtz, S., Hyberg, S., and S. Howlin. 2008. Estimating the response of ring-necked pheasants (*Phasianus colchicus)* to the Conservation Reserve Program. *Auk* 125:434–444.

Niemuth, N.D. 2000. Land use and vegetation associated with greater prairie-chicken leks in an agricultural landscape. *Journal of Wildlife Management* 64:278–286.

Niemuth, N.D. 2003. Identifying landscapes for greater prairie chicken translocation using habitat models and GIS: a case study. *Wildlife Society Bulletin* 1:145–55.

Niemuth, N.D. 2011. Spatially explicit habitat models for prairie grouse. *Studies in Avian Biology* 39:3–20.

Noss, R.F., LaRoe III, E.T., and J.M. Scott. 1995. Endangered ecosystems of the United States: a preliminary assessment of loss and degradation. U.S. Department of the Interior, National Biological Service, Biological Report 28.

Partch, M.C. 1973. A history of Minnesota's prairie chickens. Pages 15-29 *in* W.D. Svedarsky and T.J. Wolfe, editors. The prairie chicken in Minnesota. University of Minnesota, Crookston, Minnesota, USA.

Poiani, K.A., Merrill, M.D., and K.A. Chapman. 2001. Identifying conservation-priority areas in a fragmented Minnesota landscape based on the Umbrella Species Concept and selection of large patches of natural vegetation. *Conservation Biology* 15:513–22.

Princé, K., Lorrillière, R., Barbet-Massin, M., Léger, F., and F. Jiguet. 2015. Forecasting the effects of land use scenarios on farmland birds reveal a potential mitigation of climate change impacts. *PLoS ONE* 10(2):e0117850

Prose, B.L. 1985. Habitat suitability index models: Greater prairie-chicken (multiple levels of resolution). U.S. Fish Wildlife Service. Biological Report 82(10.102). 33 pp.

Riley, T.Z. 2004. Private-land habitat opportunities for prairie grouse through federal conservation programs. *Wildlife Society Bulletin* 32:83–91.

Robel, R.J., Briggs, J.N., Cebula, J.J., Silvy, N.J., Viers, C.E., and P.G. Watt. 1970a. Greater prairie chicken ranges, movements, and habitat usage in Kansas. *Journal of Wildlife Management* 34:286–306.

Robel, R.J., Briggs, J.N., Dayton, A.D., and L.C. Hulbert. 1970b. Relationships between visual obstruction measurements and weight of grassland vegetation. *Journal of Range Management* 23:295-297.

Roy, C. 2014. 2014 Minnesota prairie-chicken survey. Minnesota Department of Natural Resources. 8 pp.

Roy, C., Wright, R., and D.E. Andersen. 2015. Quantifying the relationship between grasslands, Conservation Reserve Program (CRP) enrollments, and greater prairie-chicken populations in Minnesota- research phase I proposal. Minnesota Department of Natural Resources Section of Wildlife. 10 pp. Unpublished Report.

Ryan, M.R. 2000. Impact of the Conservation Reserve Program on wildlife conservation in the Midwest. Pages 45–54 in W.L. Hohman and D.J. Halloum, editors. A comprehensive review of farm bill. A contribution to wildlife conservation, 1985–2000. U.S. Department of Agriculture Natural Resource Conservation Service, Wildlife Habitat Management Institute Technical Report USDA/NRCS/WHMI-2000, Washington, D.C., USA.

Schroeder, M.A. and C.E. Braun. 1993. Greater prairie-chicken attendance at leks and stability of leks in Colorado. *The Wilson Bulletin* 104:273-284.

Shirk, A.J., Schroeder M.A., Robb, L.A., and C.E. Braun. 2017. Persistence of greater sage-grouse in agricultural landscapes. *Journal of Wildlife Management* early view articles.http://dx.doi.org.ezp3.lib.umn.edu/10.1002/jwmg.21268.

Soil Survey Staff. 2011b. National Resources Conservation Service, United States Department of Agriculture, Official Soil Series Descriptions. Available Online.

Soil Survey Staff. 2011a. National Resources Conservation Service, United States Department of Agriculture, Soil Survey Geographic (SSURGO) Database for the Central U.S.

Steiner, E.M. and S.L. Collins. 1996. Prairie ecology - the tallgrass prairie. Pages 39-52 *in* F.B. Samson and F.L. Knopf, editors. Prairie conservation. Island Press, Washington, D.C.

Stempel, M.E. and S. Rodgers Jr. 1961. History of prairie chickens in Iowa. *Proceedings of Iowa Academy of Science* 68:314–322.

Stubbs, M. 2014. Conservation Reserve Program (CRP): status and issues. Congressional Research Service Report 7-5700 R42783. 20 pp.

Stoebner, T.J. and C.L. Lant. 2014. Geographic determinants of rural land-covers and the agricultural margin in the central United States. *Applied Geography* 55:138–54.

Svedarsky, W.D. 1979. Spring and summer ecology of female greater prairie-chickens in northwestern Minnesota. Ph.D. Diss., University of North Dakota, Grand Forks. 166 pp.

Svedarsky, W.D., Wolfe, T.J., and J.E. Toepfer. 1997. The greater prairie-chicken in Minnesota. Minnesota Department of Natural Resources Wildlife Report 11. 19 pp.

Svedarsky, W.D., Toepfer, J.E., Westemeier, R.L., and R.J. Robel. 2003. Effects of management practices on grassland birds: greater prairie-chicken. Northern Prairie Wildlife Research Center, Jamestown, ND. 42 pp.

University of Minnesota MN Land-cover Classification (UMN-MLCC). 2013. Published land-cover data layer [Online]. Available at https:// http://portal.gis.umn.edu/

U.S. Department of Agriculture (USDA). 2008. Farm program fact sheet: Minnesota CRP-SAFE Practices; CP38-Back forty pheasant habitat. Farm Service Agency. St. Paul, Minnesota, USA.

U.S. Department of Agriculture (USDA). 2017a. Farm program job sheet: establishment of permanent introduced grasses and legumes CP-1. Minnesota Natural Resources Conservation Service (NRCS).

U.S. Department of Agriculture (USDA). 2017b. Farm program job sheet: Conservation Reserve Program-grassland management. Minnesota Natural Resources Conservation Service (NRCS).

USDA National Agricultural Statistics Service (NASS) Cropland Data Layer. 2015. Published crop-specific data layer [Online]. Available at https://nassgeodata.gmu.edu/CropScape/ USDA-NASS, Washington, D.C., USA.

Whisler, K.M., Rowe, H.I., and J.S. Dukes. 2016. Relationships among land use, soil texture, species richness, and soil carbon in Midwestern tallgrass prairie, CRP, and crop lands. *Agriculture, Ecosystems, & Environment* 216:237–246.