Viability analyses for conservation of sage-grouse populations:

Buffalo Field Office, Wyoming

Final Report

27 February 2012

Prepared for Bureau of Land Management

Buffalo Field Office

Buffalo, Wyoming

by

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BLM Contract 09-3225-0012

Number G09AC00013 (8/10/10)

EXECUTIVE SUMMARY

Impacts from energy development to sage-grouse (*Centrocercus urophasianus*) present a challenge to public land managers tasked with maintaining large and intact landscapes that support viable populations. We provide decision support to Bureau of Land Management (BLM) managers tasked with maintaining sage-grouse populations in the oil and gas (energy) fields of northeast Wyoming by assessing four aspects of energy development as they relate to sage-grouse. Findings reflect the status of a small remaining sage-grouse population that has already experienced an 82% decline within the expansive energy fields (Walker et al. 2007a), a level of impact that has severely reduced options for delineating core areas that are large enough and in high enough quality habitats to sustain populations.

1) We identified the spatial scale at which energy development most influences sage-grouse populations, as indexed by counts of males at leks. Ignoring state boundaries to include counts from unimpacted leks in Montana was critical to identifying the far reaching impacts of development on grouse in Wyoming. Using a statistical technique (AIC, Burnham and Anderson 1998) that is akin to using a dial to tune a radio to pick up the strongest signal, we detected that development had the greatest influence on male counts within 12.4 mi (20 km) surrounding a lek. The signal is much stronger at the 12.4-mi radius than any of the smaller radii we tested, encompassing a large spatial scale that covers an area of 483 mi^2 (1,257 km^2).

2) We evaluated the current viability of sage-grouse populations. We linked lek count data to energy development and West Nile virus (WNv) by associating the density of producing wells within the 12.4-mi (20-km) radius to each lek count, and the occurrence of widespread WNv outbreaks in the year preceding the count. Predictions of resulting male lek counts were

consistently within 0 to 1% of the observed counts, underscoring the success of our approach (Table 2).

Declines in number of active leks and number of attending males indicate that both energy development and WNv outbreaks reduce sage-grouse populations. At current well spacing (328 ac spacing, 0.75 wells/km^2) and without accounting for WNv outbreaks, our predicted number of males on leks is 3,648 (95% CIs = 3,147, 4,204, Table 3). Absent an outbreak year, the lower 95% confidence limit on the count is 3,147 males, suggesting that immediate extirpation of the northeast Wyoming population is unlikely if all environmental conditions for sage-grouse other than energy development remain favorable.

Wyoming's core area policy will be most effective where implemented in advance of extensive energy development, and in southwest portions of the state where high elevation populations are less susceptible to WNv impacts. But in northeast Wyoming, WNv outbreak years are the wild card in core area management, and predictions made without accounting for WNv are optimistically high. The effect of a WNv outbreak year alone can more than cut a population in half, which is similar to drilling an undeveloped landscape at 4-8 wells/mi^2 (1.5-3.1 wells/km^2, Table 3). When we include impacts of an outbreak year at all leks, we predict 1,473 males given current well densities (Table 3). With outbreak years as part of the equation, the lower confidence limit on our prediction is 65 males, which, if reached, would indicate functional extinction. Incorporating outbreaks into analyses suggests that even with no additional energy development many local populations may be one bad WNv year away from extirpation.

3) We formulated and simulated potential, realistic future management scenarios for sage-grouse populations, using the models we developed above to evaluate viability. Our results

suggest that if development continues, future viability of the already small sage-grouse populations in northeast Wyoming will be compromised. Small populations are vulnerable to extirpation by chance events (Soule and Mills 1998), and WNv outbreaks are an excellent example of this type of catastrophic event. Despite impacts, the potential may still exist to maintain a population inside core areas, but further drilling in and around cores will compromise their remaining value. Notably, core areas in northeast Wyoming were delineated after widespread development had already occurred, leaving few options for conserving populations. Our findings do not negate the benefits of core areas, in general. However, to achieve maximum effectiveness, core areas must be constructed proactively by conserving high quality habitat, not reactively by drawing borders around planned and existing development.

4) We provide recommendations for evaluating the future viability of sage-grouse populations if restoration efforts begin as the energy play subsides. First and foremost we recommend that BLM commit to monitoring outcomes of restoration as measured by the distribution and number of sage-grouse in northeast Wyoming. Focusing restoration where plugged and abandoned wells are clustered would increase the size of habitats available to birds, thus enhancing the chance of increasing their abundance and distribution. Leaving energy infrastructure such as roads, power lines, and water impoundments on the landscape for other purposes is an unintended impact of development that will compromise restoration success. Appropriate monitoring of leks as wells are removed from production is imperative to allow for a rigorous analysis of restoration success, which cannot be supported by currently available data. Lek counting needs to be conducted at least across the area of northeast Wyoming, and preferably across the entire study region including eastern Montana (Fig 1).

Genetic connectivity is the glue that holds populations together, and remaining core areas, though impacted, may help maintain connectivity among populations further south in Wyoming and those in Montana. Until genetic studies currently underway delineate the degree to which sage-grouse populations are connected, we recommend maintaining the potential areas of connectivity outlined in the Wyoming Governor's Executive Order as undeveloped, contiguous habitat.

INTRODUCTION

Conservation strategies that target single stressors may be inadequate because they fail to account for the multiple factors at play in ecological systems. Energy development is an ongoing stressor to wildlife populations on public lands throughout the West (McDonald et al. 2009), and in 2002, West Nile virus (WNv) emerged as an additional stressor to these populations (Centers for Disease Control 2010). Given the anticipated magnitude of energy development impacts, identifying and prioritizing lands with low human disturbance is critical for the Bureau of Land Management (BLM) to follow its multiple use mandate (Federal Land Policy and Management Act 1976) by conserving some areas while developing others. The management challenge will be to site future developments in such a way that large, intact landscapes can maintain their biological functions (Kiesecker et al. 2010), even in the presence of multiple stressors such as development and WNv.

The sagebrush (*Artemisia* spp.) ecosystem in the West is representative of the struggle to maintain wildlife populations in a landscape that bears the debt of our ever-increasing demands for natural resources (Knick et al. 2003). The greater sage-grouse (*Centrocercus urophasianus*, hereafter 'sage-grouse') is a landscape species that requires large, intact expanses of sagebrush habitat during every part of its life cycle to maintain robust populations (Connelly et al. 2011). As a result, the sage-grouse is an umbrella species that represents the conservation needs of many other species that also depend on sagebrush (Hanser and Knick 2011). Loss and degradation of sagebrush habitat has resulted in at least a four decade long sage-grouse population decline (Connelly et al. 2004, Garton et al. 2011) and extirpation of the species from ≥ 46% of its original range (Schroeder et al. 2004).

Wyoming provides habitat for nearly two-thirds of the sage-grouse occupying the eastern portion of their range, and landscapes being developed for energy extraction contain some of the highest sage-grouse abundances in North America (Doherty et al. 2011). The surge in energy development over the past decade (Naugle et al. 2011a) has resulted in rapid, large-scale changes in portions of northeast Wyoming, and a growing recognition of the need to fully understand and monitor potential impacts to wildlife populations.

The potential for management to influence populations is large, and a method currently in place for conserving sage-grouse populations is the core area concept. Core areas have been designated by the state of Wyoming as priority areas for sage-grouse conservation, and by Governor's order, new energy development is limited to one oil or gas well pad per square mile, on average, and a 5% total disturbance cap (EO 201105). Core areas result in a smaller energy footprint than would otherwise occur and provide an avenue for partners to maximize their conservation investments by targeting them within priority landscapes (Copeland et al. 2011, Kiesecker et al. 2011). Conservation planning is most effective when implemented before the number and extent of impacts limit options for maintaining large and intact landscapes that support populations. Large core areas containing a majority of sage-grouse populations in southern and southwest Wyoming were delineated before energy fields became large and abundant. In contrast, the sizes, shapes and locations of core areas in northeast Wyoming were chosen after substantial energy development had already taken place. From 2001 to 2005, sage-grouse populations declined by 82% within the expansive coal bed natural gas fields (Walker et al. 2007a) in northeast Wyoming, further reducing options for delineating large and intact core areas containing an abundance of high quality sage-grouse habitats. As a result, questions remain regarding the ability of core areas in northeast Wyoming to support viable sage-grouse populations.

