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Final Report
Sage-Grouse Grazing Project

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THE EFFECTS OF GRAZING ON GREATER SAGE-GROUSE POPULATION DYNAMICS AND HABITAT IN CENTRAL MONTANA

Executive summary

In 2015, collaborative conservation efforts among agencies and private land owners culminated in the decision not to list the greater sage-grouse under the Endangered Species Act (ESA). The Sage-Grouse Initiative (SGI) implemented by the United States Department of Agriculture Natural Resources Conservation Service (NRCS) formed a large part of the conservation efforts that contributed to this decision. While the success of these efforts is laudable, the effects of grazing on sage-grouse and their habitat are still largely unknown. This information is needed to support conservation efforts, given the ubiquity of livestock grazing across sage-grouse range.

The goal of our study was to evaluate the effectiveness of one of SGI's tools – rotational grazing systems – to conserve and manage sage-grouse habitat in central Montana. To do so, we measured sage-grouse vital rates (including nest success, chick survival, and hen survival) within these grazing systems and compared them with vital rates in non-SGI grazing strategies concurrent within central Montana. We included factors describing vegetation structure and composition to evaluate the effects of grazing on sage-grouse habitat.

We collected data during 2011-2020. Our long-term objectives were to evaluate the effects of SGI grazing strategies on (1) sage-grouse vital rates; (2) sage-grouse adult female and chick habitat selection; and (3) sage-grouse habitat (i.e., effects of grazing directly on vegetation). Herein, we report on preliminary results of the effects of grazing on vital rates and vegetation.

We used radio telemetry to collect vital rate data. We used the line-intercept technique to measure vegetation structure and composition at sage-grouse nests, and random points within nesting habitat to evaluate vegetative factors that may influence the nest success or nest site selection of hens. We assessed the effects of habitat on nest site selection and nest success at a larger spatial scale using remotely sensed data in geographical information system layers including bare ground, herbaceous, and shrub percent cover; distance to roads and water; and distance to and proportion of crop fields in the landscape. We used these predictors at the 30 m scale in chick survival models. We measured herbaceous vegetation in potential sage-grouse habitat using the line-intercept technique at a set of random field plots stratified by grazing treatment (SGI and non-SGI) to test for differences in indicators of habitat quality across the project area. We used weather data, including daily (nest success and chick survival), monthly, seasonal, and breeding season summaries (chick survival only) of precipitation and maximum

and minimum temperatures, to evaluate how much variation in nest success or chick survival was due to weather versus other variables.

Nest success of 664 nests across the 37-day exposure period averaged 0.36 (95% CI = 0.31-0.40) from 2011-2019. We used a Kaplan-Meier survival function to evaluate chick and hen survival with staggered entry designs and right-censoring for individuals with unknown fates, dropped transmitters, or that survived until their transmitters expired. The median survival time for chicks with data from all years pooled was 42 d (95% CI=33-59 d). The probabilities of chicks surviving until the end of the monitoring periods differed among years (χ^2=33.23, df=8, p<0.01). Annual survival estimates for 521 chicks radio marked during 2011-2019 to 75 d post-hatch (when they are the size of adults) ranged from 0.19-0.60. The median survival time estimated for 495 marked hens monitored from 2011-2020 was 1.25 years (95% confidence interval [CI]=1.16-1.40 yrs).

We used linear mixed effects models to test for effects of grazing management on vegetation metrics while accounting for variation across years and ranches. While effects were not statistically significant, we observed tendencies for total herbaceous vegetation, live grass height, RAP annual perennial forb cover, and RAP shrub cover to vary with SGI grazing management, and an effect of SGI grazing management on RAP litter cover, indicating that there was more herbaceous vegetation and less forb and shrub cover present in pastures currently being grazed according to the SGI program protocols. The variation among years and pastures was greater than differences observed in these metrics, reflecting the wide variation in vegetation growth in rangelands. Although there appear to be measurable differences, they do not amount to differences that likely affect sage-grouse. Our results are consistent with preliminary analyses from Smith et al. (2018a) that found negligible effects of SGI grazing management on vegetation in sage-grouse habitat.

Together, our results suggest that annual and pasture (spatial) variation have more of an effect on sage-grouse demographics and habitat than grazing management, though there were some potential relationships of grazing management with demographics and vegetation that could be further explored. Our preliminary conclusions concur with Smith et al. (2018a) that preserving sagebrush habitat by keeping working ranches in sagebrush habitat intact may be more important than recommending particular grazing management.

These results should be considered preliminary and are subject to change as analyses are in progress. We will continue analyses through 2024 with a PR Grant (Federal Award Notification Number F21AF01330) to complete final deliverables including analyses of the effects of grazing on seasonal habitat selection of hens and chicks and population dynamics, and exploring linking lek counts with population vital rates as a technique for evaluating population health. Smith et al. (2018c) reported on results for the effects of grazing on nest-site selection during the first five years of the study.

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Background

Project Context

The greater sage-grouse (*Centrocercus urophasianus*; hereafter "sage-grouse") is a large, ground-dwelling bird endemic to sagebrush-dominated (*Artemisia* spp.) habitats in western North America (Schroeder et al. 1999, Knick et al. 2013). This species uses both sagebrush steppe and sagebrush semi-desert systems year-round to support its life history needs (Crawford et al. 2004). Sagebrush is often the only food source available during winter in these systems, and it provides hiding cover during nesting (Sveum et al. 1998, Guttery et al. 2013, Lockyer et al. 2015). In addition to sage-grouse, more than 600 species of conservation concern depend on sagebrush ecosystems (Rich et al. 2005), including Brewer's sparrow (*Spizella breweri*), elk (*Cervus elaphus*), mule deer (*Odocoileus hemionus*), and pronghorn (*Antilocapra americana*). Thus, efforts to sustain sage-grouse populations will benefit other wildlife, especially sagebrush-obligate wildlife species (Rowland et al. 2006).

The loss and degradation of sagebrush habitat has extirpated sage-grouse from nearly half its original range (Schroeder et al. 2004). The causes of habitat loss and degradation include conversion of sagebrush to agriculture (Connelly et al. 2004, Smith et al. 2016); fragmentation resulting from energy (Naugle et al. 2011) and subdivision development (Leu and Hanser 2011); conifer invasion (e.g., in Oregon and western Montana; Connelly et al. 2004, Beck et al. 2012); and modifications such as prescribed fire, herbicides, and certain grazing practices that have led to exotic, annual grass establishment (particularly in the Great Basin) (Davies et al. 2009). In 2010, due in large part to habitat degradation concerns, several petitions to list the sage-grouse for protection under the Endangered Species Act (ESA) led the United States Department of Interior Fish and Wildlife Service (USFWS) to place the sage-grouse on the candidate list for threatened and endangered species (United States Fish and Wildlife Service 2010). In 2015, USFWS determined that efforts by state and federal agencies and other partners had been adequate to conserve this species and its habitat without listing it under the ESA (United States Fish and Wildlife Service 2015). However, conservation efforts must be maintained to prevent further population declines and a future ESA listing. Since livestock grazing is the most widespread land use in sage-grouse habitat (Dinkins et al. 2017), knowledge of how livestock grazing affects sage-grouse populations provides important information to manage this species.

A top priority of sage-grouse conservation is preventing further habitat loss and fragmentation (Connelly et al. 2000, United States Fish and Wildlife Service 2013, Smith et al. 2016). The USFWS, in partnership with several state agencies, has outlined range-wide conservation

objectives and management zones for sage-grouse (Figure 1) with specific conservation needs for each zone (United States Fish and Wildlife Service 2013). Our project falls within Management Zone 1, where conservation actions are focused on incentivizing producers (i.e. ranchers, farmers, and other land owners) to conserve habitat (United States Fish and Wildlife Service 2013, p. 48). Additionally, the United States Department of Agriculture Natural Resources Conservation Service (NRCS) implemented the Sage-Grouse Initiative (SGI) to help conserve

Figure 1. The location of Management Zones (MZ) and Priority Areas for Conservation (PAC) across the current range of the greater sage-grouse. Figure from <https://www.fws.gov/greatersagegrouse/maps.php>. Last accessed September 2, 2021.

sage-grouse habitat across the range of the species. In Montana, the implementation of the State's Sage-Grouse Habitat Conservation program in 2014 was another key step toward Montana's sage-grouse and sagebrush habitat conservation. Together, these efforts intend to keep working ranches on the landscape and prevent further reduction of sage-grouse habitat. Below, we expand on how our project contributes to these existing sage-grouse conservation efforts.

Livestock Grazing in Sagebrush Systems

Livestock grazing is the largest land management practice in the world (Krausman et al. 2009), and the dominant land management practice in sagebrush habitat (e.g., Dinkins et al. 2017), affecting 70% of land in the western United States (Fleischner 1994). Livestock grazing (hereafter "grazing") affects sagebrush habitat by altering its vegetation structure, composition, and productivity (Beck and Mitchell 2000, Krausman et al. 2009). These effects can be either positive or negative depending on the timing and intensity of grazing; thus, grazing can be manipulated to achieve desired habitat conditions (Fuhlendorf and Engle 2001, Connelly et al. 2004, Chambers et al. 2017).

While substantial evidence suggests that improper grazing degrades rangeland (Davies et al. 2014), there is still uncertainty about selecting the best grazing regime to achieve different goals. This uncertainty results from the many confounding factors that exist when comparing grazing systems (Heady 1961), which include both ecological variables (e.g., rainfall and vegetation structure) and management attributes (e.g., goals and opportunities) (Briske et al. 2008, 2011). In

cases where multiple goals exist concurrently (e.g., producing livestock, enhancing wildlife habitat, and grazing sustainably), rotational systems may be preferred over continuous (i.e., season-long) grazing with low stocking rates to meet all of the objectives (Krausman et al. 2009). Rest and deferment from grazing may also provide small benefits to rangeland soil crusts (Davies et al. 2014) and keep residual grass on the landscape as protective cover for wildlife (Krausman et al. 2009), but other studies suggest that rotation is not necessarily better than continuous grazing. These studies indicate that weather variation, stocking rate, and rangeland productivity account for the majority of variability in plant and animal production (Briske et al. 2008, Lipsey et al. 2017, Vold et al. 2019).

Effects of grazing are likely locally or regionally specific, and wildlife species will each exhibit unique responses depending on their specific habitat and life history needs (Schieltz and Rubenstein 2016). For example, Golding and Dreitz (2017) show that thick-billed longspurs (*Rhynchophanes mccownii*) and western meadowlarks (*Sturnella neglecta*) in our study area exhibited different responses to varying grazing management. Thick-billed longspurs were more abundant on lands that participated in the SGI grazing management program. In contrast, western meadowlarks were more abundant on lands not participating in the SGI program. These responses could be due to indirect effects of grazing on the structure of vegetation and the different structural needs for each species during the breeding season. Additionally, effects on wildlife might occur indirectly via food sources. Some work has shown that the biomass of invertebrates, an important food source for sage-grouse and several other bird species, may be lower in grazed than ungrazed areas (Sutter and Ritchison 2005, Goosey et al. 2019).

The Sage-Grouse Initiative (SGI) Program

The SGI grazing program in central Montana focused on improving livestock production and rangeland health while simultaneously alleviating threats to and improving habitat for greater sage-grouse (USDA 2015). The SGI program was implemented on private ranches containing potential sage-grouse habitat as defined by topography and sagebrush canopy cover ≥5% (NRCS pers. comm.) within sage-grouse core areas (Figure 2). FWP has designated core areas in Montana as locations of highest conservation value for sage-grouse based on habitat and number of breeding males (Figure 2). FWP has estimated that the core areas included ~76% of the displaying males in Montana as of 2013.
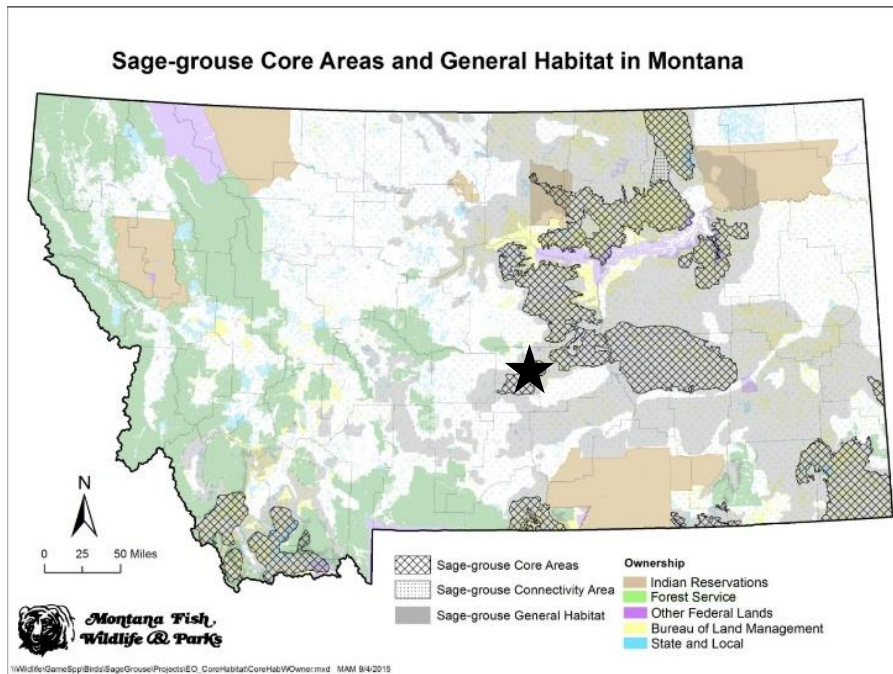
Figure 2. Greater sage-grouse core areas as defined by Montana Fish, Wildlife and Parks in 2013. The black star represents the location of the study area for this project in Golden Valley and Musselshell Counties, Montana, USA.

Livestock producers enrolled in the SGI program implemented an approximately three-year grazing regime developed with NRCS range management specialists. SGI grazing regimes were rotational and used a combination of rest and deferment to increase vegetation cover for nesting hens (Doherty et al. 2014, Smith et al. 2018b), in addition to other strategies. Range management specialists suggested pasture rest, pasture deferment, changed the number of animal units, or installed fences or water sources to adjust pasture size or livestock distribution. SGI grazing regimes were tailored to each ranch and varied by needs of the producer or pasture condition while following the NRCS Conservation Practice Standard for Prescribed Grazing (Natural Resources Conservation Service 2017, Smith et al. 2018b). Additionally, plans align with four minimum criteria intended to support sage-grouse habitat:

1. Grazing utilization rates of ≤50% of the current year's key forage species growth,
2. ≥20-day shift annually in the timing of grazing,
3. A plan to address unexpected circumstances like drought or fire, and
4. ≤45-day continuous grazing durations within any one pasture (Smith et al. 2018b).

Our work evaluated the effects of these recommendations to determine if this program yields biologically-relevant benefits to vegetation or sage-grouse.

Our Grazing Study: Investigating the Effects of SGI Grazing Management on Sage-Grouse Habitat and Demography in Central Montana

We evaluated the effects of the SGI grazing program on the demography and habitat of a sage-grouse population in central Montana. The project spanned approximately a decade because both sagebrush habitat and sage-grouse may exhibit "lag" responses to grazing management (e.g., Crawford et al. 2004), whereby some effects are only observable or fully realized after several

years. The study was observational, and we did not design the grazing implementation. Instead, we took advantage of the SGI program's structure. We evaluated bird and habitat responses to grazing management implemented by NRCS and also on private lands not enrolled in SGI. We collected data for ten years beginning in 2011. We reduced our field effort during the final year in 2020 due to the COVID-19 pandemic.

We focused on the three most important drivers of population growth in sage-grouse: 1) nest success, 2) chick survival, and 3) survival of adult and yearling females (hereafter "hens") (Taylor et al. 2012, Dahlgren et al. 2016). We also evaluated the response of sagebrush steppe vegetation to grazing in our study area. This project had six long-term objectives related to the effects of SGI grazing:

1. Measure the vegetation response in pastures receiving different grazing management, relative to published sage-grouse habitat needs;
2. Identify movements by sage-grouse between pastures undergoing different grazing management to quantify use proportional to habitat availability and other drivers of sage-grouse habitat use;
3. Create habitat-based measures of fitness which can be compared in each type of grazing management by measuring individual vital rates known to affect population growth in sage-grouse and relating these estimated vital rates directly to habitat variables and other important drivers;
4. Create a habitat-linked population model to:
   a. Evaluate and forecast the effects of management variables within a rotational grazing system on sage-grouse populations in the context of other drivers of sage-grouse vital rates, so as to put the influence of grazing management on population dynamics in context, and
   b. Identify current areas that are most important to sage-grouse to prioritize locations where habitat management will have the most benefit to populations;
5. Quantify the population-level response of sage-grouse to grazing management by indexing lek counts to our population modeling results, then by comparing lek counts within the Roundup study area to surrounding populations. To the extent that lek counts represent population changes reflected in population models, sage-grouse population response to grazing might be forecast in other areas where only lek count data are available; and
6. Generate spatially-explicit maps for areas with high quality seasonal habitat. Specifically, we will produce maps that delineate areas with habitat attributes that define relative probability of use and that have a positive influence on vital rates during the nesting, brood-rearing, and winter periods, and extrapolate to similar landscapes to the extent that these models validate well.

Herein, we present our findings on sage-grouse demographics – nest success, chick survival, and hen survival – and how SGI grazing management influenced these vital rates. In addition, we

explore potential changes in sagebrush steppe vegetation following SGI grazing management. We first provide information on how we define our grazing metrics. Then we detail the influence of SGI grazing on each demographic rate, followed by sagebrush-steppe vegetation. We conclude with overall conclusions from this preliminary work. We will continue analyses through 2024 with a PR Grant (Federal Award Notification Number F21AF01330) to complete final deliverables including analyses of the effects of grazing on seasonal habitat selection of hens and chicks and population dynamics, and linking lek counts with population vital rates as a technique for evaluating population health. Smith et al. (2018c) reported on results for the effects of grazing on nest-site selection during the first five years of the study. We will update and provide final management recommendations in the final 2024 report.

Study Area

The study area was in central Montana in rolling topography that ranged from 975-1,250m in elevation (Smith et al. 2018b) and covered approximately 150,000 hectares in Musselshell and Golden Valley counties (Figure 2). The vegetation was consistent with big sagebrush steppe, the most widely distributed sagebrush system in Montana. Wyoming big sagebrush (*Artemisia tridentata* ssp. *wyomingensis*) and silver sagebrush (*A. cana*) were both common and co-dominant, with a mix of perennial bunchgrasses, perennial rhizomatous grasses, and forbs composing up to 25% of cover (Montana Natural Heritage Program 2021). This region has cooler soil temperature and higher soil moisture than other parts of the sage-grouse range (Pyke et al. 2015). The average monthly temperature in Roundup (2009-2020) ranged from a low of -3.8⁰ Celsius (25.1⁰ Fahrenheit) in January to a high of 21.8⁰ Celsius (71.2⁰ Fahrenheit) in July (National Centers for Environmental Information 2021). Average monthly precipitation in Roundup (2009-2020) ranged from a low of 9.40 millimeters (0.37 inches) in January to a high of 73.41 millimeters (2.89 inches) in June (National Centers for Environmental Information 2021). The climate is cold semiarid (Pyke et al. 2015), with distinct seasons that include cool and wet springs, hot and dry summers, cool and wet autumns, and cold, snowy winters. The study area is a mosaic of public (federal, state, and county) and private ownership dominated by cattle rangeland, with some sheep rangeland and some dryland farming (Smith et al. 2018a, Smith et al. 2018b).

Grazing metrics

Methods for Grazing Data Synthesis

The data compilation process for the grazing dataset required synthesizing several data streams (ten years of data from more than 40 ranches) into one cohesive spatially and temporally referenced layer. The first step of the process involved in-person conversations with livestock producers and NRCS staff. FWP staff met with representatives from the NRCS and producers to collect data on pasture boundaries over time, grazing timing, grazing duration, SGI enrollment

status, and other livestock-related variables. FWP staff recorded the data by hand on maps and then translated it to a digital spreadsheet. The detail of the grazing information we obtained varied by producer and pasture. We collected data after grazing was completed in case grazing plans changed due to weather, fire, or other factors.
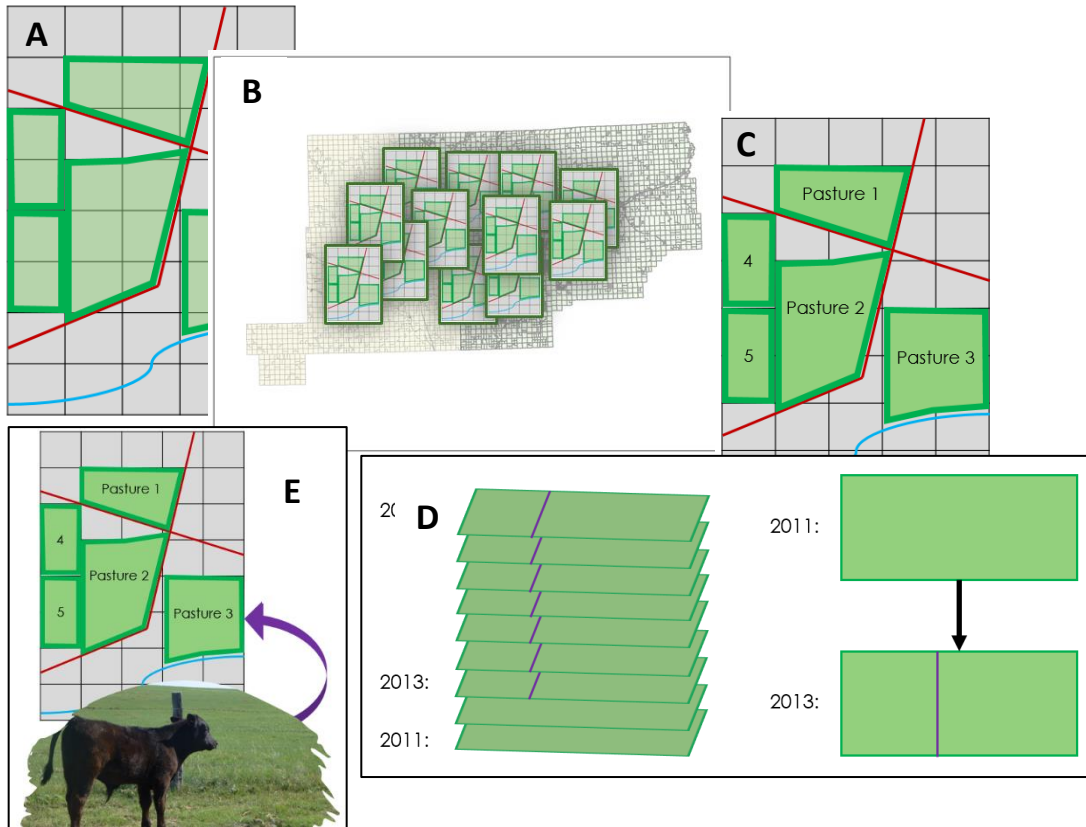
Figure 3. A) A stylized example of a hand-drawn map created during a meeting with a producer, where pasture boundaries are highlighted in green, roads are red, water bodies are blue, and map sections are gray. B) Hand-drawn maps are georeferenced to their location in space, here shown superimposed over Musselshell and Golden Valley counties (not to scale). C) Georeferenced pastures are digitized and associated with their names. D) Digitized pastures are checked across time and any changes in pasture boundaries (e.g., a fence addition, here shown in purple) are added for each year. E) Grazing data variables including grazing timing and duration are joined to the digitized time-varying pasture polygons.

After we gathered the grazing data, we compiled it into a final product by georeferencing, digitizing, and joining the datasets. First, approximately 97 hand-drawn maps created during FWP staff's meetings with livestock producers (Figure 3A) were georeferenced (Figure 3B). We then used these maps to digitize approximately 523 pastures per year (Figure 3C) to account for

any changes, such as fence lines, yielding 5,234 digitized pastures over nine years, 2011-2019,
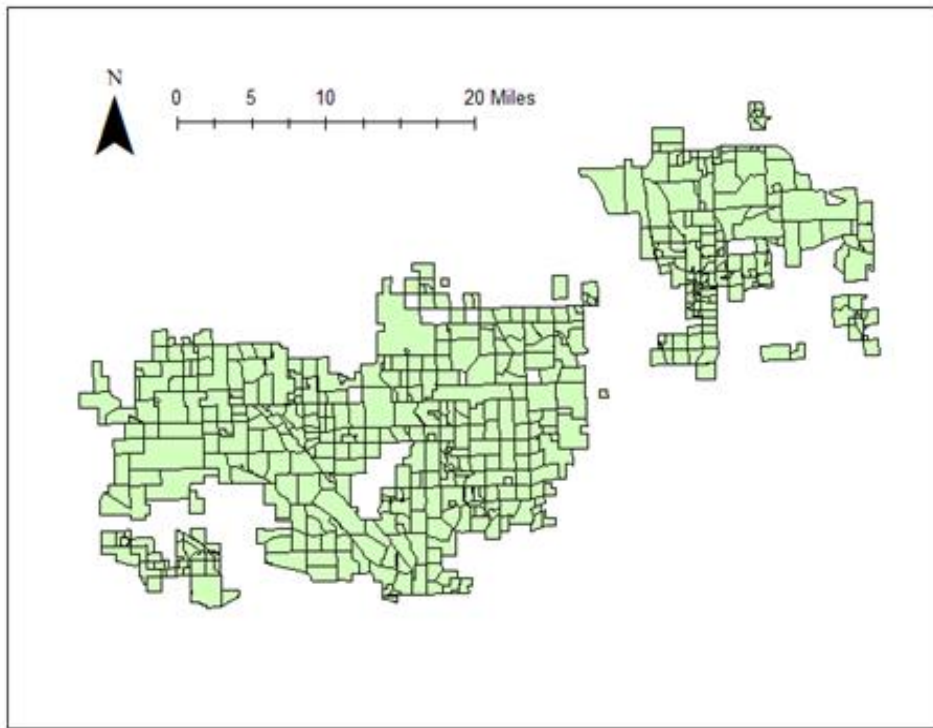
Figure 3D). Lastly, we linked the grazing information (e.g., timing and duration) for each pasture-year to the digitized pastures (Figure 3E). These data served as the baseline for all the analyses that use grazing data in this report (Figure 4).

Figure 4. A map of the pastures digitized in the Roundup area of central Montana.

Quantifying the Sage-Grouse Initiative (SGI) Grazing Program

We were interested in both the long- and short-term effects of SGI grazing as well as direct effects (i.e., concurrent presence of livestock and sage-grouse) and indirect effects that were relevant to sage-grouse. Potential direct effects of livestock grazing included protection against nest predators due to the presence of livestock or associated human activity (Kirby and Grosz 1995, Foster et al. 2014, Milligan et al. 2020a) and nest damage by trampling. Potential indirect effects include changes to the vegetative community that, in turn, affected sage-grouse.

We investigated the effects of the three-consecutive-year grazing regime developed as part of SGI (hereafter, "three-year grazing regime"). We quantified the three-year grazing regime in three distinct ways. These three categorizations enabled us to explore the effects of grazing management from multiple perspectives. For example, we predicted that if sage-grouse did not respond to grazing during implementation (i.e., direct effects of grazing), they might show delayed responses after grazing occurred due to changes in vegetation composition and structure (indirect effects). Our three categorizations were:

1. **"Direct effect" (SGI-D) categorization:** This categorization encompasses the direct effects (D) of the three-year grazing implementation on the landscape. Subcategories include "D-Yes", when the three-year grazing regime was actively implemented, and "D-

No" otherwise (Figure 5). D-No refers to pastures that were never enrolled in an SGI grazing program (non-SGI).

2. **"Cumulative effect" (SGI-C) categorization:** This categorization combines the effects of the three-year grazing implementation and the long-term vegetative response following a three-year grazing implementation. Sub-categories include "C-Pre", "C-Post", and "C-No. We defined a pasture as C-Pre during the time prior to SGI grazing if it was enrolled, and C-Post from the start of the three-year grazing regime to the end of the study, including the period when pastures were no longer within the three-year grazing regime after the SGI contract had ended. The number of years a pasture was considered C-Pre or C-Post could vary by pasture because ranches could enroll throughout the study. C-No refers to pastures that were never enrolled in an SGI grazing program (non-SGI).

3. **"Partitioned effect" (SGI-P) categorization:** This categorization enables us to explore longer-term effects that may not show up until multiple years after a three-year grazing regime was implemented. Subcategories include "P-Pre", "P-During", "P-Post", and "P-No". The P-Pre period includes preparations for the three-year grazing regime such as installing fences or water, the P-During period is when grazing was actually implemented, and the P-Post period occurred when the pastures were no longer within the three-year grazing regime and the SGI contract was done. The number of years a pasture was considered P-Pre or P-Post could vary by pasture because ranches could enroll throughout the study. P-No refers to pastures that were never enrolled in an SGI grazing program (non-SGI).
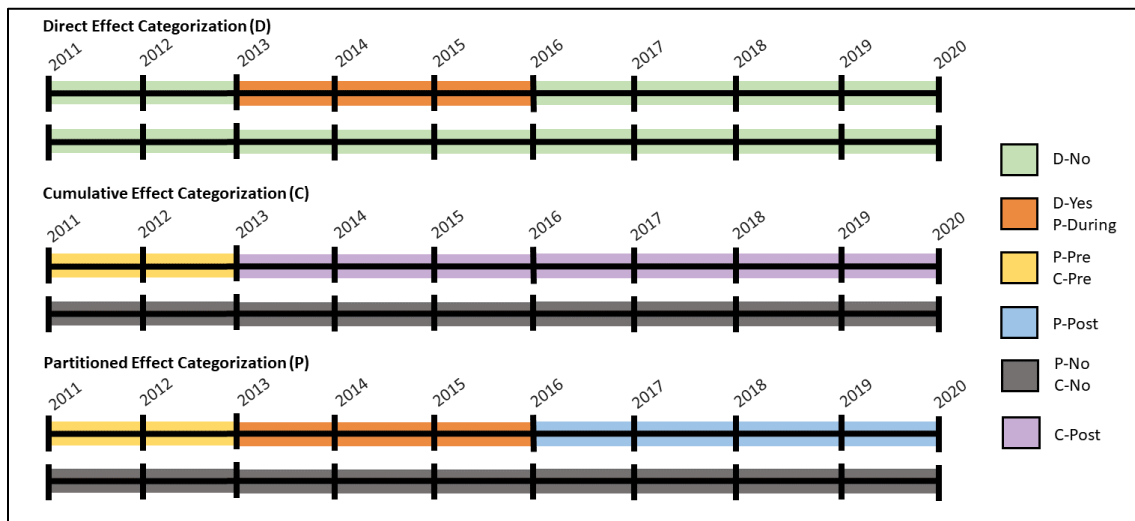
Figure 5. The three SGI categorization schemes that account for both direct and indirect effects of three-year rotational grazing regimes. In each pair of timelines (D, C and P), the top timeline represents the same pasture that implemented an SGI grazing regime from 2013 through the end of 2015, while the bottom timeline represents a different pasture that was never enrolled in an SGI grazing regime. If the colors are the same across grazing categorizations (e.g. the two orange sections), they are labeled as the same subcategory.