For management-oriented science to be of maximum use, it must be conducted at a spatial scale large enough to capture how population status has changed in response to stressors that vary in intensity, both locally and regionally. The goal of management-oriented science is to connect the dynamics of focal species, either likelihood of extirpation or potential for recovery, to actions that managers can implement on the ground to maintain or enhance populations. In practice, however, land management actions are often implemented without a clear connection to how those actions affect the dynamics of the wildlife population of interest. This is particularly true when managers must try to counteract multiple stressor impacts, because the science on which this management is based is often conducted at too small a spatial scale to capture populations responding to multiple stressors that vary in intensity over a large area. Furthermore, the disparity between the scale of individual management actions and the scale at which populations respond is a persistent problem in understanding impacts on population viability (Schultz 2010).

This report links sage-grouse counts and population dynamics with stressors to evaluate the viability of populations under future land use scenarios. Our objectives were to provide decision support to BLM officials at field office, state and national levels by 1) identifying the spatial scale at which energy development most influences populations, 2) evaluating current viability of sage-grouse populations in northeast Wyoming, 3) formulating and simulating potential, realistic future management scenarios for populations and 4) providing recommendations to evaluate the future viability of sage-grouse populations as the oil and gas play subsides and wells are plugged and abandoned.

Literature Synthesis

Oil and gas development and WNv are the primary large-scale factors impacting sage-grouse populations in northeast Wyoming. Together, these factors represent large-scale stressors that limit populations and options available to managers to maintain and enhance bird numbers on public lands. Below we synthesize the current scientific literature to provide readers with an understanding of the biological response of sage-grouse populations to these two factors.

Oil and Gas Development

Oil and gas (energy) development has emerged as a range-wide issue in conservation because areas being developed contain large sage-grouse populations (Connelly et al. 2004) and other sagebrush obligate species (Knick et al. 2003). Breeding sage-grouse populations are severely impacted at oil and gas well densities commonly permitted in Wyoming (Naugle et al. 2011b). Impacts have been indiscernible at < 1 well/mi^2 (0.4 wells/km^2), but above this threshold, lek losses have been 2-5 times greater inside than outside of development, and abundance at remaining leks declines by 32 to 77% (Doherty et al. 2010). Magnitude of losses vary from one field to another, but impacts are universally negative and typically severe (Harju et al. 2010). High site fidelity, but low survival of adult sage-grouse combined with lek avoidance by younger birds (Holloran et al. 2010) results in time lags of 2-10 years between onset of development activities and local extirpation (Holloran 2005, Walker et al. 2007a, Harju et al. 2010). Energy development also impacts sage-grouse habitats and vital rates outside the breeding season away from leks. Vital rates are measures such as nest success, hatching and survival which indicate the nature of and possible changes in a population (Taylor et al. 2012). Risk of chick mortality is 1.5 times higher for each additional well site visible within 0.6 mi (1 km) of brood locations compared to random locations (Aldridge and Boyce 2007), and sage-grouse avoid otherwise suitable winter habitat disturbed by energy development (Doherty et al. 2008, Carpenter et al. 2010).

Previous estimates of the spatial extent of oil and gas impacts on sage-grouse have differed depending on whether or not the study region included large, undeveloped areas. Research in already developing locales (Holloran 2005, Walker et al. 2007a, Harju et al. 2010) has detected impacts at smaller spatial extents than have regional studies (Tack 2009, Johnson et al. 2011). Energy impacts in Wyoming's Pinedale anticline were not detectable beyond 4 mi (6 km) from the lek (Holloran 2005); whereas effects across the Great Plains and Wyoming Basin might extend to a distance of 12 mi (20 km, Johnson et al. 2011). Distance from lek to development that explained the most variation in the Powder River Basin (WY and MT) lek counts were 0.5 mi (0.8 km) and 2 mi (3.2 km, Walker et al. 2007a) versus 7.6 mi (12.3 km) across the sage-grouse range of Montana (Tack 2009).

West Nile Virus

West Nile virus emerged as a threat to sage-grouse in 2002 and is now an important new source of mortality in low and mid-elevation populations throughout the West (Walker et al. 2011). West Nile virus simultaneously reduces juvenile, yearling, and adult survival, three vital rates important for sage-grouse population growth. Persistent low-level WNv mortality, combined with severe disease outbreaks, results in local and regional population declines

(Naugle et al. 2004, 2005). Mortality from this disease reduces growth rate of susceptible populations by an average of 6-9% per year (Walker and Naugle 2011), and lab experiments show 100% mortality following infection (Clark et al. 2006). Resistance to WNv in the wild is low (Walker et al. 2007b) and is expected to increase slowly over time (Walker and Naugle 2011). Eliminating mosquito breeding habitat from anthropogenic water sources is crucial for reducing impacts (Zou et al. 2006). Better range-wide data are needed on geographic and temporal variation in infection rates, mortality and seroprevalence.

West Nile virus is a particular problem because it is an exotic disease, and a species is more likely to become extinct in response to a threat that is new, and outside its evolutionary experience (Brook et al. 2008). Small, isolated and peripheral sage-grouse populations are most at risk from WNv, particularly those populations at lower elevations, and those experiencing large-scale increases in distribution of surface water (Walker et al. 2011). Despite the emergence of WNv over a decade ago, and the subsequent occurrence of two outbreak years, to date, lek analyses have averaged over WNv outbreak and non-outbreak years, potentially washing out the effect of a critical new stressor.

METHODS

Focal Area and Study Region

The focal area of our analyses, northeast Wyoming, is of particular management interest to the BLM's Buffalo Field Office for multiple reasons, including historically large sage-grouse populations and high realized levels of oil and gas development. Furthermore, sage-grouse have declined concomitant with oil and gas development and northeast Wyoming continues to have high potential for further development.

While our focal area is northeast Wyoming (Figs 1, 2), the study region that provided the strongest foundation for our analyses was the portion of Sage-grouse Management Zone I that lies south of US Hwy 2 (Fig 1). By including leks from areas beyond northeast Wyoming, such as unimpacted leks in eastern Montana, we were able to include a wide range of oil and gas development densities at both local and regional scales, and we maximized our ability to capture the effect of WNv outbreaks (Table 1). West Nile virus has been documented throughout the region in multiple species (Centers for Disease Control 2004), and in sage-grouse specifically in Montana, Wyoming and the Dakotas (Naugle et al. 2004, 2005, Walker et al. 2004, Walker and Naugle 2011). At the same time, our study region is composed of habitat similar to that found in the focal area it encompasses. This habitat is largely dominated by Wyoming big sagebrush (*Artemisia tridentata wyomingensis*), with grass cover typical of the eastern portion of the sage-grouse range.

To best estimate the magnitude of development impacts, data must be collected across a range of development levels at both local and regional scales. Estimated development effects may be negatively or positively biased if the study region does not capture the full range of development intensities. Studies contained within already developing areas may incorrectly estimate the spatial extent and magnitude of energy impacts, as any truly landscape scale effects that exist may have already affected all leks in the area. If the spatial extent of impacts to leks is underestimated, the loss of birds may also be underestimated, as loss predictions will not account for impacts of more distant development. Alternatively the same underestimation of scale of impact might also lead to an *overestimate* of loss, as the leks deemed to not be impacted may actually lie on the periphery of development, and peripheral leks may increase in size, at least temporarily, due to the emigration of yearling grouse from highly developed areas to leks on the edge of development (Holloran et al. 2010). Finally, studies that encompass large undeveloped areas, but only a few point sources of development may fail to capture the full extent of energy development impacts. To resolve these discrepancies of scale, a comprehensive analysis of sage-grouse lek response to energy development needs to be conducted at a scale large enough to encompass regional, as well as local variation in levels of energy development.

To capture the regional variation in lek size and natural landscape attributes, we divided the study region into the focal area (northeast Wyoming) and four supporting areas (Fig 1), based on the Western Association of Fish and Wildlife Agencies (WAFWA) subpopulation designations (Connelly et al. 2004). Our areas (followed by the WAFWA subpopulation name) are as follows: north-central MT (north-central MT), central MT (central MT), eastern MT (eastern interior MT/northeast tip WY), Dakotas (MT/ND/northwest SD) and northeast WY (northeast WY/southeast MT and Fall River SD/eastern edge WY). We combined the latter two because of the small size of the Fall River subpopulation and its proximity to the northeast WY/southeast MT subpopulation.

Notably, each of our areas is large, and the supporting areas contain a range of oil and gas development intensities (Table 1). This is critical for the analysis to correctly distinguish between regional variation in lek size and the variation in lek size due to intensity of oil and gas development. In contrast, each of the core areas in northeast Wyoming is much smaller, and contains little oil and gas development. As a result, we did not assign separate focal area status to each of the cores. Had we done so, we would have confounded area effects with oil and gas effects, negating the purpose of our analyses.