We collected grazing data from an area spanning 1,516 km^2 (585 mi^2). The SGI status was available for 100% of our study area. We detailed the number of pastures (sampling units) for the SGI grazing categorizations (Table 1) below; each pasture was counted separately for each year it was in the study.

Table 1. Sample sizes of number of pastures in each subcategory within each of the three SGI grazing categorizations. Colors of the table cells match the color scheme in Figure 5.

Categorization	Category (Factor level)	Number of pastures (%)
Direct effect (D)	D-Yes	684 (13%)
	D-No	4,550 (87%)
Cumulative effect (C)	C-Pre	443 (9%)
	C-Post	1,854 (35%)
	C-No	2,937 (56%)
Partitioned effect (P)	P-Pre	443 (9%)
	P-During	684 (13%)
	P-Post	1,170 (22%)
	P-No	2,937 (56%)

We were also interested in quantifying the time-varying components of each three-year grazing regime that had the potential to directly influence sage-grouse vital rates. These components included variation in the intensity, duration, timing, and frequency of grazing. The majority of pastures were grazed for <50 days each year and from June-October (Figure 6). To quantify grazing timing and frequency, we divided the grazing periods into categorical "treatments." We defined these treatments in collaboration with range scientists at Montana State University based on seasonal periods of importance to both vegetative habitat components and sage-grouse life stages (Figure 7), and we categorized pastures in our study area according to these categorizations (Table 2). We also planned to use animal units per month (AUMs) to represent grazing intensity, but these data were only available for approximately 25% of our pastures, so we we did not incorporate AUMs. Treatments are categorized as follows:

1. **Treatment 1:** April 1-July 15: Vegetation growing season and the nesting season for sage-grouse; grazing during this time period could affect plant growth and reproduction.

2. **Treatment 2:** July 16-September 15: The end of growth and reproduction for vegetation and the brood-rearing season for sage-grouse; grazing during this season could affect plant reproduction and seed-set.

3. **Treatment 3:** September 16-March 31: Vegetation was dormant; grazing during this season removed residual vegetation that may otherwise have been used for hiding cover during the following nesting season.

4. **Treatment 4:** No grazing occurred for an entire year.

Combining our three SGI grazing categorizations and the variables related to grazing timing, frequency, and duration will enable us to investigate the indirect and direct effects of SGI grazing management on sage-grouse habitat and vital rates.
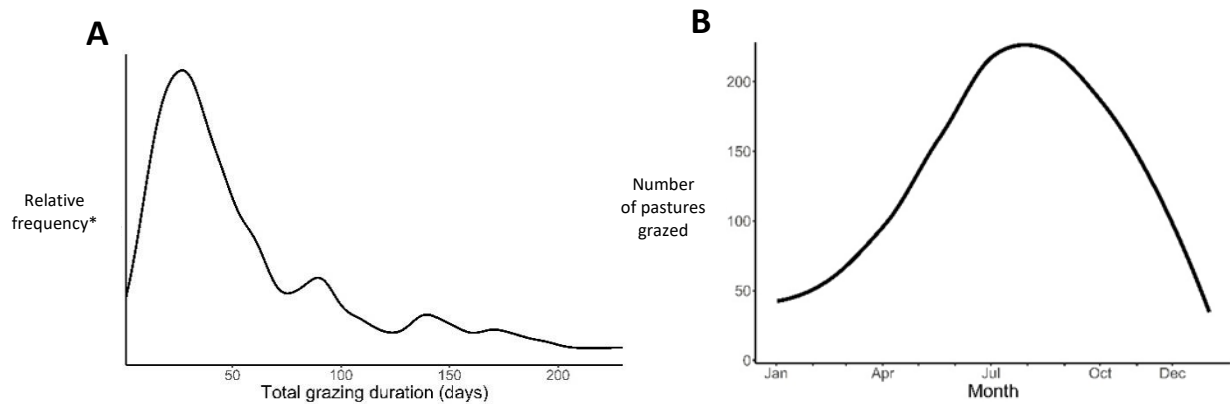
Figure 6. A. Average grazing duration of pastures in our study area across all years. *Note that pastures without grazing (i.e. a duration of zero days) were removed to simplify this figure. B. The average number of pastures grazed during each month of the year in our study area across all years.
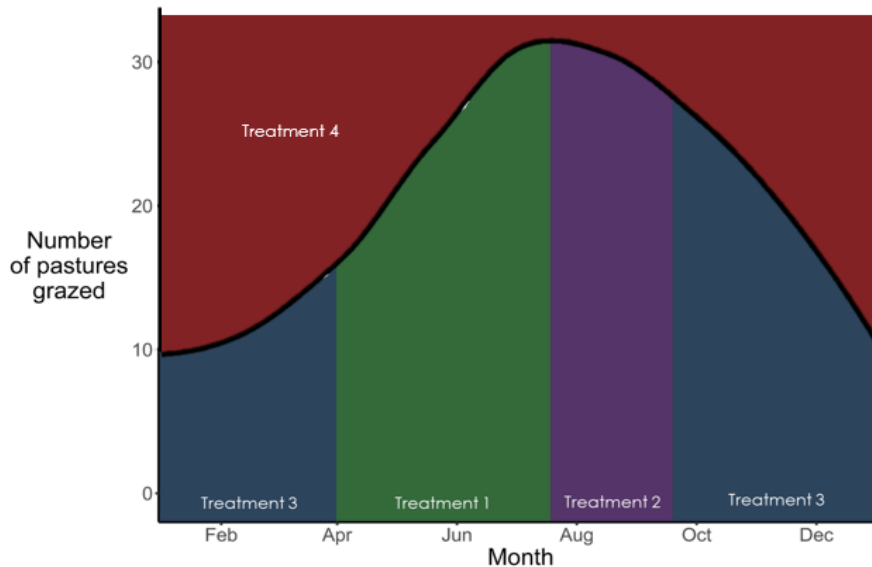
Figure 7. A schematic diagram showing the timing of grazing treatments in relation to time of year.

Table 2. Sample sizes of number of pastures in each grazing treatment. Colors of the table cells match the color scheme in Figure 7.

Treatment	Pastures in treatment (%)
1 (Apr 1-July15)	1,986 (19%)
2 (July 16-Sept 15)	726 (14%)
3 (Sept 16-Mar 31)	965 (18%)
4 (Not grazed)	183 (3%)

Part 1. Demographic Rates

Nest Success

Introduction

Nest success is one of three vital rates that are important to sage-grouse population dynamics (Taylor et al. 2012, Kirol et al. 2015), and as such, it has been well-studied (Table 3). Managing habitat to improve nest success maintains population stability when conducted in conjunction with habitat management for other key vital rates (Taylor et al. 2012). We investigate the potential of using livestock grazing as a habitat management tool to support sage-grouse nest success.

Table 3. Nest success estimates from several studies conducted in different parts of greater sage-grouse range.

Nest success	Location	Years	Study
24-42% *	Montana (eastern)	2001-2003	Moynahan et al. 2007
35% **	Montana (central)	2011-2016	Smith et al. 2018a
38-46% ***	Wyoming (central; southwest)	2008-2014	Dinkins et al. 2016
51%	Intact habitats (unspecified)	Review	Connelly et al. 2011
37%	Altered habitats (unspecified)	Review	Connelly et al. 2011
37% ****	Wyoming (central, southwest)	1994-2002	Holloran et al. 2005
22% **	Nevada	2009-2011	Lockyer et al. 2015
46%	Alberta, Canada	1998-1999	Aldridge & Brigham 2001

* 28-day exposure period. **37-day exposure. *** 27-day exposure. **** 34-day exposure.

Grazing changes plant community composition, productivity, and sage-grouse forage quality (Krausman et al. 2009, Vavra 2005), indirectly affecting sage-grouse nest success. In some areas, sage-grouse tend to select nest sites with broader (Cutting et al. 2019) and taller (Gibson et al. 2016) residual grass cover, an important component for nest concealment that is decreased by livestock grazing during fall or winter (Beck and Mitchell 2000). Similarly, in some areas, sage-grouse also select nest sites with broader, taller, and more diverse forb communities (Gibson et al. 2016), which are depleted by heavy grazing during the growing season (Harniss and Wright 1982). However, in our study area from 2011-2016, there was little evidence that sage-grouse hens were selecting nest sites in relation to the way that livestock grazed on grass and forbs, and there was not much support that rotational grazing is linked to hiding cover and thus nest success (Smith et al. 2018b). We continued this work by investigating whether livestock grazing decreased the vegetation needed for sage-grouse nest cover and food, thus influencing sage-grouse nest success, for another four years.

Direct effects of livestock grazing on nest success include nest trampling and predator behavioral changes (Beck and Mitchell 2000), including predator avoidance of pastures with cattle present. Currently, little evidence suggests a negative, direct effect of grazing on sage-grouse nest success (Beck and Mitchell 2000). Still, there is evidence for a slight positive, direct effect of livestock presence on sharp-tailed grouse (*Tympanuchus phasianellus*) nest survival, potentially due to altered predator behavior (Kirby and Grosz 1995, Foster et al. 2014, Milligan et al. 2020a). In addition to exploring the indirect effects of grazing on nest success outlined above, we explore whether managing the timing, duration, and intensity of livestock grazing affects sage-grouse nest success.

We investigated the effects of SGI grazing management, including timing, duration, and intensity of grazing on sage-grouse nest success over ten years in central Montana. Work conducted during the first half of this ten-year study reported SGI grazing metrics that were equivalent to the direct effect categorization of grazing. In that work, Smith et al. (2018a, 2018b) found that SGI grazing did not significantly affect residual grass cover, and neither residual grass cover nor the presence of the livestock in the pasture during nesting affected nest success (Smith et al. 2018a).

With four additional years of data, we evaluated more grazing categories to explore short and long-term effects, including the Cumulative and Partitioned Categories, and direct effects of grazing, including Treatments 1 and 4, described in 'Grazing Metrics' above. Future work will explore the relevance of grazing during other seasons (e.g., Treatments 2 and 3) on sage-grouse nest success.

Methods

Field methods

We collected nest data from 2011-2020 on sage-grouse hens, including yearling (second-year) females and adult (after-second-year) females in central Montana. Sage-grouse nests were

located by monitoring pre-nesting females using radio telemetry twice per week at the onset of the nesting season. Once they began making localized movements indicative of nesting behavior (same location for two consecutive visits), we tried to home in on the hen without flushing her and observe her sitting on the nest. When the nest was located, we marked it with natural materials from a distance of 10-20m. To minimize disturbance, we limited nest searches to 45 minutes, did not approach nests after marking unless the female was located away from the nest during ≥ 2 consecutive nest monitoring visits, and did not approach nests if corvids or raptors were observed nearby.

Once nests were found, we monitored hens at least twice per week from at least 100m away to minimize disturbance. We classified nests as active (i.e. still alive) if the hen was still on the nest, based on the distance and bearing of the telemetry signal. We also classified nests as active if the hen was away from the nest, but the eggs were warm. We classified nests as failed if the eggs were cold or evidence of depredation and no intact eggs remained. Once females permanently departed the nest, nests were classified as failed if all eggs were either destroyed or missing and successful if at least one hatched egg with a detached membrane was present.

Covariates

SGI Status. – We extracted pasture-level livestock grazing data at each nest location (Table 4). We categorized each pasture into three SGI grazing categorizations (see 'Grazing Metrics') intended to help us make inferences about direct, cumulative, and partitioned effects of SGI grazing across different temporal scales.

Table 4. Sample sizes of number of nests located in pastures in each subcategory within each of the three SGI grazing categorizations. Colors of the table cells match the color scheme in Figure 5.

Categorization	Category (factor level)	Number of nests in categorization
Direct effect (D)	D-Yes	86 (13%)
	D-No	578 (87%)
Cumulative effect (C)	C-Pre	73 (11%)
	C-Post	255 (38%)
	C-No	336 (51%)
Partitioned effect (P)	P-Pre	73 (11%)
	P-During	86 (13%)
	P-Post	169 (25%)
	P-No	336 (51%)

Grazing treatment. – We derived two covariates from the turn-in and turn-out dates that described the timing of grazing (further detailed in 'Grazing Metrics'). We designated nests located in pastures that were actively grazed by livestock during the nesting season as Treatment 1. We designated nests located in pastures that were rested for an entire year as Treatment 4 (Table 5). Treatments 2 and 3 (grazed during the brood-rearing season and grazed during the fall and winter, resepectively) were not included in this analysis because we focused on direct effects of concurrent grazing and overall effects of grazing, rather than effects of seasonal grazing for

this report. Of note, 48% of nests in our study area had an unknown treatment status because we lacked timing of grazing information for these pastures. We assigned those nests as "not in treatment."

Table 5. Sample sizes of number of nests located in pastures in each grazing treatment. Colors of the table cells match the color scheme in Figure 7.

Treatment	Nests in treatment (%)
1 (Apr 1-July15)	173 (26%)
4 (Not grazed)	20 (3%)

Year. – This variable indicated the year in which the nest was initiated. We included this variable to account for random or unexplained variation across years.

Nest attempt. – This variable indicated whether the nest was a first, second, or third nesting attempt by a given sage-grouse hen. We included this variable because past work has suggested different rates of nest success across subsequent nesting attempts.

We included a limited set of covariates in this initial set of models to assess the effects of grazing on sage-grouse nest success in central Montana across nine years (2011-2019). However, we recognize that we excluded some covariates that may have been important (e.g., shrub volume (Smith et al. 2018a), and we will explore those in future work.

Statistical Analysis

We used nest survival modeling software available in Program MARK (White and Burnham 1999) implemented via RMark (Laake 2013) to estimate sage-grouse nest success, or the proportion of nests where at least one chick left the nest. We performed analyses in program R v. 4.0.3 (R Core Team 2020). We used four main pieces of data as inputs into our model: 1) the day of the nesting season on which the nest was found, where day 1 was the first day that technicians looked for nests during the study; 2) the last day the nest was checked when it was known to be active; 3) for failed nests: the last day the nest was checked, and for successful nests: the estimated nest hatch date; and 4) the fate of the nest (i.e. successful or failed). Using these four pieces of information enabled us to estimate the daily survival rate (DSR, the proportion of nests that remained active each day) while accounting for the uncertainty of the exact failure date of unsuccessful nests since nests were not visited daily.

To investigate the effects of livestock grazing metrics (i.e. SGI grazing categorization and grazing treatment) on estimated DSR, we associated each nest with the relevant grazing category described in the "covariates" subsection. We designed models to test different combinations of covariates based on minimizing Akaike's Information Criterion (AIC) and maximizing AIC weights (w_i; Burnham and Anderson 2002). We tested for correlation between SGI grazing categorizations and grazing treatments and found no evidence for correlation, enabling us to test models containing effects of both SGI categorization and treatment. We exponentiated the

estimated DSR from the top model across the 37-day laying and incubation period (Smith et al. 2018a, Schroeder et al. 1999) to obtain an estimate of sage-grouse nest success.

Results

Summary statistics

During 2011-2020, we collected data on 775 nests. For this analysis, we conservatively removed 12 nests whose fate was "undetermined", 91 nests with incomplete or erroneous data, and 8 nests from 2020 due to the small sample size resulting from decreased sampling effort during the global COVID-19 pandemic. This yielded 664 nests with complete data in our sample, with a mean of 73.8 nests each year (range: a low of 57 nests in 2018 to a high of 88 nests in 2012) (Table 6).

Table 6. Nests monitored per year.

Year	Number of nests
2011	87
2012	88
2013	73
2014	71
2015	63
2016	79
2017	87
2018	57
2019	59
Total	**664**

Nest initiation dates were generally similar across years, beginning in mid-April, peaking in mid-May, and tapering off by mid-June (Figure 8). The average nest initiation rate (for first nest attempts) across the study was 0.70, ranging from a low of 0.57 in 2015 to a high of 0.73 in 2012. Most hens nested at least once (N = 183 hens) or twice (N = 108 hens) during the study, but some initiated nests in three (N = 42), four (N = 13), or five (N = 2) distinct years.