Table 1. Number of lek complex centers used in analysis from focal and supporting areas. Leks are categorized by presence of wells within best fit radius circle (12.4 mi, 20 km radius; Table 1 in Appendix II) and whether or not the most recent count occurred subsequent to a WNv outbreak year [see Results].

		Area					
WNv?	Wells?	NE WY	N-cnt MT	Cnt MT	E MT	DK	Category Total
No	No	1	88	126	144	15	374
No	Yes	304	35	84	64	57	544
Yes	No	0	12	25	54	2	93
Yes	Yes	65	6	27	23	7	128
Area Total		370	141	262	285	81	1,139

Analytical Approaches to Assessing Viability

Count-based methods are used to evaluate size or growth rate of a population via counts of individuals in an area (Fedy and Aldridge 2011) and can be used to assess the effects of management actions or external stressors on viability, thereby connecting management to the dynamics, persistence, and recovery of wildlife populations (Morris and Doak 2002, Mills 2007). Ideally, managers would like extinction probabilities predicted over time based on the effects of different levels of oil and gas development on lek counts. However, data requirements for such an analysis are prohibitive (Fig 3), as they would have to simultaneously account for a stressor that varies markedly over time and space, as well as population indices that vary greatly over time, even in the absence of stressors such as oil and gas development. Just accounting for

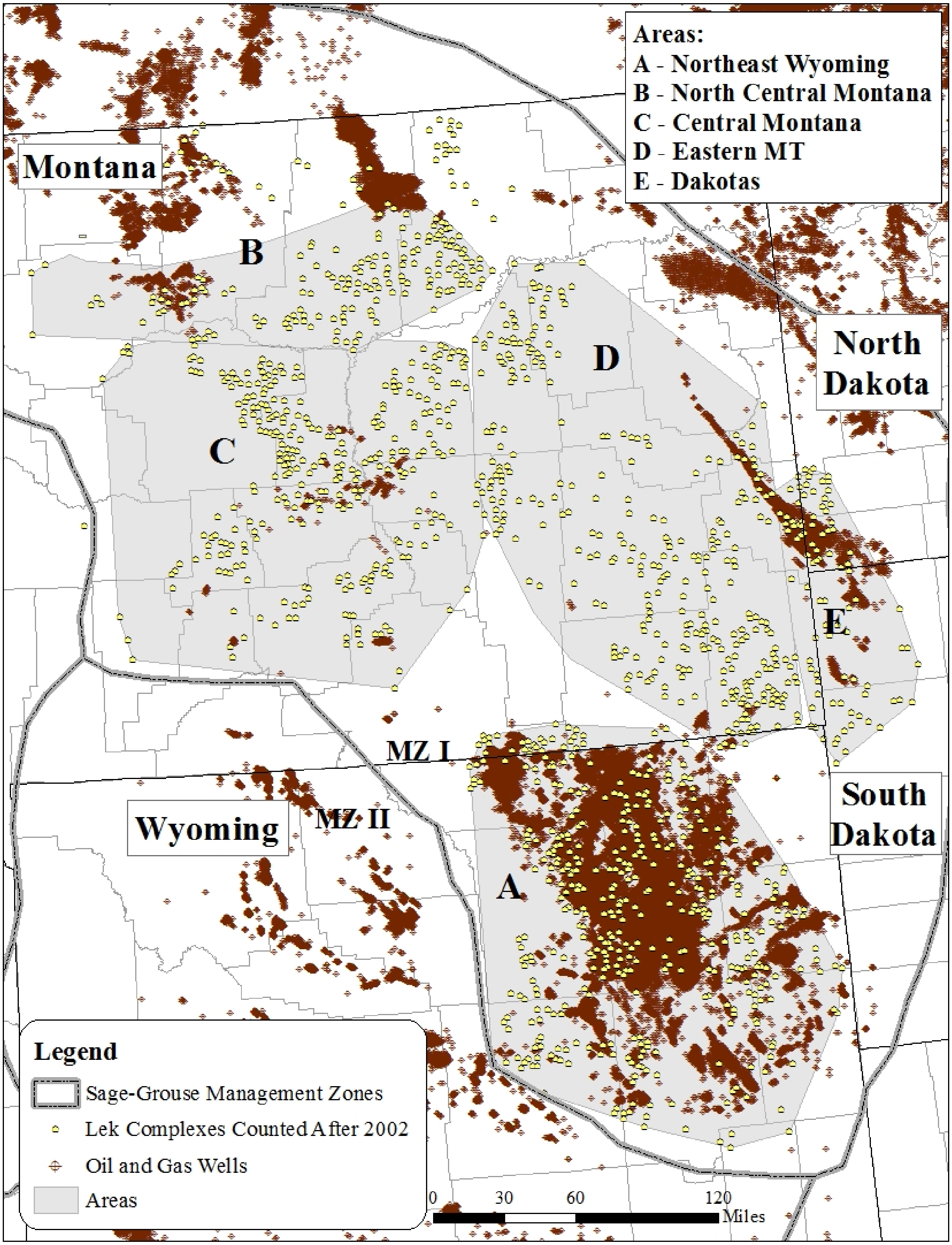


Figure 1. Distribution of oil and gas development and lek complex centers used in analysis with respect to focal and supporting areas.

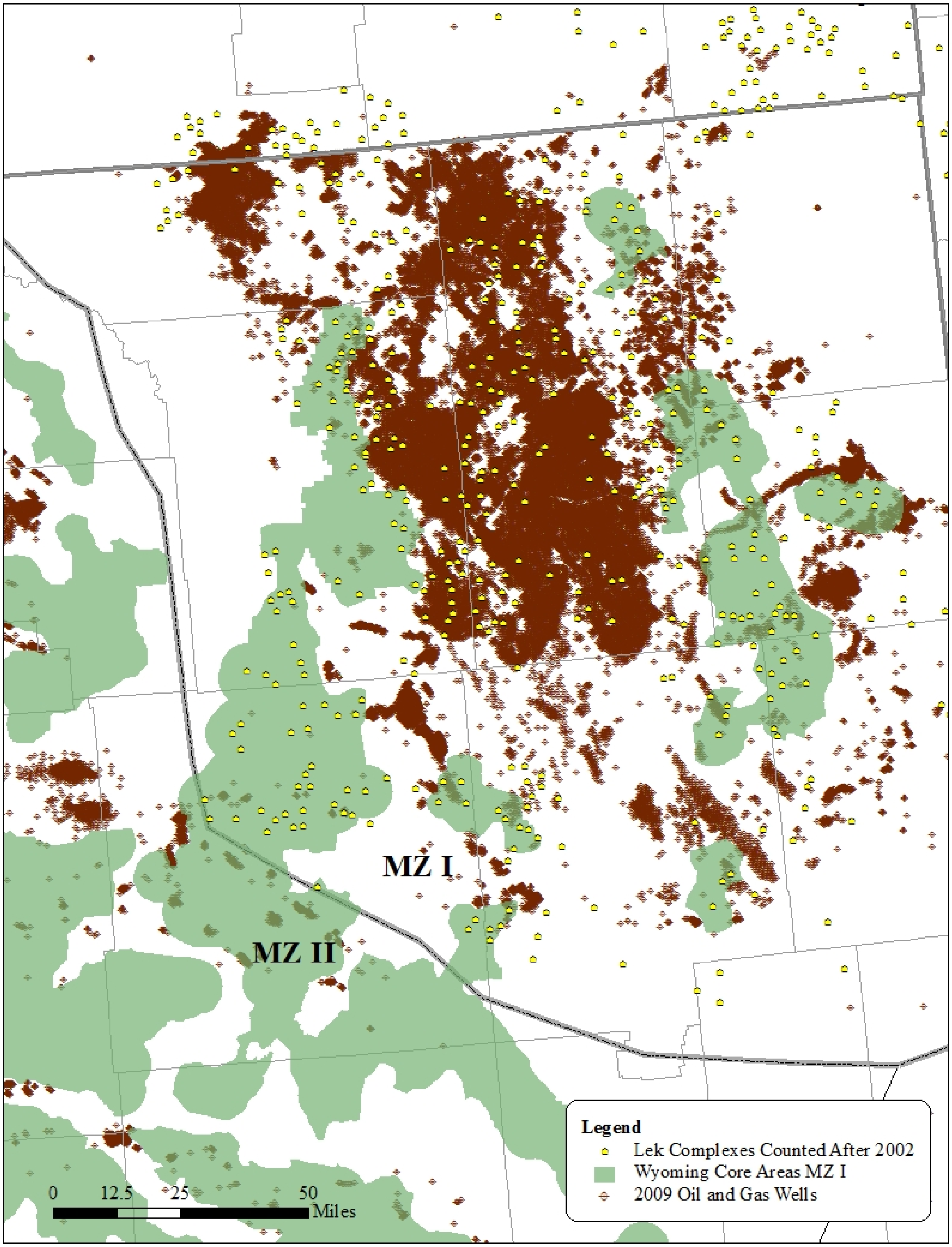


Figure 2. Distribution of oil and gas wells and lek complex centers used in the analysis with respect to northeast Wyoming core areas.

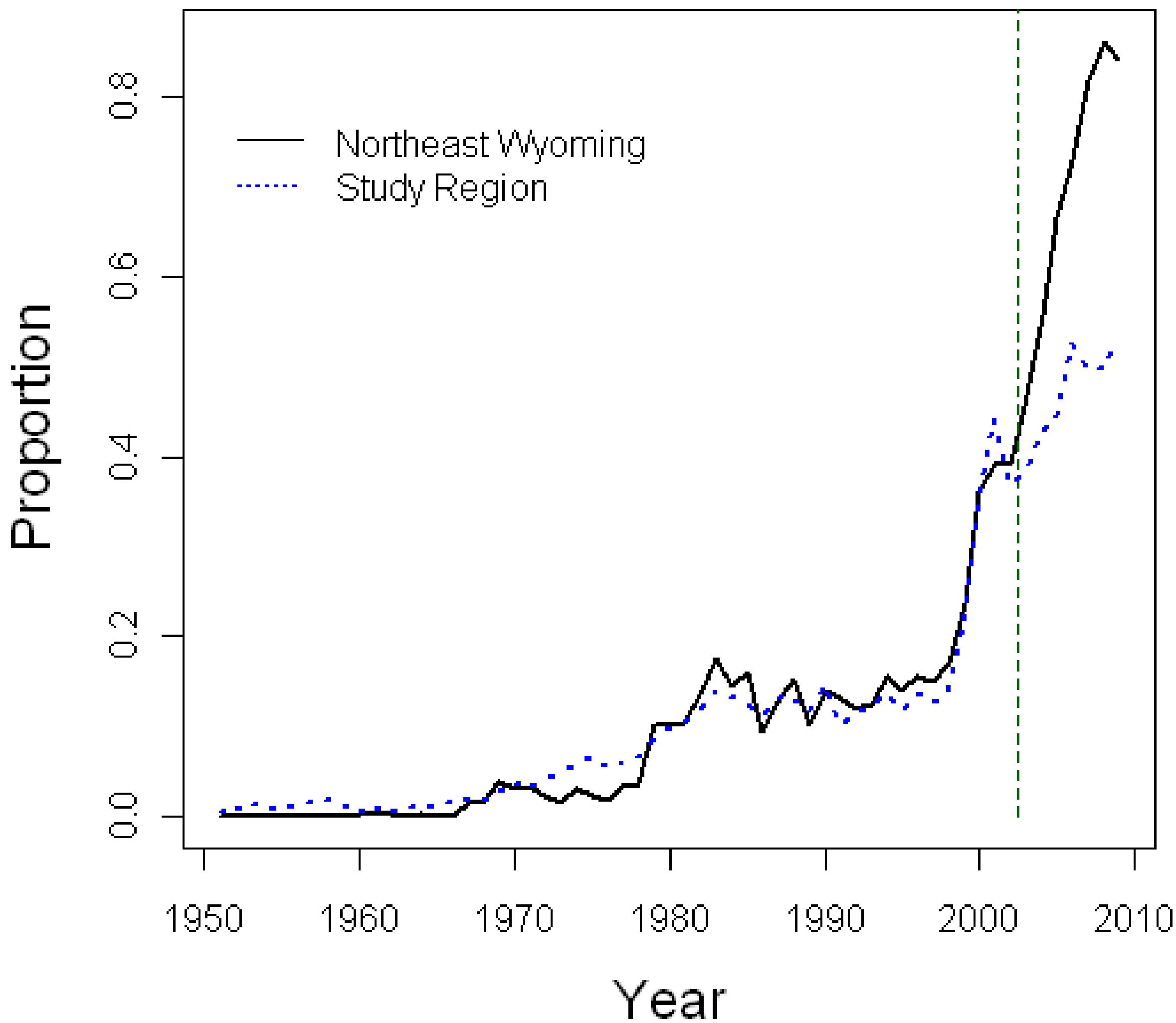


Figure 3. Proportion of lek centers in northeast Wyoming (n=428) and study region (n=1,508) counted during the year. Proportion of northeast Wyoming core area leks counted each year was similar to that in the focal area as a whole (difference < 0.07). Only counts to the right of the dashed line were used for analyses.

fluctuations in time (ignoring site and time specific stressors) requires multiple decades of annual counts (Fedy and Doherty 2010, Garton et al. 2011).

Because of the prohibitive data requirements for an analysis that is both spatially and temporally explicit, two approaches have been taken to evaluate lek counts: a cross-sectional approach that associates a lek count or lek growth rate with the stressors at its locale (Walker et al. 2007a, Harju et al. 2010) and a time series approach that averages counts over large geographic areas to reconstruct the necessary three (Fedy and Doherty 2010) to four (Garton et al. 2011) decade time series. With thirty consecutive years of spatially averaged counts, Fedy and Doherty (2010) used a time series approach to distinguish sage-grouse population cycles from long term population trend across the state of Wyoming. Forty consecutive years of spatially averaged counts allowed the estimation of population growth rate and carrying capacity in thirty populations from across the sage-grouse range (Garton et al. 2011). By adding an assumption that the past trend continues unchanged, these methods can also be used to predict an extinction probability. The time series approach has recently been applied to the Powder River Basin (Garton et al. 2011); however, the spatial averaging used to reconstruct long series of annual counts precluded associating stressors (e.g. oil and gas well density) with counts, and therefore made it impossible for the authors to determine the effect of these stressors on the population.

We took advantage of the large spatial extent of lek counts across our study region (which encompassed a wide range of development intensities) to successfully apply a cross-sectional approach to the data. We linked lek counts to oil and gas development and WNv by associating a well density and the occurrence of a WNv outbreak year with the most recent count at each lek since 2002, the time that WNv was first detected in the study region.

Data

Lek Counts

We defined a sage-grouse lek as a site where multiple males have been recorded displaying on multiple visits (Walker et al. 2007a). After obtaining lek count and location data from government agencies responsible for maintaining these databases, we checked the data for errors. We corrected errors, when possible, after consulting with agency personnel. We censored any leks where these errors could not be resolved, as well as any leks that were known to be destroyed by subdivision or mining. If a lek was counted multiple times within a year, we used the maximum count for that year.

Because leks often occur in a complex, that is multiple leks within 1.6 mi (2.5 km) of each other, we defined the largest and most regularly attended lek in the group as the complex center (Connelly et al. 2004). We used the count from each complex center to represent the entire complex, eliminating from the database the counts from the smaller, less regularly attended satellite leks. Hereafter, the term 'lek' refers to the sample unit of our analyses, which included complex centers and single leks that were not part of a complex. We used for each lek the most recent count that was collected from 2003-2009, except for leks known to have become inactive prior to 2003, which we excluded from our analyses. We chose the 2003 cutoff for two reasons. First, in spite of the dramatic increase in lek counting effort this decade, data are still too sparse (especially in the supporting areas) to use counts from only one calendar year. By using the most recent count since 2002, we provided a buffer of at least three relatively high effort years in which observers could ascertain the status of leks that may have become inactive during a time in which they were not regularly monitored.

Furthermore, because WNv is likely to remain a permanent feature of the sagebrush ecosystem, we restricted our study to years when the birds could at least potentially have been exposed to the virus. West Nile virus was first detected in the study region in 2002 (Centers for Disease Control 2010, Fig 4), but leks are counted in early spring, before the majority of WNv transmission occurs in late summer, thus the effects of the disease could not have been apparent in lek counts until spring 2003. By confining our analyses to 2003 and beyond, we ensured that it was at least possible for all birds counted to have been exposed to WNv.