Overall, the mean clutch size was 6.54 eggs, and clutch sizes were slightly larger and more variable for first nest attempts than for second or third attempts (Table 6). Very few hens made third nest attempts (Table 7), and no instances of double brooding were detected (i.e. no hen initiated another nest after successfully hatching a nest in a given year). Reported clutch sizes are likely conservative as they are based on eggs and egg remnants observed after the nest hatches.

Figure 8. Nest initiation dates by year.

Table 7. Mean clutch sizes and associated variability across first, second, and third nest attempts of sage-grouse hens in central Montana.

Nest attempt	Mean clutch size	Standard deviation	Range	Sample size
First	6.65 eggs	2.66 eggs	0 – 11 eggs	526 nests
Second	5.84 eggs	2.45 eggs	0-10 eggs	103 nests
Third	7.67 eggs	1.15 eggs	7-9 eggs	3 nests
Overall	**6.54**	**2.64 eggs**	**0-11 eggs**	**634 nests**

Among the 400 nests with reported causes of failure, 358 (90%) failed due to predation. Predators were often unknown, but common nest predators in the area were coyotes (*Canis latrans*), bobcats (*Lynx rufus*), badgers (*Taxidea taxus*), common ravens (*Corvus corax*), red fox (*Vulpes vulpes*), small mammals, and snakes. Technicians recorded the suspected predator if they found evidence of tracks or scat at the nest site. Of the remaining failed nests, 34 (8.5%) had an unknown cause, and five (1.3%) failed due to investigator disturbance; hens were accidentally flushed off nests while technicans were initially locating them. Two nests (0.5%) were assumed to have failed due to livestock presence (i.e. nests were intact but abandoned with evidence of cattle nearby), and one (0.3%) failed due to weather (a hailstorm).

Nest Success Modeling Results

We evaluated 11 competing models (Table 8) containing grazing management, year, and nest-specific variables that we predicted would affect sage-grouse nest success. The model with the best support from AIC contained a covariate effect for "year", while none of the models with other variables (SGI grazing categorization, grazing treatment, or nest attempt) were competitive. The top model had 99.9% of the AIC weight and included the effect of year, indicating a substantially better fit than the other models in this set. The second-most supported model contained "SGI-C," but it is not a competitive model because the delta AIC was greater than 2 (Burnham and Anderson 2002, delta AIC = 17.302, Table 8).

Table 8. Nest success models evaluated, presented in order of AICc, with the top model (year-only effects) listed at the top of the table.

Model	Params	AICc	Delta AIC	Weight	Deviance
Year	9	2206.135	0.000	0.999	2188.119
SGI-Cumulative	3	2223.438	17.302	0.001	2217.436
SGI-Partitioned	4	2225.241	19.105	0.000	2217.237
SGI-Cumulative + Treatments	5	2225.783	19.648	0.000	2215.778
SGI-Partitioned + Treatments	6	2227.475	21.339	0.000	2215.467
Nest attempt	2	2230.601	24.466	0.000	2226.600
Time	2	2230.656	24.520	0.000	2226.655
SGI-During	2	2231.372	25.236	0.000	2227.371
Intercept-only model	1	2231.461	25.326	0.000	2229.461

SGI-During + Treatments	4	2234.446	28.310	0.000	2226.442
Treatments	3	2234.802	28.667	0.000	2228.800

We generated an overall estimate of nest success in our study area using the top model by exponentiating the average daily survival rate (DSR = 0.974, 95% CI = 0.969-0.975) across the 37-day laying and incubation period (Figure 9). Nest success was reported at 37 days post-initiation (the typical laying + incubation period), but we also included estimates of 27-day, 28-day, and 34-day success to enable comparison with other studies that estimated nest success across different time periods (refer to Table 9). Our estimates of nest success across these exposure periods were similar or slightly higher than these other reported estimates.

Table 9. Nest success estimates across different exposure periods commonly reported in the literature. We used a 37-day exposure period (highlighted in bold).

Exposure period	Nest success	95% CI
27 days	0.470	0.428 – 0.510
28 days	0.460	0.415 – 0.498
34 days	0.386	0.344 – 0.429
37 days	**0.355**	**0.313 – 0.398**
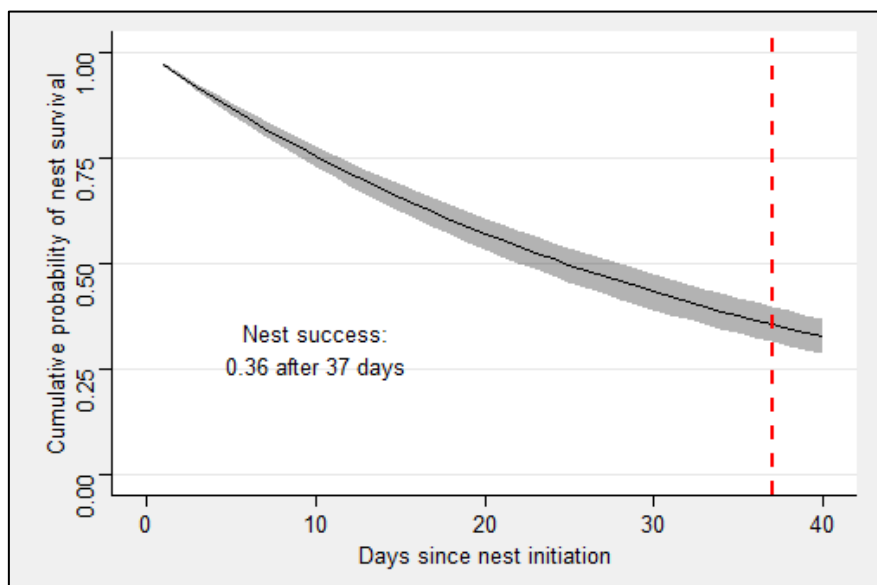
Figure 9. Nest success across the days since nest initiation.

Although the top model did not include SGI effects, we wanted to visualize whether there was a difference in nest success among SGI categories. Since the second-best model incorporated the cumulative effects of SGI grazing (SGI-C, cumulative categorization), we used that model to generate a figure displaying differences among the three categories. Although it appears that the point estimate of nest success is slightly higher in the "SGI-No" category, it is important to note

Figure 10. Nest success across SGI-C (Cumulative) grazing categories.
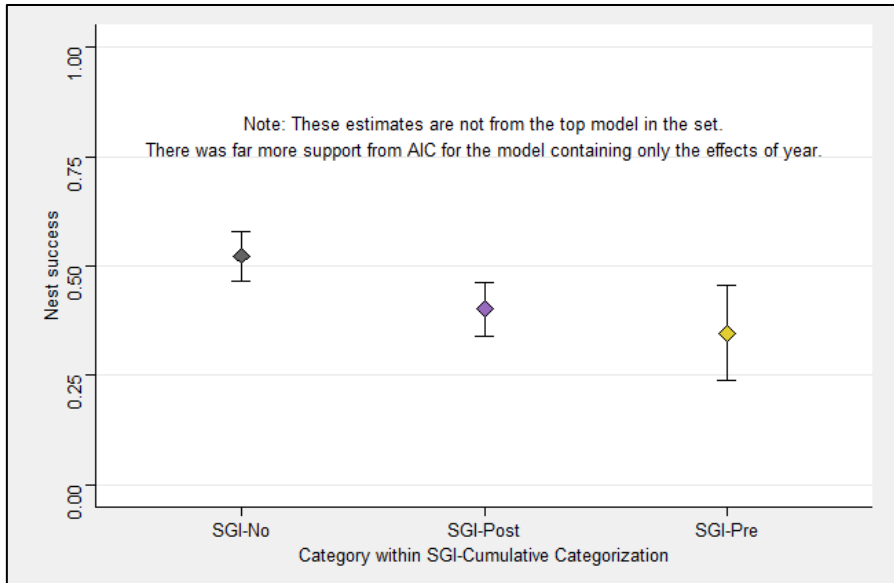
that the differences in nest success among these categories were not statistically significant (Figure 10). Additionally, since the top model in the set does not contain effects of SGI status, this further emphasizes the point that there are no biologically meaningful differences in nest success across SGI grazing categories.

We also plotted annual estimates of sage-grouse nest success based on the top model (Figure 11). In our study area, the year with the lowest nest success estimate (0.30, CI=0.21-0.41, n=59 nests) occurred in 2016, whereas the year with the highest nest success estimate was in 2019 (0.75, CI=0.608-0.852, n=79 nests). The overall nest success estimate across all years of the study period was 0.36 (CI = 0.31-0.40, n=664 nests).

Discussion

Overall, these results suggest that the year-to-year variation experienced by nesting sage-grouse is greater than any direct or indirect effect of SGI grazing management as captured by our categorizations. These results support the conclusions of the work in our study area conducted from 2011-2016 using a portion of the same dataset that showed there was not a measurable response of sage-grouse nest success to SGI grazing (Smith et al. 2018a). Smith et al. (2018a, 2018c) was only able to use grazing metrics equivalent to our direct categorization (D-Yes or D-No, referring to whether a pasture was actively implementing SGI grazing management or not). We were able to additionally evaluate long-term effects of SGI with more detailed grazing history categorizations, given more data from producers to create our
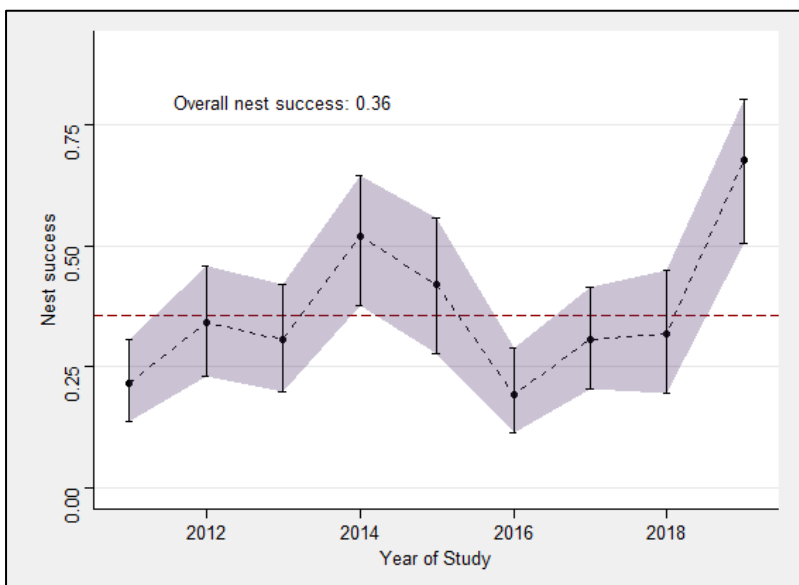
Figure 11. Nest success estimates derived from the top model in our model set (year-only effects), presented by year.

grazing data spatial layer. However, we did not incorporate weather variables into our model set. It is likely that the year-to-year variation we identified as the strongest driver of nest success could be at least partially attributed to annual weather variation. This will be investigated in future work.

Although model selection indicated that there was far more support for the year-only model than the other models containing grazing metrics, the model with the second-most support did contain the effects of grazing captured in the cumulative categorization (C-Pre, C-Post, or C-No). Additionally, it is worth noting that the direct categorization, which was most comparable to the definition used in other studies in our study area (Ruth 2019, Smith et al. 2018a, Smith et al. 2018b), was near the bottom of the model set in terms of AIC weight. This suggests the longer-term effects of grazing, captured by SGI-P and SGI-C but not SGI-D, are more influential to sage-grouse nest success. It is possible that this could also be the case for other demographic rates.

At present, our results suggest that there were no differences in nest success between SGI and non-SGI grazing management according to the way we categorized grazing metrics. However, it is also important to note that further work is needed to explore the effects of habitat predictors that have been found to be influential in other studies of sage-grouse nest success. Other studies suggest that fine-scale vegetation influences nest success in many parts of the sage-grouse range, and those variables are not included in these models. In our ongoing work, we plan to include more covariates that will encompass some of the variation in nest success that is currently only attributable to year (i.e., annual variation). These variables include weather metrics (e.g., temperature and precipitation) and fine-scale vegetation metrics (e.g., shrub, grass, and forb cover).

In light of our results, preventing further reduction and fragmentation (Smith et al. 2018c) in sage-grouse habitat and employing a variety of local grazing management strategies focused on sustainable range management may provide adequate habitat for nesting sage-grouse (Smith et al. 2018).

Chick survival

Introduction

Chick survival, which we define for this study as the period from hatching to independence from the hen, is typically the life stage of lowest and most variable survival (Davis et al. 2016) for grouse. For precocial species such as prairie grouse, this is particularly true during the first few weeks after hatching (Aldridge and Brigham 2002, Hannon and Martin 2006, Manzer and Hannon 2008), and Beck et al. (2006) suggest that survival dips again after they reach 10 weeks of age. Taylor et al. (2012) showed that chick survival up to 35 d post-hatch is one of three most influential vital rates on sage-grouse population growth, along with hen survival and nest

success. Although many studies have evaluated hen survival and population dynamics in sage-grouse, there is a big gap in knowledge about chick survival across the sage-grouse distribution (Caudill et al. 2014). Taylor et al. (2012) showed a need for additional research evaluating chick survival, particularly from 35-60 days of age. Knowing when mortality is highest helps to better manage and target conservation efforts. This work aims to determine how grazing affects chick survival through 2-3 months post-hatch, to help guide management for this life phase.

Methods

Marking Chicks

We monitored chicks from near hatching to independence from the brood hen, up to 125 days post-hatch. We first found and monitored nests using hens marked with radio transmitters. Chicks were captured 1-10 days after hatching (mean=2.8d, SE=±0.11d). We homed in on the hen with telemetry just after sunset when she was typically brooding her chicks. Hens were reluctant to flush or move their brood unless a perceived danger was in very close proximity; this behavior allowed us to get close enough to capture the chicks. We could approach close enough to touch hens and often had to gently nudge them off the brood. Hens either flushed or walked a short distance, typically remaining within 50 m throughout the entire process. The chicks were captured by hand and placed into a cooler containing a hot water bottle that helped maintain their body temperature while away from the hen. We affixed a 1.3g backpack VHF radio transmitter (Model A1065, Advanced Telemetry Systems, Isanti, MN) on up to four randomly selected chicks per brood (mean number of chicks hatched per nest during this study is 6-8, see Nest Success above) via two small sutures on the lower back (similar to Dreitz et al. 2011). This has been the most successful (<1% accidental death rate) and common method used to attach radio transmitters to sage-grouse chicks (Burkepile et al. 2002, Dahlgren et al. 2010). The transmitters were guaranteed to last 60 days, and most lasted 75-125 days, which is two to three months after hatching. We checked on chicks the morning after they were marked. The fates of chicks found dead and intact near the capture site were attributed to the marking process and excluded from analyses. We monitored chicks every other day for the first two weeks when mortality rates were typically highest, and ≥2 times per week thereafter until the chicks died, their tags expired, we lost their signals, or they were recaptured and fitted with a larger transmitter.

Analyses

Analyses were performed in program R v. 4.0.0 (R Core Team 2020). We calculated probabilities of radio-marked chicks surviving to 75 days, when their mass was similar to yearlings and adults, using staggered entry Kaplan-Meier models in package "survival" (Therneau 2021a). For survival models described below, the monitoring period was considered the duration when transmitters were functional, ≤125 days. Individuals whose signals were lost

or had unknown fates were right censored from the analysis at the last time they were successfully monitored.