Oil and Gas Development

We quantified energy development for active leks by the density of producing oil and gas wells at 6 scales around the lek as of April 1 in the year of the most recent count, and for leks that became inactive post-2002, as of April 1 in the year of the first zero count. Because of uncertainty about the scale at which sage-grouse show the greatest response to oil and gas development, we calculated the well density within the following radii of leks (in miles): 0.6, 2.0, 3.1, 6.2, 9.3 and 12.4 (in kilometers: 1, 3.2, 5, 10, 15 and 20). The 0.6 mi radius represents processes that impact breeding birds at or near leks (Walker et al. 2007a); the 2 mi radius has previously been used to predict the effects of oil and gas development on

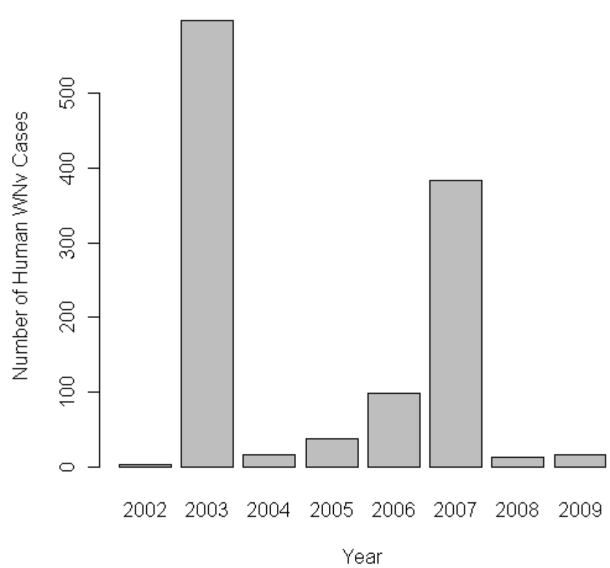


Figure 4. West Nile virus was first detected in the study region in 2002. Outbreaks occurred in 2003 and 2007.

lek counts (Doherty et al. 2010), the 9.3 mi radius should contain > 95% of nests of female grouse associated with the lek (Holloran and Anderson 2005, Tack 2009), and the 12.4 mi radius is the largest scale at which effects may have been detected in our study region (Johnson et al. 2011).

The 6.2 through 12.4 mi radii were also chosen to be larger than the estimated distance for potential edge effects to leks on the periphery of development. While previous studies have consistently demonstrated that leks less than ~ 2 mi (3 km) from oil and gas infrastructure have fewer males than those farther away (Walker et al. 2007, Harju et al. 2010, Holloran et al. 2010), evidence regarding the effect on leks between ~ 2-5 mi (3-8 km) from the nearest well pad is contradictory (Holloran et al. 2010). It is possible that leks on the periphery of development show at least temporary increases from males emigrating away from the center of development, and the upper 95% confidence limit for the mean distance from well pad to lek at which these effects occur is 4.7 mi (7.6 km, Holloran et al. 2010). While assigning outside development status to leks as close as 4.7 mi to a well pad might result in an over-inflated estimate of the count at an 'unimpacted' lek, it is unlikely that the larger scales we tested would be so affected.

<u>West Nile Virus</u>

West Nile virus outbreaks (Fig 4) in sage-grouse were documented in the summer of 2003 (Naugle et al. 2004, 2005, Walker et al. 2004) and the summer of 2007 (Walker and Naugle 2011) in intensively studied populations in Montana, Wyoming, and South Dakota. Because these outbreaks had the potential to affect spring 2004 and 2008 lek counts, respectively, we assigned positive outbreak status to each lek whose count used in the analyses occurred in 2004 or 2008. Although the rest of the document will refer simply to 'WNv outbreak' years, we note that other environmental variables (e.g., drought, low grass height) may have been associated with those years and may partly explain the population-level effects that occurred during WNv outbreak years.

Statistical Analyses

We analyzed the lek count data in two steps. First, we determined the scale of greatest impact for oil and gas development; and second, we conducted a multiple regression of male counts against the density of oil and gas wells (at its chosen scale) and a factor variable indicating whether or not the count was associated with a WNv outbreak year. Focal and supporting areas were allowed to have their own intercepts. We used a zero-inflated negative binomial error structure (Bolker 2008) and conducted model selection using Akaike's information criterion (AIC, Burnham and Anderson 1998). Detailed methods are provided in Appendix I.

RESULTS

Comparison of Actual Counts to Predicted Counts under Current Conditions

Oil and gas development and WNv were related to recent counts of sage-grouse throughout the study region. By building the model with data from the entire study region, and then applying the model to our northeast Wyoming focal area, we developed predictions of present lek count numbers, past numbers that would have been likely before the influence of stressors, and future numbers that would be likely under different

Table 2. Predicted counts for all areas were within 1% of actual counts.

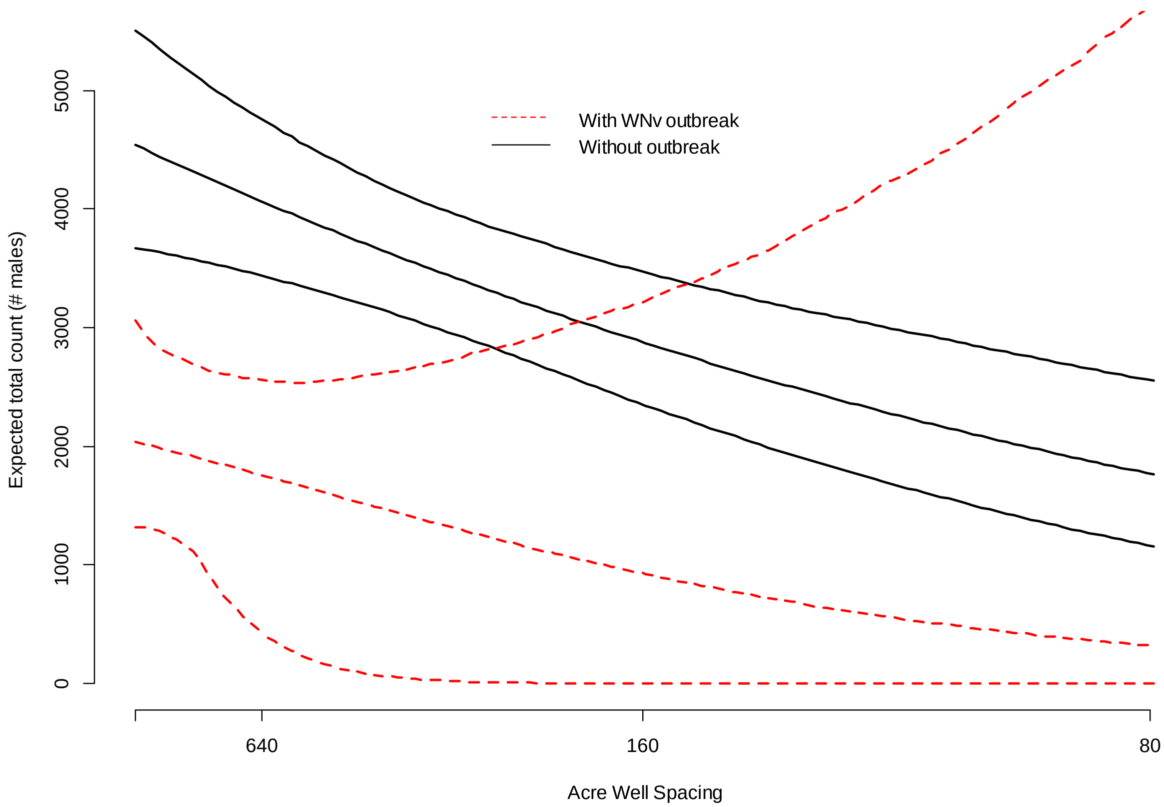
	Total Male Count	
Area	Predicted	Actual
Northeast Wyoming	3,315	3,316
Central Montana	3,661	3,693
Eastern Montana	2,789	2,770
Dakotas	661	659
North-central Montana	3,656	3,681

management scenarios. Underscoring the success of this approach is that the predicted male lek counts, based purely on the model, were consistently within 0 to 1% of the actual lek counts for the focal and supporting areas (Table 2). In particular, our model predicted a total of 3,315 males in northeast Wyoming, and 3,316 males were actually counted at leks. In short, we have high confidence that the use of the data from throughout the study region (Table 1, Fig 1) to link stressors to abundance is useful in making inferences about processes in northeast Wyoming.

Effects of Stressors

If we dial to zero the amount of energy development present in an area, we are, in practice, asking what the lek counts would have been in that area at a time in the past, before the stressor occurred. For simplicity, we can consider a range of possibilities from 'bad' to 'good' years, with WNv outbreaks being the primary driver of bad years. Thus, under predicted past conditions without energy development, the total expected male count in northeast Wyoming would have been 2,037 birds subsequent to a WNv outbreak year and 4,537 otherwise (Table 3, Fig 5). This 55% reduction in bird numbers resulted from a near doubling of the lek extirpation rate (239/123).