We used log-rank models to test for differences in survival between groups of predictors that were factors and not time-varying including year, hen age, and sex of chicks (predictors described below). We fit Cox proportional hazards models with the coxph function in the survival package to assess the effects of time-varying and continuous covariates on chick mortality risk including body condition index of the brood hen; chick mass; sexID of chicks; weather; vegetation cover metrics extracted from the Rangeland Analysis Platform (RAP); other remotely sensed variables including slope, compound topographic index, vector ruggedness measure, herbaceous vegetation heights, shrub heights; distance to crops or roads; remotely sensed anthropogenic disturbance metrics including human structure density and human disturbance index; and grazing metrics. A Cox proportional hazard ratio (hereafter ratio) of 1.00 was considered baseline, above 1.00 was interpreted as an increased risk of mortality, and below 1.00 was interpreted as a decreased risk of mortality. We used the cox.zph function to test if models met the assumptions for proportional hazards. For models that did not, we included a time-dependent covariate using the time-transformation function (Therneau et al. 2021b).

Because we marked ≤4 chicks per brood, there could have been some intrabrood dependence. In addition, we monitored some hens during multiple years (2 yrs = 19 hens; 3 yrs = 1 hen; 4 yrs = 1 hen) and chicks monitored during different years might have been born of the same hen. Violation of the assumption of intrabrood independence in survival does not bias survival estimates, but causes underestimation of the variance (Flint et al. 1995, Ringelman and Longcore 1982, Pollock et al. 1989). We dealt with the lack of independence by using the robust variance estimator and hen identity as a random effect using the cluster function in the Cox proportional hazards models (Murray 2006, Therneau 2021a). The survival probabilities of chicks differed significantly among years (χ^2=33.23, df=8, p<0.01), so for all Cox models, we used the strata argument in the coxph function to stratify by year.

Covariates

All remote sensed metrics were obtained at a 30 m resolution, which is the same resolution of the chick locations. We obtained chick locations by homing in on their signal and circling the signal to ensure we were within 30 m, but not getting closer than 30 m to avoid flushing the brood hen or chicks. Each location was given the predictor values of the pixel in which they were located.

Hen Age.— Hens were primarily captured during the spring (Mar-Apr) when 2 age classes could be determined: yearling (second year) or adult (after second year; Braun and Schroeder 2015). Some hens were captured during the fall (Aug-early October) when yearlings can be classified as juveniles (hatch year) or yearlings (2nd year), but to keep things consistent we only used the yearling (hatch year plus 2nd year) and adult classifications (after 2nd year). We aged hens as

adults or yearlings according to characteristics of primary wing feathers and weights (Braun and Schroeder 2015). We had data on the brood hen age for 535 of the 539 chicks that were marked.

Hen Body Condition Index.— When hens were captured and marked with transmitters, we recorded morphometric measures, including hen mass, tarsus lengths, and natural wing chord lengths. We used these measures to calculate the body condition indices of hens by first using principal components analysis to combine wing chord lengths and tarsi lengths from both right and left sides (R packages 'FactorMineR' v 2.4 [Husson et al. 2020] and 'stats' v 4.0.0 [R Core Team 2020]). We regressed hen mass on the first principal component and used the residuals as the body condition indices (Warren et al. 2014). We could only calculate the hens' body conditions during the year they were captured, and not in subsequent years when they may have had broods but were not recaptured. We only used body conditions from hens captured during the spring (Apr-May), as hen weights may vary during different times of year.

Chick Mass.—We recorded chick mass at the time of capture and used their mass adjusted for age at capture as a predictor in survival models.

Chick Sex Identification (sexID).—During 2014-2017, we collected a blood quill (i.e., pin feather) from each chick during capture to extract a drop of blood for sexID. The blood samples was analyzed by Utah State University's Molecular Ecology Laboratory.

Weather.—Weather conditions during the time of highest mortality, which occurs within the first 2 weeks after hatching and peaks in early June for many prairie grouse, may have a large effect on chick survival (Flanders-Wanner et al. 2004). For example, chicks cannot initially thermoregulate after they hatch (Guttery et al. 2013), and must rely on the hen to keep them warm and survive heavy rain events during the early post-hatch period. In addition, weather could indirectly affect chick survival through its influence on vegetation (Gillen and Sims 2006) and food availability (Flanders-Wanner et al. 2004). Some studies have shown that climatic variables including precipitation (amount and timing), temperature, and drought are the primary drivers of sage-grouse reproductive success in Nevada and Utah (Dahlgren et al. 2010, Guttery et al. 2013), and preliminary results show they are also important drivers for our study population in central Montana (Smith et al. 2018b).

We tested weather variables (<https://daymet.ornl.gov/>) at multiple temporal scales including daily, monthly, seasonal, and breeding season. We defined seasons to be comparable with other sage-grouse studies: spring=Apr-May, summer=Jun-Jul, fall=Aug-Oct, winter=Nov-Mar. We defined breeding season as Apr 1-Aug 31, and the non-breeding season as Sep 1-Mar 31. At each scale we extracted variables including precipitation, maximum temperature, and minimum temperature. At the monthly and seasonal scales, in addition to total precipitation, maximum and minimum temperatures for those periods, we also extracted mean precipitation and mean

maximum and minimum temperatures for each time period. At the daily scale, these variables were total precipitation, maximum temperature, and minimum temperature.

RAP Variables.—We obtained remotely sensed vegetation metrics from the Rangeland Analysis Platform (Jones et al. 2021; http://rangeland.ntsg.umt.edu/data/rap/rap-vegetation-cover, last accessed July 2021) for the study period of 2011-2019. The variables we extracted from this platform included percent cover of annual forbs and grasses, perennial forbs and grasses, shrubs, litter, bare ground, and trees.

Other Remote Sensed Variables.—We obtained herbaceous vegetation heights and shrub heights from LANDFIRE (2016) Existing Vegetation Height at 30m resolution. We used FWP's Digital Elevation Model raster to extract slope, compound topographic index, vector ruggedness measure, and heat load index covariates at 30m resolution. Compound topographic index (CTI) is a wetness index that is a function of slope and upstream flow direction (https://evansmurphy.wixsite.com/evansspatial/arcgis-gradient-metrics-toolbox, last accessed Dec 3, 2021). "The vector ruggedness measure (VRM) measured terrain ruggedness as the variation in three-dimensional orientation of grid cells within a neighborhood. Vector analysis is used to calculate the dispersion of vectors normal (orthogonal) to grid cells within the specified neighborhood. This method effectively captures variability in slope and aspect into a single measure. Ruggedness values in the output raster can range from 0 (no terrain variaton) to 1 (complete terrain variation). Typical values for natural terrains range between 0 and about 0.4" , and our metric used a neighood size of 5 pixels (https://www.arcgis.com/home/item.html?id=9e4210b3ee7b413bbb1f98fb9c5b22d4, last accessed Dec 3, 2021). The heat load index was an estimate that accounts for steepness of slope and the direction in which the slope is facing, with highest values in the southwest and lowest values in the northeast (https://evansmurphy.wixsite.com/evansspatial/arcgis-gradient-metrics-toolbox), and the value falls within a range from 0 (coolest) to 1 (hottest).

Distance Variables.— We calculated and used distance from chick locations to nearest cropland and paved or county roads as covariates. These distances were calculated using ArcGIS (ESRI Inc., Redlands, CA).

Anthropogenic Disturbance.—We obtained human structure density (HSD; number of structures/mi^2; https://geoinfo.msl.mt.gov/Home/msdi/structures_and_addresses, last accessed Dec 3, 2021; Point Density tool [1 sq. mi. circle neighborhood]), and human disturbance index (HDI; https://mslservices.mt.gov/Geographic_Information/Data/DataList/datalist_Details?did=%7B639 e7c86-8224-11e4-b116-123b93f75cba%7D, last accessed Dec 3, 2021) at 30 m resolution from the Montana State Library. The HSD from a state-wide database of primary structures and buildings. The HDI includes development, transportation, agriculture, resource extraction/energy

development, introduced vegetation, and forestry practices and ranges from 0-4,314. Chick locations were given the score of the pixel the location was in.

Grazing.—To address our objective, we used radio telemetry to monitor sage-grouse in pastures enrolled in SGI grazing management. The grazing management in pastures was intermixed across the study area (Figure 4). The status of pastures changed across years, and we structured the grazing data spatial layer to deal with this temporal heterogeneity and account for this in analyses. Our grazing management categories included the direct category with D-yes and D-no subcategories, cumulative category with C-pre, C-post, and C-no subcategories, or partitioned category with P-pre, P-during, P-post, and P-no subcategories. The 'pre' and 'no' subcategories were equivalent across categorizations (Table 10). This study was observational; we could not control the number of birds within or the distribution of grazing management types. We did not use the finer-scale, timing of grazing treatments because sample sizes were too low for these assessments.

Table 10. Sample sizes of chick locations per grazing management categories for our marked population of greater sage-grouse chicks in Golden Valley and Mussellshell Counties, MT, 2011-2019, all years combined.

Grazing Categorization	Subcategory	Number of Locations
Direct (D) Categorization	D-no	356
	D-yes	100
Cumulative (C) Categorization	C-no	276
	C-pre	26
	C-post	154
Partitioned (P) Categorization	C-no	276
	P-pre	26
	P-during	57
	P-post	97

Results

During 2011-2019, we marked 539 sage-grouse chicks with radio transmitters (Table 11). We attributed the fates of 14 chicks to the marking process: 2011=1, 2012=0, 2013=4, 2014=1, 2015=2, 2016=2, 2017=0, 2018=0, 2019=4. Analyses were completed with the remaining 521 chicks. With data pooled across years, the Kaplan-Meier median survival time for these chicks was 42 d (95% CI=33-59d, Figure 12). The annual probabilities of chicks surviving until 75 d (when chick weights were similar to yearlings and adults) ranged from 0.19-0.60 (Table 11).

Table 11. Kaplan-Meier survival estimates of greater sage-grouse chicks in Golden Valley and Musselshell Counties, MT, 2011-2019. These represent the probability that chicks survived to 75 days, when they are adult-sized.

	Total Number of Marked Chicks	Kaplan-Meier Survival Estimate	Standard Error	95% Confidence Interval
2011	22	0.44	0.16	0.22-0.89
2012	81	0.19	0.05	0.11-0.33
2013	53	0.41	0.11	0.25-0.68
2014	76	0.40	0.10	0.25-0.64
2015	56	0.56	0.08	0.42-0.74
2016	43	0.33	0.08	0.20-0.54
2017	84	0.47	0.07	0.35-0.62
2018	52	0.24	0.07	0.14-0.42
2019	56	0.60	0.07	0.48-0.76
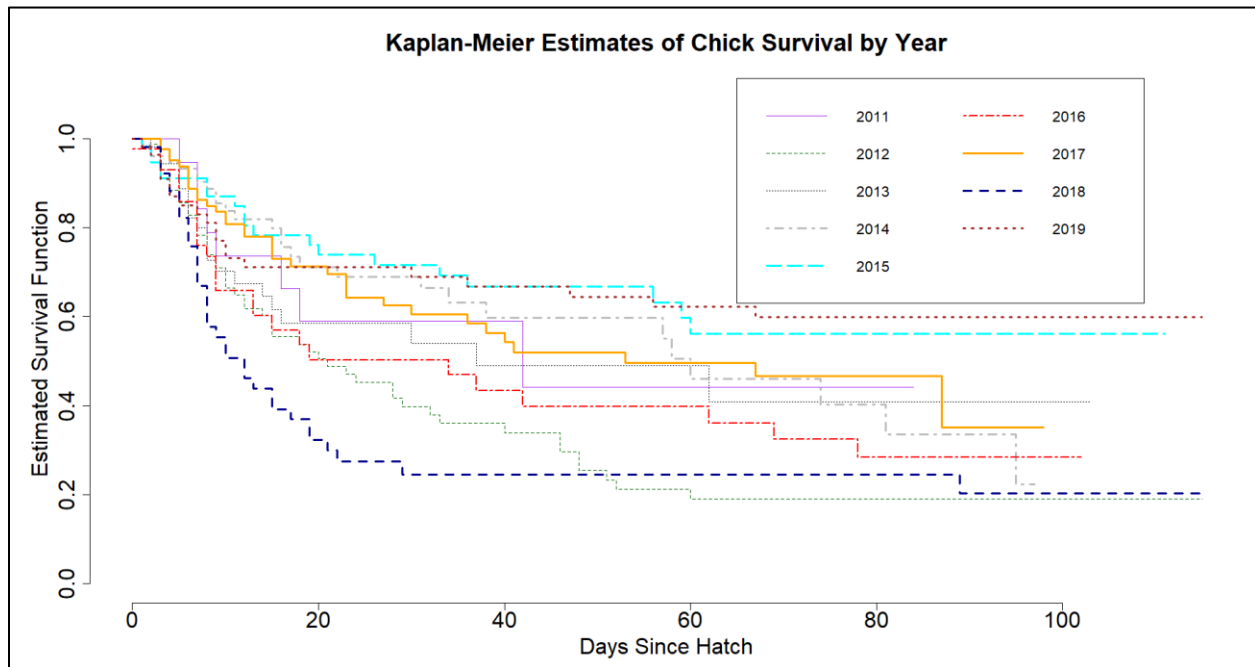
Figure 12. Kaplan-Meier survival curves by year for marked greater sage-grouse chicks in Golden Valley and Musselshell Counties, MT. The 95% confidence intervals were removed to facilitate interpreting the figure.

The age of the brood hen had no measurable effect on chick survival (χ^2=0.1, *df*=1, *p*=0.8; Figure 13). The median survival time for chicks with adult hens was 40d ± 2.89 (95% CI=30-60d), and for chicks with yearling hens was 46d ± 6.55 (95% CI=24-67d).
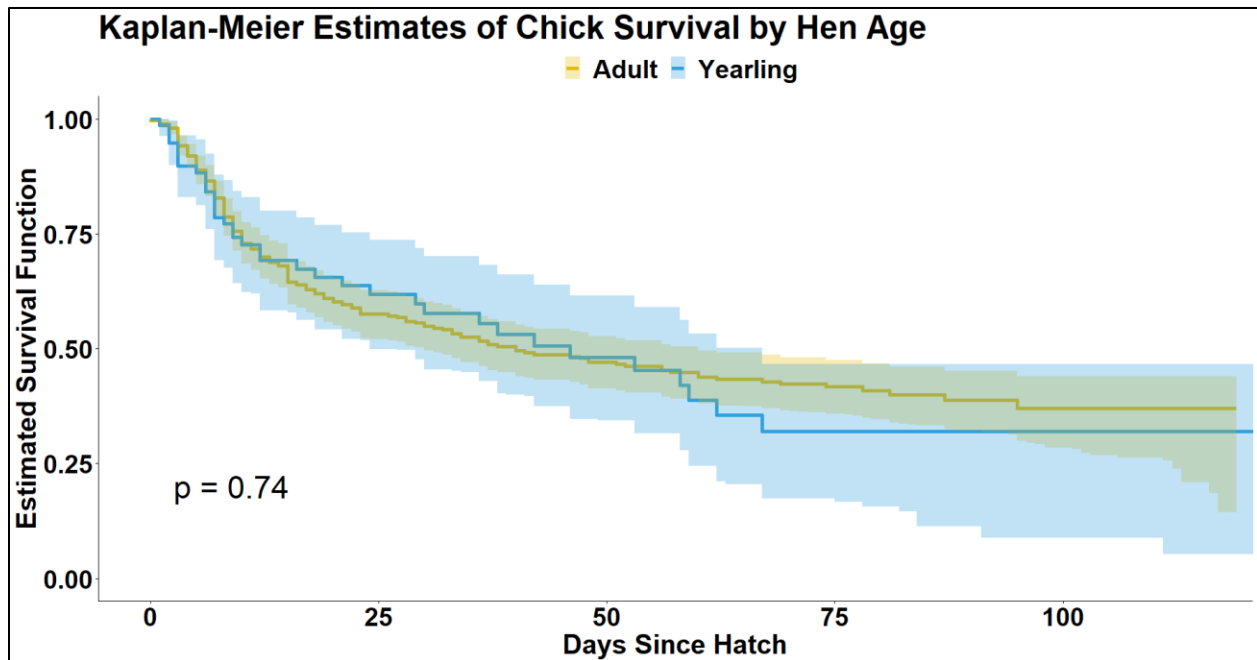
Figure 13. Kaplan-Meier survival curves with 95% confidence intervals by hen age for greater sage-grouse chicks marked with radio transmitters in Golden Valley and Musselshell Counties, MT, 2011-2019.

During 2014-2017, we identified the sex ('sexID') of 248 sage-grouse chicks from 135 nests. Of these chicks, 120 were female and 128 were male. The difference in survival probability curves between male and female chicks was not significant (χ^2=1.9, *df*=1, *p*=0.16; Figure 14), though females tended to exhibit higher survival than males. The median survival time of female chicks was 95d ± 4.69 (95% CI=42-NA[*]), and for male chicks was 53d ± 4.41 (95% CI=34-74d). When modeling the effect of sexID on chick mortality risk using a Cox proportional hazards model, male chicks had a 30% greater mortality risk than females, though the effect of sexID on mortality risk was not significant (Cox proportional hazards ratio for male chicks =1.30, 95% CI=0.93-1.98, Z=1.57, *p*=0.116).

[*] Not enough chicks mortalities to estimate
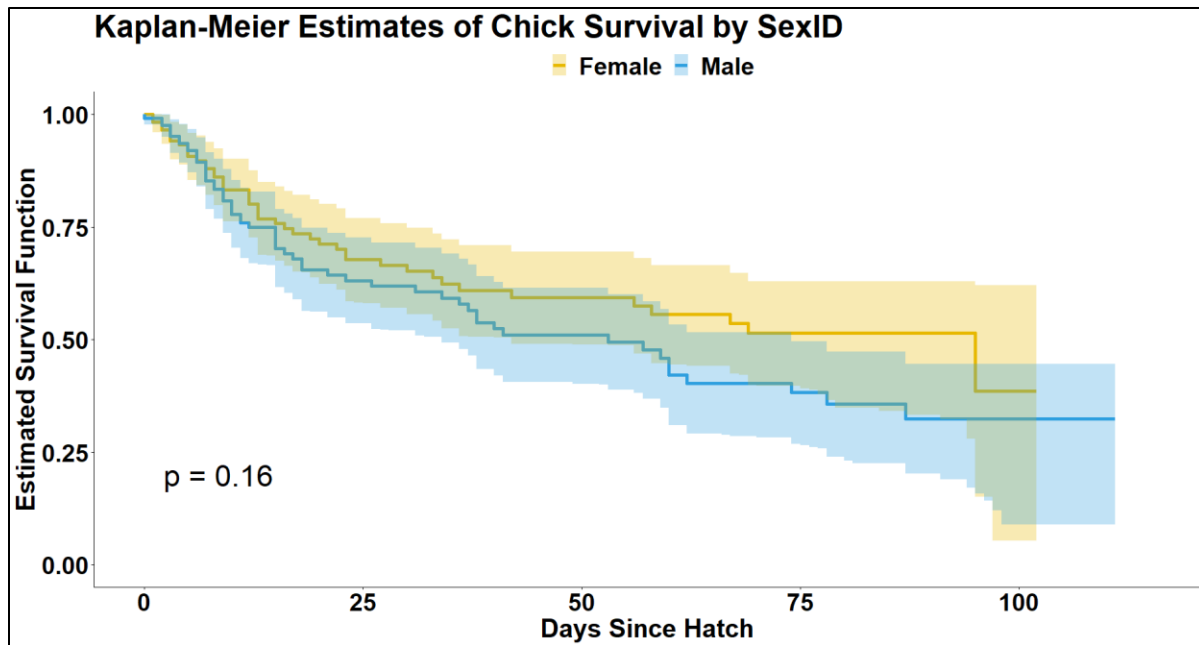
Figure 14. Kaplan-Meier survival curves with 95% confidence intervals by chick gender for marked greater sage-grouse chicks from which we sampled blood during 2014-2017 in Golden Valley and Musselshell Counties, MT.

For the remaining analyses, we used Cox proportional hazards models to assess the effects of continuous and time-varying covariates on the probability of chick mortality. The mortality risk for chicks was influenced by the seasonal maximum high temperature (Cox proportional hazards ratio=0.89, 95% CI=0.84-0.94, Z=-4.06, p<0.01). Chick mortality risk was 11% less with a 1 degree increase in the seasonal maximum temperature.

None of the remote-sensed vegetation metrics obtained from the Rangeland Analysis Platform had a significant effect on the mortality risk of chicks. The degree of slope at a location significantly affected chick mortality risk, but the effect size was small (β=0.01; ratio=1.01, 95% CI=1.00-1.02, Z=2.17, p=0.03). The distance of the nearest cropland to chicks significantly affected mortality risk, though the effect size was small (β<0.01), increasing the risk for chicks with each 1m increase away from cropland (ratio=1.00, 95% CI=1.00-1.01, Z=2.62, p=0.01). But with a hazard ratio of 1.00, this means that mortality risk was neutral. The combination of slope and distance to nearest crops was significant (Z=18.25, df=2, p<0.01) as were the effects of each variable within the model (slope: ratio=1.01, 95% CI=1.00-1.02, Z=1.96, p=0.05; distance to nearest crops: ratio=1.01, 95% CI=1.00-1.02, Z=1.96, p=0.05), but again the effects of each variable were small and ratios of 1.00 show the effects on mortality risk were neutral.

Mortality risk as a function of the cumulative grazing category was significant (Z=23.07, df=3, p<0.01), showing 59% higher mortality risk for chicks when using pastures during/post implementation of SGI (C-post pastures: ratio=1.80, 95% CI=1.16-2.08, Z=2.64, p<0.01; C-pre pastures: ratio=0.79, 95% CI=0.32-2.00, Z=-0.50, p=0.63). The sample sizes of chick locations for C-/P-pre subcategories were relatively low (Table 10). Consequently, we had limited power to detect differences among subcategories.

Discussion

Chick survival is important in maintaining and contributing to population growth and persistence of multiple gallinaceous species, including greater sage-grouse (Wisdom and Mills 1997, Clark et al. 2008, Sandercock et al. 2008, Hagen et al. 2009, Taylor et al. 2012). Many different sampling techniques and duration of monitoring periods have been used to estimate sage-grouse chick survival across their distribution, making it difficult to compare studies (Schreiber et al. 2016). For example, Gregg and Crawford (2009) and Dahlgren et al (2010) monitored sage-grouse chicks to 28 and 42 days, respectively. In contrast, in our study, we monitor chicks up to 125 days due to the recent availability of smaller, lighter radio transmitters with longer battery life. We define chick survival as the period between hatching and the time when chicks become adult-sized and independent from the brood hen (2-3 mo post-hatch).

Most studies of juvenile sage-grouse survival have found differential survival by sex favoring females (Swenson 1986, Caudill et al. 2014, Apa et al. 2017). Though we did not measure a statistically significant difference in survival between female and male chicks, there was a tendency for females to have a higher probability of survival than males. Caudill et al. (2014) found differential survival between female and male juvenile sage-grouse (age defined from brood independence through the start of breeding the following year), with females having higher survival. Capercaillie (*Tetrao urogallus*) and black grouse (*Tetrao tetrix*), species that are also sexually dimorphic like sage-grouse, also exhibit this discrepancy in survival between sexes during adverse conditions (Wegge 1980, Caizergues and Ellison 1997). There seems to be a pattern in lekking grouse species that sexual dimorphism has a cost for males during the first few months of life before they reach sexual maturity (Swenson 1986). The large dimorphism exhibited in capercaillie, black grouse, and sage-grouse requires a higher energy expenditure from males, who grow much faster and larger than females when they are juveniles (Swenson 1986, Linden 1981). Swenson (1986) suggests that poor habitat quality or unfavorable weather years that affect food availability may result in female-biased survival. For our purposes, managers might expect female-biased survival and fewer males displaying on leks in the spring following a year of challenging weather such as a cold, wet spring (late-May through June), because chick mortality risk declined slightly as maximum temperature increased. Additionally, Smith et al. (2018b) showed that nest success was negatively affected by big rain events (sum of precipitation four days prior to nest fate). Because chicks cannot thermoregulate and need the brood hen for warmth during the first couple weeks after hatching, we speculate that cold wet springs result in higher chick mortality for sage-grouse, though precipitation was not influential in our survival models.

We estimated statistically significant effects of slope and distance to nearest crops on chick mortality risk. However the hazard ratios for each variable indicated a neutral effect. These could be artifacts of sampling, but the potential of these as important variables could be studied further.

Our analyses suggested that the probability of chick mortality was higher when using pastures during/post SGI grazing management. This result might be explained if pastures that were enrolled in SGI were of lower quality than those not enrolled. The purpose of SGI grazing management was to maintain or improve potential sagebrush habitat for sage-grouse primarily by resting or deferring vegetation from grazing and allowing it to recover, especially grass because it was considered protective cover for nesting hens. The grazing management part of SGI focused on the nesting phase of the grouse life cycle. But grass has been shown to be less important for nest success than previously thought (Gibson et al. 2016, Smith et al. 2018b), and there is no guarantee that this assumed benefit would carry over to the brood-rearing stage and benefit chicks. Kirol et al. (2012) showed that perennial grass and sagebrush cover was important, and might be more important than forbs, for brood-rearing habitat in xeric sagebrush (≤25 cm of annual precipitation). However, average annual precipitation for our study area is ~35cm. Invertebrates and forbs have been shown to be an important food source for chicks (Gregg and Crawford 2009, Thompson 2012), and chicks are more likely to encounter these food resources in mesic areas and wet meadows. The NRCS did focus on these types of habitats in a later part of the SGI program in different areas across the sage-grouse distribution. However, improving mesic areas and wet meadows was not a focus of the grazing program. We included a distance to water covariate in survival models which did not have a significant effect on mortality risk, but we did not include any other metrics related to mesic areas or similar habitats because our goal was to assess the relationship of grazing with chick survival. Overall, our sample sizes of chick locations for C-/P-pre subcategories were relatively low (Table 11), so this result may be spurious given that we had limited power to detect differences among subcategories.

The SGI grazing management did not seem to benefit the survival of sage-grouse chicks. Our limited data suggest SGI grazing might have been detrimental for chick survival, at least in the way we categorized grazing management for analyses. But analyses are ongoing, and we are in the process of analyzing habitat use of chicks. We will determine if habitat selection aligns with areas of high or low chick survival, and how this is affected by SGI grazing management. We will address this in the PR grant to complete this work: Federal Award Identification Number F21AF01330.

Hen survival

Introduction

Hen survival is one of three vital rates important to sage-grouse population dynamics (Taylor et al. 2012). Studies investigating the drivers of hen survival probability and estimating hen survival have been conducted in study areas throughout the range (Table 12), but less comprehensively than the work done on sage-grouse nest success (see "Nest Success"). Like other vital rates, published hen survival estimates are variable (Table 12). Hen survival may

depend on season (Moynahan et al. 2006, Smith et al. 2018), year (Moynahan et al. 2006), disease dynamics (Moynahan et al. 2006), or reproductive state, such as between hens that initiate nests and those that do not (Smith et al. 2018). Since hen survival depends on region-specific factors, investigating hen survival in central Montana is important to understand population dynamics in this portion of sage-grouse range.

Table 12. Hen annual survival probability estimates for some studies conducted in different parts of sage-grouse range.

Annual Survival Probability	Location	Study
Range: 38-75%	Montana (central)	Sika 2006
Average: 63% (Range: 12-100%)	Montana (eastern)	Moynahan et al. 2006
Average: 59% (females), 37% (males)	Colorado	Zablan et al. 2003
Range: 46-54% (males) Range: 68-85% (females)	Idaho	Connelly et al. 1994
61% (95% CI: 46-74%)	Colorado	Hagen et al. 2018
Average: 58%	Range-wide	Taylor et al. 2012

Because much of sagebrush habitat in central Montana is rangeland, it is important to understand how livestock grazing affects hen survival. Since sage-grouse hens require sagebrush for both cover and forage throughout their annual cycle (Connelly et al. 2011), rangeland management practices that decrease sagebrush availability (e.g., herbicide application or targeted sagebrush removal) could affect sage-grouse hen survival, particularly if sagebrush is a limiting resource. However, no published studies have investigated whether livestock grazing affects hen survival, either indirectly (through vegetation responses) or directly (through concurrent effects of livestock and sage-grouse inhabiting the same pasture at the same time). This section investigates the influence of SGI grazing regimes on sage-grouse hen survival. Ultimately, we aimed to determine the effectiveness of SGI grazing as a management tool for maintaining or increasing hen survival, and identify the best practices for managing sage-grouse hen habitat using livestock grazing.To explore the effects of the three-year SGI grazing regime on hen survival, we used the categorizations of direct effects, partitioned effects, and cumulative effects. We did not examine the influence of finer-scale, grazing timing metrics on hen survival because of low sample sizes within individual grazing timing categories.

Methods

Field methods

We captured and marked hens at the start of the breeding season (March and April) from 2011 - 2019. In 2011 we marked 101 hens, and in the following years, we caught and marked enough hens to replace any that died during the previous year. Hens were captured on or near leks using

night-time spotlighting (Giesen et al. 1982, Wakkinen et al. 1992) and fit with either a 25-g necklace style VHF transmitter (Model A4060, Advanced Telemetry Systems, Isanti, MN) or a 25 g solar global positioning system platform transmitter terminals (GPS PTTs). The VHF transmitters were equipped with a mortality switch. The tempo of the signal would pulse twice as fast if a transmitter stopped moving for ≥4 hrs, suggesting 'mortality' the next time we listened for that bird. We attempted to recapture hens two years after initial capture to replace old transmitters with new ones before the old transmitter batteries expired. In this way, we attempted to monitor individual hens for as long as possible. This population of sage-grouse was not migratory and could be monitored continuously throughout the year.

We collected data from hens that were marked and monitored by very high frequency (VHF) radio telemetry (both ground-based monitoring and aerial monitoring) as well as some hens that were marked and monitored via solar GPS PTTs that use satellites to transmit an individual's location to a central database at a predetermined schedule. For this report, we focus on VHF hen locations; results with both VHF and GPS PTT data will be compiled in the final report for our current PR Grant to complete this work: Federal Award Identification Number F21AF01330.

Ground-based monitoring
After capturing and marking hens, we monitored hens the next day to account for capture-related mortality. We then monitored hens twice per week from Apr-Aug by homing in on the hen to within 30m of her location using telemetry. We monitored hens with broods every other day for the first two weeks post-hatch, and then at least two times per week thereafter. Technicians only noted if they found a hen and not if they attempted to locate it, so we do not have data on detection probability.

Aerial monitoring, Lost Signals, and Mortalities
We located lost hens during Apr-Aug and collected locations of hens once per month during Sep-Mar using aerial telemetry. If a bird was lost, it was censored on the last day it was heard active. If a bird died between observations, we used the midpoint between observations as the estimated fate date.