Without energy development, active leks were comprised of roughly 40% small leks (1-10 males), 40% medium-sized leks (11-25 males) and 20% large leks (> 25 males). Absent an outbreak year, development to an average of 80 ac spacing within 12.4 mi (20 km) of leks reduced predicted counts by 61%, from 4,537 to 1,768 males. These reductions resulted from a decrease in average lek size, as shown by a decreasing number of large leks and an increasing number of small leks, beginning with the onset of development. For example, without oil and gas development, the 91 small leks comprised 37% of active leks in the area, and the 60 large leks comprised 24%. At 80 ac spacing, the number of small leks had risen to 232 (83% of the area's active leks); whereas only 2 large leks remained. Number of medium-sized leks began to decline at 1 well per 160 ac (65 ha), and they declined at a slower rate than did the number of



None 640 160 80

Acre Well Spacing

Figure 5. Predicted number of males counted on 370 leks in northeast Wyoming (with 95% confidence bands) versus the average spacing of oil and gas wells within 12.4 mi of each lek.

large leks; comprising only 16% of the active leks at 80 ac spacing. Increasing well density had a negligible effect on lek extirpations, which remained between 25% and 33%, regardless of the intensity of oil and gas development.

In contrast, a WNv outbreak year caused a near doubling of lek extirpations, even in the absence of oil and gas development (239/123, Table 3, Figure 6). Extirpations increased with oil and gas development: when an outbreak year was superimposed on development at 160 ac spacing, the number of extirpated leks more than tripled (337/100, Table 3), and by 80 ac spacing, it quadrupled (364/91, Table 3).

Where sufficient data exist, the relationship between population size and outbreak-year lek extirpations is clear. For example, at the current average well spacing in northeast Wyoming, we predict an outbreak year to reduce the number of males counted on leks by 60% (1-1473/3648). This difference is underscored by non-overlapping confidence intervals on the count predicted with an outbreak year (1473, CI =(65, 2616)) and without (3648, CI= (3147, 4204)). Common sense indicates that the relationship between lek extirpations and the total number of males counted should continue at higher well densities, but data were insufficient to quantify this relationship. In particular, only two active leks at well densities higher than the current average spacing were last counted subsequent to a WNv outbreak year, prohibiting us from estimating the size of active leks under these conditions. This in turn prohibited us from estimating the total expected count in the presence of both an outbreak year and high well densities.

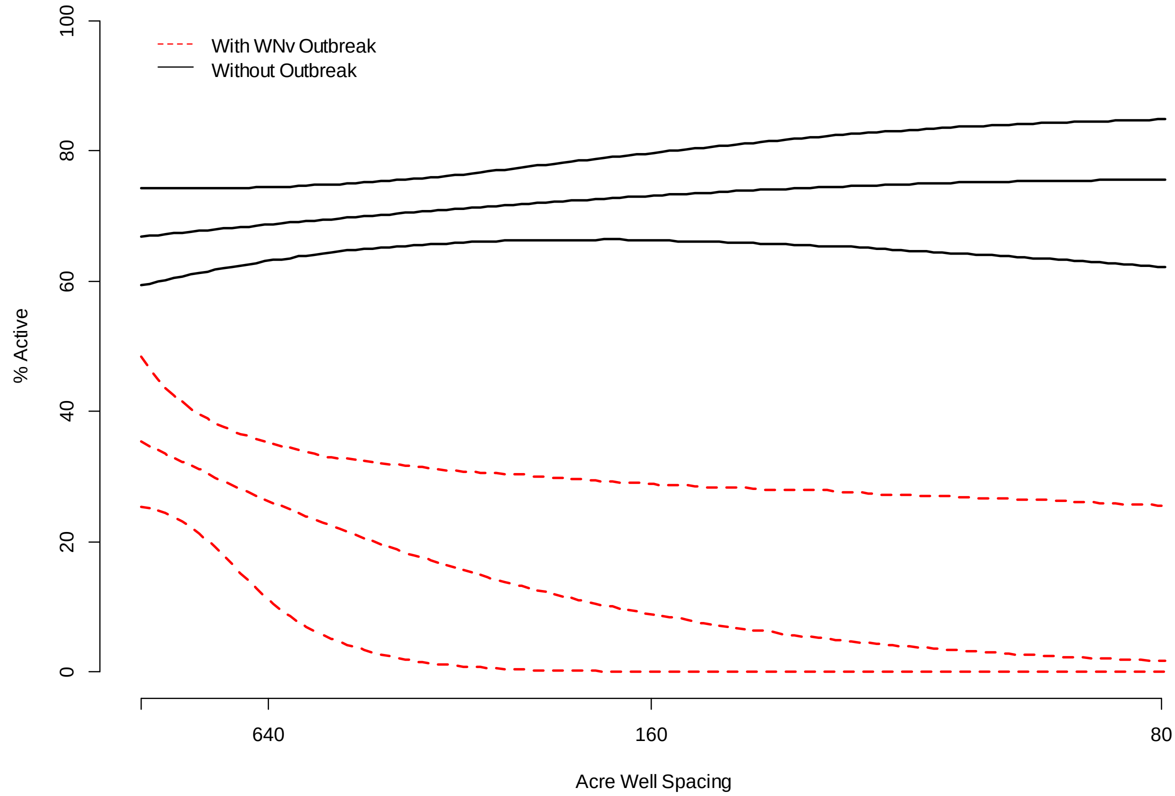


Figure 6. Percent of 370 leks in northeast Wyoming expected to remain active (with 95% confidence bands) versus the average spacing of oil and gas wells within 12.4 mi of each lek.

Table 3. Predicted total lek count and number of leks that are inactive (0 males), small (1-10 males), medium-sized (11-25 males) and large (> 25 males) for northeast Wyoming as a function of oil and gas well density and presence or absence of a West Nile virus outbreak year. As the lower limit of the confidence interval (CI) approaches 0, population extirpation is more likely.

Without West Nile Virus Outbreak Year										
Acre Spacing[1]	Total Lek Count		Number of Leks: Inactive		Small		Medium-sized		Large	
	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI
None	4537	(3668, 5507)	123	(95, 151)	91	(73, 111)	96	(84, 108)	60	(42, 80)
640	4062	(3439, 4753)	116	(94, 136)	108	(91, 125)	98	(89, 108)	48	(34, 62)
328[2]	3648	(3147, 4204)	110	(91, 129)	125	(109, 142)	99	(90, 108)	37	(26, 49)
160	2876	(2352, 3471)	100	(75, 125)	163	(138, 190)	89	(74, 103)	18	(10, 29)
86[3]	1895	(1288, 2670)	91	(57, 137)	224	(175, 259)	52	(25, 84)	3	(0, 12)
80	1768	(1162, 2554)	91	(56, 140)	232	(180, 266)	46	(19, 80)	2	(0, 10)

With West Nile Virus Outbreak Year										
Acre Spacing[1]	Total Lek Count		Number of Leks: Inactive		Small		Medium-sized		Large	
	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI
None	2037	(1318, 3062)	239	(191, 277)	57	(38, 82)	51	(36, 69)	23	(11, 41)
640	1757	(430, 2558)	273	(240, 329)	36	(13, 53)	38	(11, 51)	23	(2, 37)
328[2]	1473	(65, 2616)	299	(252, 361)	23	(2, 39)	27	(1, 45)	21	(0, 39)
160	927	(1, 3212)	337	(263, 370)	7	(0, 23)	11	(0, 35)	14	(0, 50)
86[3]	373	(0, 5246)	362	(274, 370)	1	(0, 11)	2	(0, 21)	5	(0, 67)
80	319	(0, 5712)	364	(275, 370)	1	(0, 9)	1	(0, 19)	4	(0, 68)

[1] measured within a 12.4-mi (20-km) radius of the lek

[2] average spacing around all leks in the northeast Wyoming area

[3] most dense spacing around any lek in the northeast Wyoming area

DISCUSSION

Oil and Gas Development Affects Sage-grouse at a Large Spatial Scale

Our analyses clarify an ongoing debate regarding the spatial scale at which oil and gas development most affects sage-grouse in the eastern portion of their range. Using AIC, as we did, to determine at what spatial scale an effect is best detected is analogous to using a dial to tune an analog radio while driving across a landscape. For oil and gas development, the signal is strongest within a 12.4-mi (20-km) radius of a lek, and it is much stronger at this radius than at any smaller radii. Furthermore, because we conducted analyses across a 30 million ha (74,000,000 ac) area encompassing a wide range of local and regional levels of oil and gas development, our best-fit spatial scale is robust to the conditions in any one locality, and it is generalized to the eastern portion of the sage-grouse range. While previous studies have found the best-fit spatial scale of impact to be anywhere from 2 mi (3.2 km) to over 12 mi (20 km) from the lek (Holloran 2005, Walker et al. 2007a, Tack 2009, Harju et al. 2010, Johnson et al. 2011), the different results are associated with the overall level of oil and gas development in the region analyzed. In particular, effects appear to be more localized if large undeveloped areas are not included in the study region for purposes of comparison. For this reason, sage-grouse in the Powder River Basin may be better served if BLM offices in Wyoming and Montana made their land use management decisions based on population boundaries rather than state boundaries.

The large spatial scale at which oil and gas development affects sage-grouse results from two aspects of the species' biology. First, the sage-grouse is a landscape species that requires large, intact areas of sagebrush in order to flourish (Connelly et al. 2011). Second, female sage-grouse that visit a lek use an approximately 9-mi (15-km) radius surrounding the lek for nesting; a 2-mi (3.2-km) radius encompasses only 35-50% of nests associated with the lek (Holloran and

Anderson 2005, Tack 2009). While a lek provides an important center of breeding activity, and a conspicuous location at which to count birds, its size is merely an index to the population dynamics in the surrounding habitat. Thus attempting to protect a lek, without protecting the surrounding habitat, provides little protection at all.

Past predictions of the number of males at leks impacted by oil and gas development (Doherty et al. 2010) should be updated to account for the large spatial extent of development impacts. Management would benefit from future analyses that include a decay function that quantitatively describes the non-linear relationship between bird numbers and the relative impact of oil and gas wells located at variable distances from the lek (e.g., see Holloran 2005; Fig 5, page 94).

<u>Oil and Gas Development Results in Declining Lek Counts</u>

Oil and gas development alone is a major threat to sage-grouse, and land managers can use Table 3 and Figure 5 to evaluate changes to predicted counts on leks under a myriad of different oil and gas development scenarios. Two scenarios include decisions on whether to develop a landscape from 0 to 4 wells per section (0 to 1.5 wells/km^2), and then from 4 to 8 wells per section (1.5 wells/km^2 to 3.1 wells/km^2). In both cases, the total northeast Wyoming lek count decreased by ~ 37% (1-2,876/4,537 and 1-1,768/2,876, Table 3), leaving only 39% of the original number of males on leks (1,768/4,537, Table 3) when development reached 8 wells per section (80 ac spacing).

A warning signal of declining populations is given by the accompanying decline in large leks, which showed a 70% decrease from no development to 160 ac spacing (1.5 wells/km^2, 1-18/60, Table 3). By 80 ac spacing (3.1 wells/km^2), only 2 large leks remained on the landscape (Table 3). Because we predicted the immediate effects of oil and gas development on lek size, we found the decline in the number of large leks to be part of an overall decline in average lek size, but not a decline in lek activity. However, time lags of 2-10 years between onset of development activities and local extirpation (Holloran 2005, Walker et al. 2007a, Harju et al. 2010) are known to result from the high site fidelity, but low survival of adult sage-grouse combined with lek avoidance by younger birds (Holloran et al. 2010).

West Nile Virus Results in Lek Extirpations

Our ability to detect the impact of a WNv outbreak year despite inherent variability in lek monitoring data is evidence of its large effect size. We found a substantial increase in zero counts at leks subsequent to outbreak years, which is consistent with the extreme susceptibility of sage-grouse to WNv and local extirpations observed in the field. Two outbreak years (2003 and 2007) are known since WNv first appeared in the West in 2002 (CDC 2010), and now persistent low-level mortality and periodic, large mortality events are expected (Walker et al. 2011). Our predicted baseline population for northeast Wyoming (3,315 males, Table 2) may be optimistic because < 18% of leks (65/370, Table 1) were last surveyed following an outbreak year. Even if northeast Wyoming were not further developed, a WNv outbreak year would be predicted to reduce the area lek count by 60% compared to a non-outbreak year (1-1,473/3,648, Table 3), as a direct result of a near tripling of lek extirpations (299/110, Table 3).

Findings suggest we may have to live with lower sage-grouse numbers with WNv as part of the system. Decision-makers should incorporate disease impacts into resource management plans to account for potentially frequent outbreaks and the extreme susceptibility of sage-grouse to WNv (Clark et al. 2006). Reducing the threat of WNv by reducing the number of new man-made water sources is a sensible option (Walker et al. 2011). Although we could try to fight WNv with mosquito control, the cost associated with treating tens of thousands of acres may be prohibitive, and benefits of spraying must be weighed against its likely detrimental effects (Marra et al. 2004).

West Nile Virus and Oil and Gas Development have a Synergistic Effect on Lek Extirpations

Oil and gas development and WNv outbreak years compound each other to increase the rate of lek extirpations. Two possible mechanisms are consistent with a disproportionately high rate of lek extirpation with increasing oil and gas development. First, within coal bed natural gas fields, ponds created from ground water brought to the surface during gas extraction provide additional habitat for mosquitoes that vector WNv (Walker et al. 2004, Zou et al. 2006, Walker et al. 2007b), possibly increasing the prevalence of WNv in these areas (Walker et al 2007, Walker and Naugle 2011). In other types of oil and gas development, the interaction between well density and outbreak year may simply reflect the more likely extirpation of populations that are already small. Regardless of mechanism, the interactive effects of energy development and outbreak years on lek extirpations are severe.

Sage-grouse populations in areas developed for oil and gas are small enough that they are at risk of extirpation due to a stochastic event, such as a WNv outbreak year. While disease is one obvious stressor, small populations are vulnerable to multiple habitat and population stressors. A different stressor, for example an extreme weather event, might also interact with development in a negative, synergistic manner, threatening viability of populations in developed areas.

MANAGEMENT IMPLICATIONS

Implications for Further Drilling in the Powder River Basin

Effects of energy development and past WNv outbreaks have depressed sage-grouse numbers in northeast Wyoming (Walker et al. 2007, Walker and Naugle 2011), placing the remaining small population at risk of extirpation. The species' current lack of adaptation to WNv (Walker et al. 2007b) means that managers will have fewer birds following imminent outbreaks, whether or not drilling continues in northeast Wyoming. At current average well spacing (328 ac spacing, 0.75 wells/km^2) 3,316 males remain (Table 2). Even at 80 ac spacing (3.1 wells/km^2), northeast Wyoming might have supported a small residual population of 1,768 males (95% CIs = 1162, 2554, Table 3), were it not for the additional impacts of WNv outbreaks. The effect of an outbreak year can more than cut a population in half (1-2037/4537, Table 3), which is similar to drilling an undeveloped landscape at 4-8 wells/mi^2 (1.5-3.1 wells/km^2, 1-2876/4537 and 1-1768/4537, Table 3).

The severity of WNv impacts has narrowed BLM's decision space if the goal is to maintain a viable sage-grouse population in northeast Wyoming. Decisions to continue drilling heighten the risk to sage-grouse because higher well densities increase the severity of energy impacts and exacerbate lek extirpations resulting from disease. At 80 ac spacing, subsequent to an outbreak year, 98% of northeast Wyoming's leks are predicted to be inactive (364/370, Table 3). Additional monitoring of leks following outbreaks years is crucial if BLM wants to predict the size of the remaining active leks (Fig 5).

Relevance of Findings to Wyoming's Core Area Policy

Wyoming's state-wide policy will be most effective where core area planning has accounted for the far reaching impacts of oil and gas before widespread development occurs. Such delineation of large and intact core areas in south central and southwest Wyoming will help to conserve sage-grouse populations if the policy continues to be fully implemented. In contrast, core areas in northeast Wyoming were delineated after widespread development had already occurred, leaving few options for conserving populations. In northeast Wyoming, the far reaching influence of development has already negatively impacted the 103 remaining active leks inside core areas, largely because the large scale of impacts (12.4-mi radius) spans an area 38 times that of a 2-mile radius. Despite impacts, the potential may still exist to maintain a population inside core areas, but further drilling in and around cores will compromise their remaining value. Furthermore, disease outbreaks in northeast Wyoming are the wild card in core area management, and management must be geared to preserving sage-grouse affected by multiple stressors, not just energy development.

Genetic connectivity is the glue that holds populations together, and remaining core areas, though impacted, may help maintain connectivity among populations further south in Wyoming and those in Montana. Sage-grouse follow a pattern of isolation by distance; that is, populations that are closer geographically also tend to be closer genetically (Oyler-McCance et al. 2005). Unfortunately, we lack a detailed understanding of connectivity, and these genetic linkages are being altered as the landscape is altered (Knick and Hanser 2011). Genetic analyses are underway to identify areas important for connectivity, but until these linkage zones are identified, we recommend a cautionary approach to management to at least maintain as undeveloped habitat the connectivity corridors outlined in the Wyoming Governor's Executive Order.