Covariates
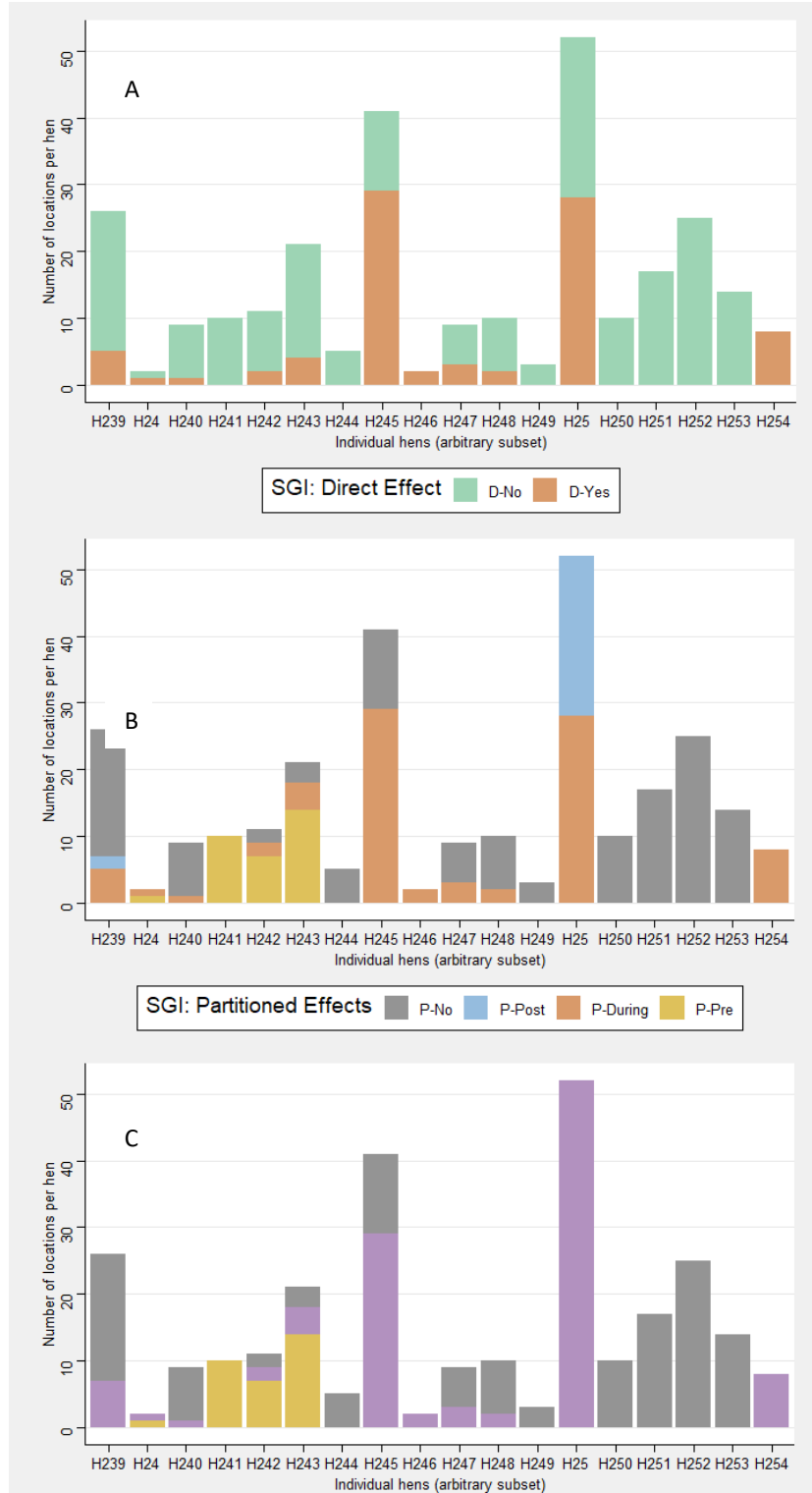
Figure 15. The distribution of SGI grazing categories visited by sage-grouse hens over the course of their monitoring period. Each bar corresponds with an individual hen. This is an arbitrary subset of hens in the sample, selected to visualize differences in use of pastures by different hens. It does not necessarily represent common patterns in pasture use.

We included a limited set of covariates in this analysis to provide a preliminary look at the effects of grazing on sage-grouse hen survival in central Montana across nine years. We included the covariates of the three SGI grazing categorizations and the year in which the hen died or was lost to follow-up.

SGI Status. – To investigate the effect of SGI grazing status on annual hen survival, we incorporated a variable to address whether and when a pasture was actively enrolled in the three-year rotational grazing program that is part of SGI. In contrast to nests that are stationary in a given pasture with a set SGI categorization for the year, hens move through pastures undergoing different grazing regimes over time. For example, hen "H239" spent the majority of its time in pastures that were not enrolled in the SGI grazing program, but it spent some time in pastures that were (Figure 15). Additionally, those pastures enrolled in SGI grazing can be categorized differently depending on the categorization being used (Figure 15, Panels A, B and C). We categorized each hen into

the grazing category where the majority of its locations occurred. If a hen spent time in 2 categories, we assigned it the category with >50% of locations. If a hen spent time in 3 categories, we assigned it the category with >33.33% of locations. If a hen spent time in 4 categories, we assigned it the category with >25% of locations. For example, hen "H239" was sub-categorized as "No" (non-SGI) across grazing categorizations (Direct, Cumulative, or Partitioned; "D-No Panel A"), "P-No" (Panel B), and "C-No" (Panel C)), whereas hen "H245" was categorized as "D-Yes" (Panel A), "P-During" (Panel B), and "C-Post" (Panel C) because most of its locations were in pastures undergoing SGI grazing programs (Figure 15). Note that for this preliminary analysis, given the complexity of each hen's monitoring period spanning multiple years, we simplified to a single SGI category for each hen for all of the years it was alive (Table 13), but in the future we aim to explore the time-varying effects of SGI categories on hen survival.

Year. – This variable indicated the year in which the hen was monitored. Year was measured from April 1 of a given year through March 31 of the following year (i.e. the 2011 monitoring year refers to April 1, 2011 through March 31, 2012). We included this variable to account for variation across years that affected survival probability.

Table 13. Sample sizes of number of hens located in each subcategory within each of the three SGI grazing categorizations. Colors of the table cells match the color scheme in Figure 5. A hen was assigned a single grazing category across all of the years it was alive, as described above.

Categorization	Category (factor level)	Number of hens in categorization
Direct effect (D)	D-Yes	43
	D-No	452
Cumulative effect (C)	C-Pre	49
	C-Post	130
	C-No	253
Partitioned effect (P)	P-Pre	49
	P-During	43
	P-Post	94
	P-No	262

Analytical methods

We used package "survival" (Therneau 2021) in program R v. 4.0.3 (R Core Team 2020) to run Kaplan-Meier survival models that estimated sage-grouse hen survival from Mar 2011-Jun 2020.

We pooled data across all years and then used the Kaplan-Meier model to estimate the survival of individuals over the monitoring period or the duration that the radio transmitter was functional or before the hen died or her signal was lost. This produced an estimate of cumulative survival probability through the monitoring period (Kaplan and Meier 1958).

We used two main pieces of data as inputs into our survival models: 1) the number of days (or years) the hen was observed to be alive, and 2) whether the hen died or was censored. We right-censored individuals with unknown fates, dropped transmitters, or that survived until their transmitters expired. We used a staggered-entry design to account for marking individuals at different times throughout the monitoring period and estimated the survival probability of hens across the study period.

We investigated the effects of livestock grazing metrics (i.e. SGI grazing categorization) on estimated survival by associating each hen location with the relevant grazing category (described in the "covariates" subsection).

Results

Summary statistics

Between 2011-2020 we monitored 500 hens. Capture effort varied across the study as needed to maintain approximately 100 hens in the sample during each year. We captured and marked 100 hens in 2011, and a mean of 42 hens were captured each year from 2012-2019 (range: 12 hens [2020] to 67 hens [2012]). We did not capture additional hens in 2019 because field data collection for the study ended that year. We omitted five hens due to incomplete data entry, resulting in a total of 495 hens for this analysis. Of these 495 hens, 234 (47%) died due to predation. This included 99 mammal depredations, 58 avian depredations, and 77 predations of unknown cause. Four hens died due to fence collisions, one died from a vehicle collision, and one was thought to be a capture-related mortality. Hens were monitored frequently (Table 14).

Table 14. A summary of the average number of visits to hens per calendar year.

Year	Median visits per bird per year	Range of visits per bird per year	Total hen locations per year
2011	7	1 – 73	873
2012	7	1 – 60	1201
2013	9	1 – 32	1024
2014	5	1 – 32	952
2015	18	1 – 44	2145
2016	22	1 – 52	2540
2017	22	1 – 45	2268
2018	25	1 – 44	1970
2019	2	1 – 55	1150
2020	4	1 – 15	284
2021	2	1 – 2	19

Survival modeling results

We evaluated Kaplan-Meier models containing variables we predicted would affect sage-grouse hen survival based on our knowledge of the effects of grazing on forage and cover resources (see

methods above for description of variables). Overall, the median survival time for 495 marked hens monitored from 2011-2020 was 1.25 years (95% confidence interval=1.16-1.14 years).

Annual survival probability

Sage-grouse hen survival probability across the monitoring interval differed significantly among monitoring years (χ^2=54.5, df=9, p<0.001, Table 15, Figure 16), where a monitoring year was defined as April 1 of one calendar year until March 31 of the next calendar year. The lowest median survival time was 1.12 years in 2011, whereas the highest median survival time was 2.44 years in 2014 (Table 15).

Table 15. Median survival time by monitoring year for sage-grouse hens in central Montana.

	Number of Hens Monitored	Mortalities during monitoring year	Median Survival Time (Years)	95% Confidence Interval
2011	127	45	1.12	0.79 – 1.42
2012	138	47	1.54	1.42 – 1.99
2013	101	29	2.34	2.06 – 3.43
2014	127	28	2.44	2.00 – 3.31
2015	121	19	2.41	2.13 – 2.77
2016	148	35	1.57	1.37 – 2.13
2017	111	54	1.96	1.41 – 2.28
2018	95	38	1.42	1.25 – 2.10
2019	85	23	1.22	1.11 – 1.86
2020	46	31	1.34	0.84 – 2.13

Kaplan-Meier annual survival estimates for 2011-2020 ranged from a high of 0.91 (95% CI=0.85-0.97) in 2013 to a low of 0.54 (95% CI=0.46-0.63) in 2011. There appears to be a slight decline in annual survival probability from 2015 through 2020, although the uncertainty of the estimates has also increased during that period. It is important to note that many hens were monitored in multiple years, in which case those hens were counted multiple times (once per year in which they were monitored).
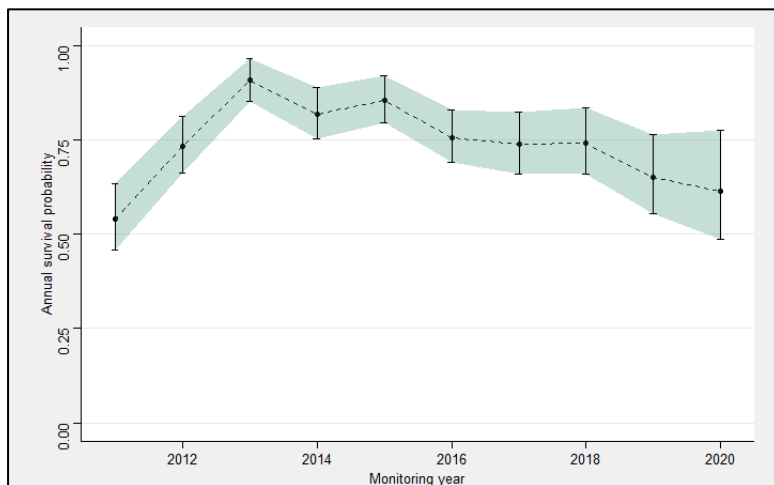
Figure 16. Annual hen survival estimates (from April 1 through March 31 of the next year).

Survival across SGI status
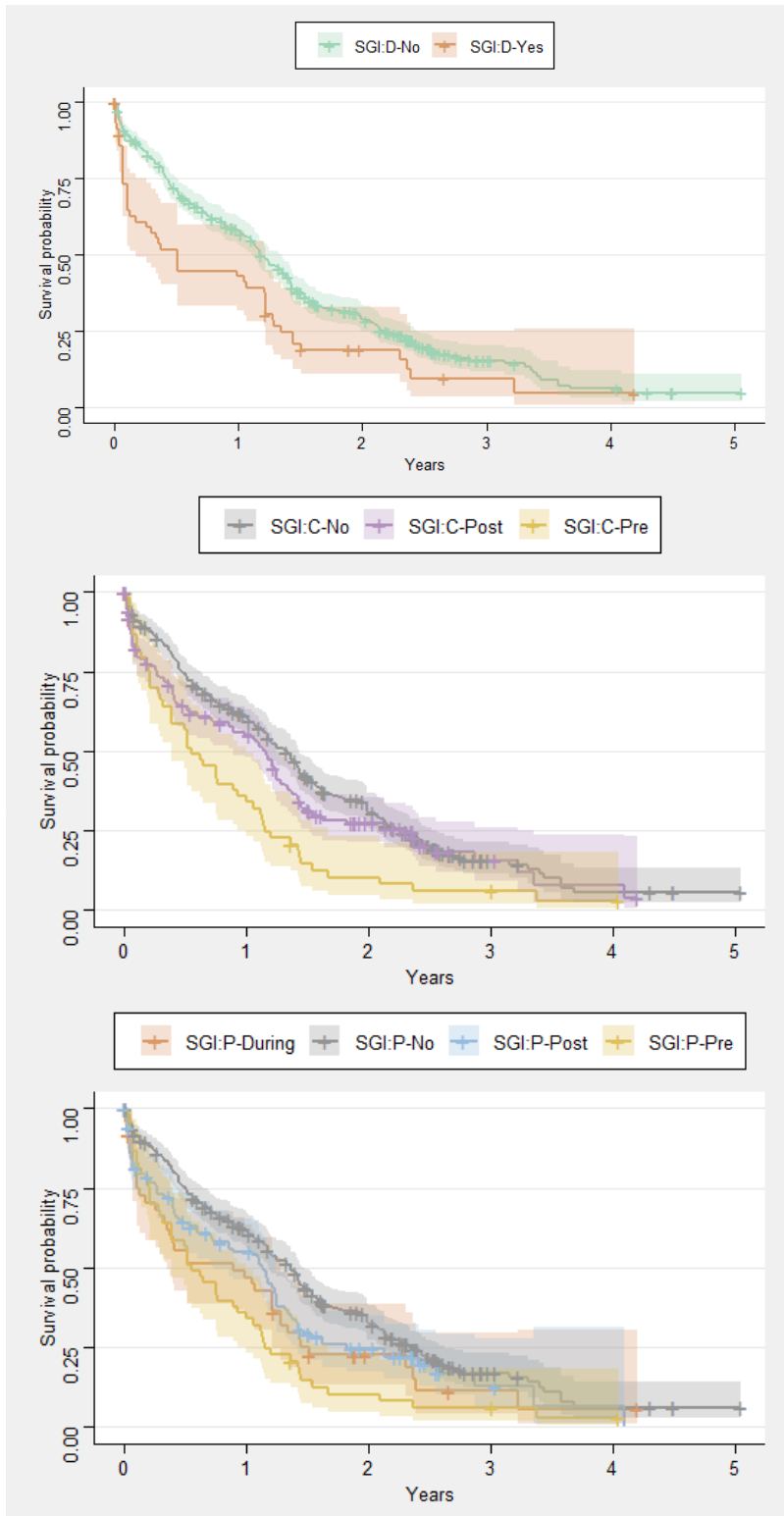
Figure 18. Hen survival across SGI categorizations and categories.

Over the whole monitoring period, there was evidence that hen survival was different across SGI-Direct categories (χ^2=10.7, df =1, p= 0.001, Figure 17), SGI-Partitioned categories (χ^2= 23.1, df =3, p<0.001, Figure 17), and SGI-Cumulative categories (χ^2= 17.2, df =2, p= 2e-04, Figure 17).