Future Monitoring to Assess Effectiveness of Restoration

Core areas are small, and the far reaching effects of development extend inside their boundaries, decreasing their intended conservation benefits to populations. Nevertheless, habitat enhancements may bolster sage-grouse populations inside the larger core areas, such as Natrona, and undeveloped areas may provide a source of birds to re-colonize restored habitats after extraction is complete. Maintaining a local population of birds may increase the chance for a successful restoration because strong site fidelity hinders re-colonization from more distant sites and past precedence shows that translocations, while problematic, are more apt to succeed in areas with resident populations (Reese and Connelly 1997, Baxter et al. 2008).

Carefully planned, landscape scale monitoring of sage-grouse populations will be critical to evaluate the restoration efforts after the oil and gas play has ceased. Data must be collected across a range of development levels at local and regional scales, and failure to do so could result in mis-estimation of the development effects. These problems are compounded when multiple effects (e.g., the effect of development and the effect of abandonment) are considered, because the data must contain a large range of intensities for both land uses, and the different intensities for each land use need to be observed in combination with the different intensities of the other land use. For example, consider conducting a lek count-based analysis when oil and gas wells are just starting to be plugged and abandoned. Plugged and abandoned wells would occur in low to moderate densities in areas where the density of active wells was high. Areas with neither active nor abandoned wells would exist, but there would be no areas in which the density of abandoned wells was high and the density of active wells was low. An analysis based on such data might incorrectly predict that plugging and abandoning wells is detrimental to sage-grouse, simply because the plugged and abandoned wells occurred in areas where the density of active wells was high. While current data will not support an appropriate analysis of the effect of plugging and abandoning wells, such an analysis will be possible once appropriate combinations of active and abandoned well densities exist. We strongly urge that such an analysis be conducted, as it would guide sage-grouse management not only in northeast Wyoming, but also in areas across the West that have been developed for oil and gas.

Lek monitoring to assess restoration outcomes must be large scale, encompassing at least the area of northeast Wyoming that we used, and preferably the entirety of our study region. Furthermore, the statistical methods used herein are repeatable, and they provide a template for a multiple effects analysis. We also note that the metric we used in our analyses, density of active wells, represents intensity of development, and as such it provides a surrogate for the roads, power lines and other infrastructure that accompany wells. Should infrastructure be removed when some wells are abandoned, but not when others are abandoned, these different effects would need to be monitored and included as separate effects in the analysis. For example, water impoundments from coal-bed natural gas development might be retained by private landowners as stock ponds, and might, in fact, provide better breeding habitat for WNv carrying mosquitoes under this new usage. Conversely, we acknowledge and encourage the efforts of some companies to bury power lines and reduce their overall footprint in other ways. The benefits of these actions should be monitored at large scales when they become common enough to assess at biologically relevant scales. We cannot stress enough the importance of monitoring populations at a scale large enough to encompass multiple levels of development, abandonment and lack thereof, and large enough to not be hampered by project or political boundaries unrelated to sage-grouse biology.

The other method likely to provide a fruitful assessment of the impacts of plugging and abandoning wells would be a small scale, but highly intensive, designed before-after-control-impact study. This type of study requires that birds be radio-marked and that data be collected on all vital rates across space and time. Holloran (2005) provides an excellent example of such a design.

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APPENDIX 1: STATISTICAL METHODS

We regressed oil and gas well density, a factor for WNv outbreak year and a factor for area on lek counts, using AIC to determine the most parsimonious model. We used our best-fit model to predict the effects of different well densities on lek counts, in the presence of a WNv outbreak year, and in its absence.

Model Selection

Our model selection proceeded in two steps. First we determined the best fit radius for energy development; second we quantified the effects of energy development and WNv on sage grouse using the best fit radius obtained in the first analysis. We determined which radius best explained the variation in lek counts by repeating, for each radius, a univariate regression of lek count against well density, and comparing the resulting six regressions with AIC (Burnham and Anderson 1998). We then fit a saturated, multivariate model that contained the main effects of well density at its best fit scale, factors for WNv years, well density by WNv interactions, and separate intercepts for each of the five areas. We did not include any interactions with area, as we had no reason to believe that stressors would affect lek counts differently in the different areas; we simply needed to adjust for the different starting sizes of the leks in each area. We reduced the saturated model by testing whether or not removing each interaction would cause AIC to increase by more than two units (Burnham and Anderson 1998). We then reduced main effects in the same fashion, but did not test for removal any of the main effects on which the interactions depended.

Predictions

We used the best-fit, multivariate model to predict how changing stressors would affect northeast Wyoming's total lek count, which we calculated as the product of the expected size of a northeast Wyoming lek (including both active and inactive leks) and the number of leks from northeast Wyoming that were used in the analysis. We calculated the number of leks that were extirpated, as well as the number in small (< 11 males), medium (11-25 males) and large (> 25 males) size categories (Tack 2009), by calculating the probability a lek would fall into each of the four size categories and multiplying it by the number of leks from northeast Wyoming that were used in the analysis.

Error Structure

We used a zero-inflated negative binomial (ZINB) error structure. The ZINB is a mixture of a negative binomial distribution and a point mass at zero, meaning that some zero counts are generated by the negative binomial distribution, and some are generated by the point mass of extra zeros, but all positive counts come from the negative binomial distribution. This structure is ideally suited to overdispersed count data such as ours, where the variance is a strongly increasing function of the mean, and there are an unusually large number of zero counts (Hardin and Hilbe 2007). We parameterized the ZINB so the negative binomial distribution was described by a mean and overdispersion parameter, and the mixing parameter was the probability that a count belonged to the negative binomial distribution. We used a log link for the negative binomial mean and a logit link for the mixing parameter.

Confidence Intervals and Model Diagnostics

We calculated parameter confidence intervals with profiled likelihoods and used case-based, nonparametric bootstrapping to place 95% confidence bands on the predicted lines. We calculated randomized quantile residuals (Dunn and Smyth 1996) for diagnostic plots because the normal distribution of these residuals make them much more interpretable than other generalized linear model residuals that exhibit only asymptotic normality. Analyses were conducted in the R programming environment, version 2.14.0 (R Development Core Team).

APPENDIX II: STATISTICAL RESULTS

Table 1. Delta AIC values used to determine the best fit radius surrounding a lek within which to measure the number of oil and gas wells. Univariate models demonstrated that the 12.4 mi radius better explained the variation in the data than did 4 of the 5 other radii (dAIC > 2). While the 12.4 mi radius provided a nominally better fit than did the 3.1 mi radius, it was statistically indistinguishable (dAIC < 2). To confirm whether or not the 12.4 mi radius better explained the variation in the data than did the 3.1 mi radius, we compared AIC values for these two radii using the saturated model. The 3.1 mi radius had a dAIC value > 4 points higher than the 12.4 mi radius, confirming that the best fit was achieved using the 12.4 mi radius.

	Delta AIC	
Radius mi (km)	Univariate	Saturated
12.4 (20.0)	0.00	0
3.1 (5.0)	1.44	4.89
9.3 (15.0)	2.09	NA
0.6 (1.0)	4.50	NA
2.0 (3.2)	4.52	NA
6.2 (10.0)	4.78	NA

Table 2. Maximum likelihood estimates and profile likelihood confidence intervals for parameters of the reduced model. Parameters belonging to the negative binomial (NB) model component are presented on the log scale. Parameters belonging to the zero-inflation (ZI) model component (mixing parameter) are presented on the logit scale. The mixing parameter was defined as the probability that a count belonged to the negative binomial distribution.

	Parameter	Model Component	MLE	CI
	Overdispersion	NB	1.539	(1.354, 1.738)
	Intercept	ZI	2.897	(2.240, 3.077)
	Intercept	NB	3.352	(3.211, 3.499)
Factor for Area	Central MT	ZI	-1.431	(-2.329, -0.711)
Factor for Area	Central MT	NB	-0.413	(-0.600, -0.228)
Factor for Area	Eastern MT	ZI	-1.047	(-1.949, -0.305)
Factor for Area	Eastern MT	NB	-0.809	(-0.997, -0.624)
Factor for Area	Dakotas	ZI	-0.652	(-1.778, 0.618)
Factor for Area	Dakotas	NB	-1.023	(-1.277, -0.764)
Factor for Area	NE Wyoming	ZI	-2.135	(-3.044, -1.402)
Factor for Area	NE Wyoming	NB	-0.463	(-0.672, -0.254)
	Well Density	ZI	0.269	(-0.079, 0.656)
	Well Density	NB	-0.369	(-0.505, -0.230)
	Outbreak Year	ZI	-1.328	(-1.732, -0.930)
	Outbreak Year	NB	-0.168	(-0.351, 0.019)
	Well*Outbreak Year Interaction	ZI	-1.406	(-2.751, -0.380)
	Well*Outbreak Year Interaction	NB	0.765	(0.199, 1.514)