Discussion

Overall, these preliminary results suggest that both year-to-year variation and SGI grazing have the potential to affect hen survival. Although no previous work has evaluated the effect of SGI grazing on hen survival, the findings about the importance of year-to-year annual variation are in line with previous work showing that year-to-year conditions can affect hen survival (Moynahan et al. 2006).

Although we did not incorporate weather into our model set for these analyses, we suspect that much of the variation currently encompassed by year could result from weather-related changes amongst years. For example, high precipitation and flooding in 2011 may have contributed to the lowest survival estimate by decreasing survival of incubating hens via increasing olfactory cues available to predators. Although we cannot make any definitive statements about the effects of weather on hen survival in our study area, we know from past studies that extreme temperatures and high

snowfall can negatively affect hen survival (Anthony and Willis 2009), even as higher precipitation can benefit vital rates in other seasons (Guttery et al. 2013). We plan to investigate the influence of weather on survival in our ongoing analyses.

Interestingly, we found that the median survival time was 1.25 years, which is substantially lower than the estimate we provided in previous reports. The estimate of median survival time we provide here aligns with other work suggesting that the lifespan of a female sage-grouse is 1.5 years on average, even though they have been observed surviving for 9 years (United States Fish and Wildlife Service 2011).

Although our results suggest there may be an effect of livestock grazing on hen survival, at present, we do not believe that the minor differences we observed during these preliminary analyses are significant enough to change current management. First of all, the survival estimates for the SGI categories (Pre, During, and Post) may be confounded with the year of the study because all of the "SGI-Pre" pastures occurred at the beginning of the study, while all of the "SGI-During" pastures occurred in the middle, and all of the "SGI-Post" pastures happened near the end of the study. Second, we did not conduct model selection, meaning it is possible that models containing SGI categorizations are less parsimonious than models containing other variables. Third, our model set was not comprehensive. In our ongoing work, we plan to include more covariates that will encompass some of the variation in hen survival that is currently only attributable to year (i.e., annual variation) in our model set. These variables include weather metrics (e.g., temperature and precipitation) and vegetation metrics (e.g., shrub and residual grass cover). We will provide more information with our final deliverables.

In light of our results, continuing to prevent further reduction and fragmentation (Smith et al. 2018c, Milligan et al. 2020b) in sage-grouse habitat may be sufficient to maintain hen survival at a rate that helps to maintain the population. We are currently working on population modeling to determine how the demographic rates and habitat and grazing predictors affect population dynamics. As our work progresses, we will update our management recommendations accordingly.

Part 2: Habitat

Effects of grazing on vegetation

Analyses towards this objective are ongoing. A brief summary of how these plots were selected and measured, and results from preliminary analyses are reported below.

Methods

Rangelands are highly dynamic and spatially heterogeneous, and assessing their condition over large areas is a logistical challenge (West 2003). During 2012-2019, we used herbaceous vegetation measurements at a set of stratified random field plots (hereafter "vegetation response plots") between grazing treatments D-yes and D-no to test for differences in indicators of habitat quality across the project area. Smith et al. (2018b) conducted a pilot study in 2012 to determine how many plots were needed to detect a 10% difference in grass height (~2 cm) between D-yes and D-no plots (D-yes=50 plots, D-no=50 plots) at α=0.05. These data showed that variation due to topographic position and soil type accounted for much of the measured grass height variation in these pilot plots. Additionally, Smith et al. (2018b) speculated that distance to water would affect grass height variation because areas close to water would be heavily used by livestock, and areas farther away were less likely to be used. The locations of plots, generated using ArcGIS (ESRI Inc., Redlands, CA) and program R, and were stratified between SGI-enrolled and non-SGI pastures in the direct grazing category, and constrained based on these criteria to minimize variation in the data due to spatial heterogeneity in covariates known to affect vegetation structure and composition (Smith et al. 2018b). We predicted that D-yes pastures would have increased live and residual grass height and cover, less bare ground, and more litter cover compared to D-no pastures. Because the grazing status of a pasture changed annually, we were unable to use permanent vegetation plots, and instead generated random sample plot locations each year.

Vegetation Metrics

Vegetation response plots were constrained to sagebrush-dominated land cover in areas with ≥5% visually-estimated sagebrush canopy cover, and only sampled during July to reduce temporal variation in sampling but still be able to sample enough plots. Plots were centered at the random point and extended 15 m in each cardinal direction ("spokes"). We established plots with two, perpendicular 30 m tapes intersecting at the center (the random point). Cover of understory vegetation, height of live and senesced grasses, and height of shrubs were estimated with measurements taken at 12 points located 3, 6, and 9 m from the plot center in each cardinal direction. We used this scale to keep the measurements consistent with other field-based measurements to evaluate sage-grouse habitat. At each of these 12 points, we used a 20 x 50-cm quadrat (Daubenmire 1959) to estimate absolute percent cover of understory live (current year) and residual (dead from previous year) herbaceous vegetation (grass and forbs), litter (detached dead vegetation), and bare ground. Absolute cover estimates were made beneath the shrub canopy and included only the uppermost canopy when overlapping canopies occurred. We recorded the maximum vertical height, excluding inflorescences, of undisturbed live and senesced material on the nearest grass plant, and the tallest live portion, excluding inflorescences, of the nearest shrub. All technicians were trained to estimate cover by a single lead observer each year and periodically checked throughout the season for consistency (i.e., individual estimates within ±5% for all cover classes). We estimated visual obstruction with a Robel pole (Robel et al. 1970) placed at points 1, 3, 5, and 7 m from the center in each cardinal direction, taking readings from 4 m at the height of 1 m above the ground facing toward the

center (modified from Martin et al. 1997). The 16 readings were averaged to quantify visual obstruction at the plot scale (30 m).

Analyses

We used linear mixed-effects models to test for effects of grazing management (fixed effects) on vegetation metrics while accounting for variation across years and pastures (random effects). We used the means of vegetation metrics including percent cover of bare ground, total herbaceous vegetation (grass and forbs), live grass height, residual grass height, and shrub height per plot as response variables (Table 17). Our years were defined as the biological year for sage-grouse, beginning with nesting season in April and ending with what we defined as the end of winter towards the end of March, i.e., Apr 1-Mar 31. For example, year 2013 was defined as Apr 1, 2013-Mar 31, 2014. Linear mixed-effects models were fit using the lme4 package (Bates et al. 2015) in program R. Significance of fixed effects was assessed with likelihood ratio tests.

Results

During 2013-2019 we collected vegetation data at 1,416 vegetation response plots (Table 16). We analyzed all metrics as a function of the direct grazing categorization only; we will assess the effects of the other grazing categories in our ongoing analyses that will end in 2024.

Table 16. Sample sizes of vegetation plots in grazing management pastures for SGI-enrolled (D-yes) and non-SGI (D-no) ranches in Golden Valley and Musselshell Counties, MT, 2011-2019.

	D-yes	**D-no**	**Total**
2013	125	158	283
2014	159	199	358
2015	8	208	216
2016	61	144	205
2017	43	140	183
2018	59	22	81
2019	0	90	90
Total			1,416

All of the following results are shown in Table 17. We modeled each vegetation variable as a function of grazing management category. The effect of the direct grazing category on percent cover of total herbaceous vegetation (THV; all grass and forbs) was not significant, but D-no tended to have less THV cover than D-yes. The marginal R^2 was only 0.005, compared to a conditional R^2 of 0.25, suggesting the variation by the random effects of pastures and years was higher than the fixed effect of grazing management in this model. The effect of grazing on grass height was not significant, but D-no tended to have shorter grass heights than D-yes. However, the marginal R^2 was only 0.004, compared to a conditional R^2 of 0.33, suggesting the variation by the random effects of pastures and years was higher than the fixed effect of grazing management. We detected a significant effect of grazing on RAP litter cover. D-no had

significantly less litter cover than D-yes, but the marginal R^2 was only 0.03, compared to a conditional R^2 of 0.41, which suggests the variation associated with the random effects of pastures and years was higher than the fixed effect of grazing management. The effect of grazing on annual perennial forb ground cover extracted from RAP was not significant, but D-no tended to have more perennial forb ground cover than D-yes. However, the marginal R^2 was only 0.004, compared to a conditional R^2 of 0.30, which suggests the variation associated with the random effects of pastures and years was higher than the fixed effect of grazing management. The effect of grazing on RAP shrub cover was not significant, but D-no tended to have more shrub cover than D-yes. Again, the marginal R^2 was only 0.003, compared to a conditional R^2 of 0.39, which suggests the variation associated with the random effects of pastures and years was higher than the fixed effect of grazing management.

Table 17. Results for fixed effects from linear mixed effects analyses modeling vegetation metrics as a function of the Partitioned Category of grazing management.

Vegetation Metric	Grazing Management Factor Level[*]	β ± SE	95% CI	t-test value	p-value
THV (total herbaceous vegetation)	(Intercept): D-yes=baseline	30.05 ± 2.34	25.47, 34.64	12.84	<0.001*
	D-no	-1.96 ± 1.06	-4.04, 0.11	-1.85	0.06
Grass height	(Intercept): D-yes=baseline	21.85 ± 1.41	19.09, 24.60	15.53	<0.001
	D-no	-0.74 ± 0.42	-1.57, 0.08	-1.77	0.078
RAP Litter	(Intercept): D-yes=baseline	13.13 ± 0.90	11.36, 14.89	14.54	<0.001
	D-no	-1.14 ± 0.22	-1.56, -0.71	-5.26	<0.001
RAP annual perennial forb ground cover	(Intercept): D-yes=baseline	49.38 ± 2.06	45.34, 53.42	23.97	<0.001
	D-no	1.32 ± 0.76	-0.16, 2.80	1.75	0.08
RAP shrub cover	(Intercept): D-yes=baseline	9.02 ± 0.98	7.10, 10.94	9.21	<0.001
	D-no	0.47 ± 0.26	-0.03, 0.98	1.83	0.07

Discussion

We observed tendencies for total herbaceous vegetation, live grass height, RAP annual perennial forb cover, and RAP shrub cover to vary with SGI grazing management, and an effect of SGI grazing management on RAP litter cover, indicating that there was more herbaceous vegetation and less forb and shrub cover present in pastures currently being grazed according to the SGI program protocols. The variation among years and pastures was greater than differences observed in these metrics, reflecting the wide variation in vegetation growth in rangelands. Although there appear to be measurable differences, they do not amount to differences that likely

affect sage-grouse (e.g., see Smith et al. 2018a, Smith et al. 2018b). Our results are consistent with preliminary analyses from the first four years of data collection that used slightly different grazing categories (Smith et al. 2018b). Smith et al. (2018b) found negligible effects of SGI grazing management on vegetation in sage-grouse habitat. There were small differences in live and residual grass height, litter cover, and visual obstruction, but these differences were less than those due to annual variation, and these metrics were not correlated with nest success. In a similar study of the effects of rotational grazing management on sharp-tailed grouse in the mixed grass prairies of eastern Montana and western North Dakota, Milligan et al. (2020a) showed that stocking rate had a significant influence on visual obstruction, while effects of grazing system were minimal. In that study, visual obstruction was consistently lower in the rotational grazing system than in summer rotation and season-long systems. But the differences among grazing systems were relatively small compared to within system variation.

Overall conclusions

We reported on preliminary results of the effects of SGI grazing management on sage-grouse demographics, including nest success, chick survival, hen survival, and effects on vegetation in sage-grouse habitat. We compared nest success and effects of grazing management on vegetation with those reported by Smith et al. (2018a, 2018b). Smith et al. (2018a, 2018b) used grazing metrics equivalent to our direct grazing category (D-yes, D-no: whether a pasture was actively implementing SGI grazing management or not). We evaluated additional categorizations representing the short and long-term effects of SGI.

There are many components related to weather, vegetation, and grouse that exhibit much variation, and it is possible this variation will usually send a louder signal than grazing metrics when modeling sage-grouse demographics or effects on habitat in observational studies. Our results suggest that annual variation related to sage-grouse nest success was greater than direct or indirect effects of SGI grazing management as we categorized it, but there were some potential relationships with grazing that might be further explored with a controlled study. Our results support the conclusions of Smith et al. (2018a, 2018b) that there was not a measurable response of sage-grouse nest success or nest site selection to SGI grazing management. In addition, our nest success models with cumulative and partitioned grazing categories ranked above models with the direct grazing category used by Smith et al. (2018a, 2018b), suggesting that effects of grazing management are more likely to be detected in the long-term over multiple years, versus during grazing implementation. However, SGI grazing management has been implemented over three years, after which most producers followed a mix of the SGI grazing management with changes, such as minimizing or eliminating rest from grazing. The long-term effects we observed may not be the same as they would have been if SGI grazing management had continued beyond three years.

The SGI grazing management did not seem to benefit the survival of sage-grouse chicks. We did find that chick survival varied significantly by year and sexID. Female chicks tended to survive

better than males, though this relationship was not significant. Our limited data suggest that lands enrolled in SGI grazing management might have increased chick mortality risk, at least in the way we categorized grazing management for analyses.

As with chick survival, hen survival varied significantly among years, which we suspect was largely due to weather. Weather variables were not evaluated for this report but will be for our PR grant to finish deliverables for this project. Hen survival varied slightly with grazing management, with hens spending a majority of their time in pastures that were actively implementing SGI grazing management having slightly lower survival than those spending the majority of their time on non-SGI pastures. For our more detailed categories, hen survival was slightly lower on pastures enrolled in SGI but prior to implementation (C-pre and P-pre) than those not enrolled. However, regarding the effects of grazing management on both chick and hen survival, it is possible that enrolled pastures were in a different condition than those not enrolled, and that pasture condition was confounded with SGI grazing management. In addition, the SGI categories are likely confounded with annual variation because "pre" pastures are only present in the first few years of the study, while "post" pastures are only present during the later years of the study.

Similarly, we found that annual variation and variation among pastures were more influential on vegetation structure than grazing management as we categorized it. We observed minor effects of SGI grazing management on total herbaceous vegetation, grass height, RAP litter cover, RAP annual perennial forb ground cover, and RAP shrub cover, even though the annual and pasture variation was greater than variation observed due to grazing. Annual variation due to several components is expected; potentially controlled studies would help extricate effects of grazing management. Our results support those of Smith et al. (2018a), showing that minor variation in vegetation related to grazing management was less than annual and pasture variation. Potentially the minor differences that were observed were not large enough to effect grouse demographics or habitat.

Together, our results suggest that annual and pasture (spatial) variation have more of an effect on sage-grouse demographics and habitat than grazing management, though there were some potential relationships of grazing management with demographics and vegetation that could be further explored. Our preliminary conclusions concur with Smith et al. (2018a) that preserving sagebrush habitat by keeping working ranches in sagebrush habitat intact may be more important than recommending particular grazing management.

It is possible that effects of rotational versus other grazing management may only become pronounced during extreme events such as drought and post-drought years (e.g., see Fritts et al. 2018). Vegetation structure and composition can be altered by both grazing and drought, and communities that experience these factors together can have different responses than observed from each factor independently (Loeser et al. 2007, Fritts et al. 2018). Moreover, site productivity and vegetation responses to weather and grazing can vary greatly depending on location, and may necessitate different grazing strategies by site to sustain wildlife habitat and viable livestock operations (Loeser et al. 2007). We will attempt to address changes in

demographic rates and habitat metrics in drier versus wetter years in our final deliverables, though we may not have a big enough sample size to assess the effects of grazing in this way.

Remaining products will be delivered at the end of our current PR Grant # F21AF01330 to finish this work. These will include (1) evaluating the relationship between grazing management and habitat use of hens and chicks, (2) exploring hen and chick survival analyses further, (3) producing a population model that incorporates sage-grouse vital rates and habitat covariates, assessing the effects of grazing at the population level, and (4) exploring the link between lek counts and demographic rates.

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