Environmental Management (2017) 59:189–203
DOI 10.1007/s00267-016-0789-9

Effectiveness of Wyoming's Sage-Grouse Core Areas: Influences on Energy Development and Male Lek Attendance

R. Scott Gamo[1] · Jeffrey L. Beck[2]

Received: 12 November 2015 / Accepted: 22 October 2016 / Published online: 8 November 2016

Abstract Greater sage-grouse (*Centrocercus urophasianus*) populations have declined across their range due to human-assisted factors driving large-scale habitat change. In response, the state of Wyoming implemented the Sage-grouse Executive Order protection policy in 2008 as a voluntary regulatory mechanism to minimize anthropogenic disturbance within defined sage-grouse core population areas. Our objectives were to evaluate areas designated as Sage-grouse Executive Order Core Areas on: (1) oil and gas well pad development, and (2) peak male lek attendance in core and non-core sage-grouse populations. We conducted our evaluations at statewide and Western Association of Fish and Wildlife Agencies management zone (MZ I and MZ II) scales. We used Analysis of Covariance modeling to evaluate change in well pad development from 1986–2014 and peak male lek attendance from 958 leks with consistent lek counts within increasing (1996–2006) and decreasing (2006–2013) timeframes for Core and non-core sage-grouse populations. Oil and gas well pad development was restricted in Core Areas. Trends in peak male sage-grouse lek attendance were greater in Core Areas compared to non-core areas at the statewide scale and in MZ II, but not in MZ I, during population increase. Trends in peak male lek attendance did not differ statistically between Core and non-core population areas statewide, in MZ I, or MZ II during population decrease. Our results provide support for the effectiveness of Core Areas in maintaining sage-grouse populations in Wyoming, but also indicate the need for increased conservation actions to improve sage-grouse population response in MZ.

Keywords *Centrocercus urophasianus* · Greater sage-grouse · Core area · Impact assessment · Natural resource policy · Population monitoring · Wyoming Sage-grouse executive order

✉ R. Scott Gamo
scott.gamo@wyo.gov

[1] Wyoming Game and Fish Department and Department of Ecosystem Science and Management, University of Wyoming, Cheyenne, WY 82006, USA

[2] Department of Ecosystem Science and Management, University of Wyoming, Laramie, WY 82071, USA

Introduction

Greater sage-grouse (*Centrocercus urophasianus*; hereafter sage-grouse) have declined from historical numbers across the western United States and Canada (Garton et al. 2011). Declines include an overall annual rate of 2 % from 1965–2003 (Connelly et al. 2004) and a 56 % decline in males counted on 10,060 leks (i.e., spring breeding grounds) in 11 western states from 2007 (109,990) to 2013 (48,641; Garton et al. 2015). However, sage-grouse populations are cyclic (Fedy and Doherty 2011; Fedy and Aldridge 2011) and counts indicate range-wide increases in 2014 and 2015 (Nielson et al. 2015). Coincidentally, the distribution of sage-grouse has contracted approximately half from historical range (Schroeder et al. 2004) primarily due to degradation and loss of sagebrush (*Artemisia* spp.) habitat (Connelly et al. 2004; U. S. Fish and Wildlife Service 2010). Infrastructure and activities associated with natural resource extraction, which are most prominent in the eastern portion of sage-grouse range, adversely impact sage-grouse (Braun et al. 2002; Holloran and Anderson 2005; Walker et al. 2007; Harju et al. 2010; Holloran et al. 2010;

USFWS 2010; LeBeau et al. 2014). Energy development has been shown to specifically impact male sage-grouse lek attendance (Walker et al. 2007; Harju et al. 2010; Gregory and Beck 2014), lek persistence (Walker et al. 2007; Hess and Beck 2012), recruitment of yearling male and female grouse to leks (Holloran et al. 2010), nest initiation and site selection (Lyon and Anderson 2003), nest survival (Dzialak et al. 2011; LeBeau et al. 2014), chick survival (Aldridge and Boyce 2007), brood survival (LeBeau et al. 2014; Kirol et al. 2015a), summer survival of adult females (Dinkins et al. 2014a), early brood-rearing habitat selection (Dinkins et al. 2014b), adult female summer habitat selection (Fedy et al. 2014; Kirol et al. 2015a), and adult female winter habitat selection (Doherty et al. 2008; Carpenter et al. 2010; Dzialak et al. 2013; Smith et al. 2014; Holloran et al. 2015).

The cumulative effects of energy-related impacts in the eastern range, and other impacts such as invasive plant species and altered fire regimes in the western portion of sage-grouse range, have led to consideration of the sage-grouse for threatened or endangered species listing under the Endangered Species Act of 1973 by the United States Fish and Wildlife Service ([USFWS] 2010, 2015). The March 2010 USFWS listing decision designated the greater sage-grouse as a candidate species, warranted for listing, but precluded from listing at that time because other species were under severe threat of extinction (USFWS 2010—sage-grouse were subsequently found unwarranted for listing [USFWS 2015]). In response to anticipated threatened or endangered species listing, the State of Wyoming developed a strategy through an executive order issued by the Governor of Wyoming to conserve sage-grouse. The Wyoming Governor's Executive Order for Sage-Grouse (SGEO) was first implemented in late 2008 and provides a voluntary regulatory mechanism designed to limit and/or minimize anthropogenic disturbance within defined boundaries identified as sage-grouse population areas (State of Wyoming 2008; Doherty et al. 2010, 2011[Fig. 1]). A major component of this mechanism is the establishment of

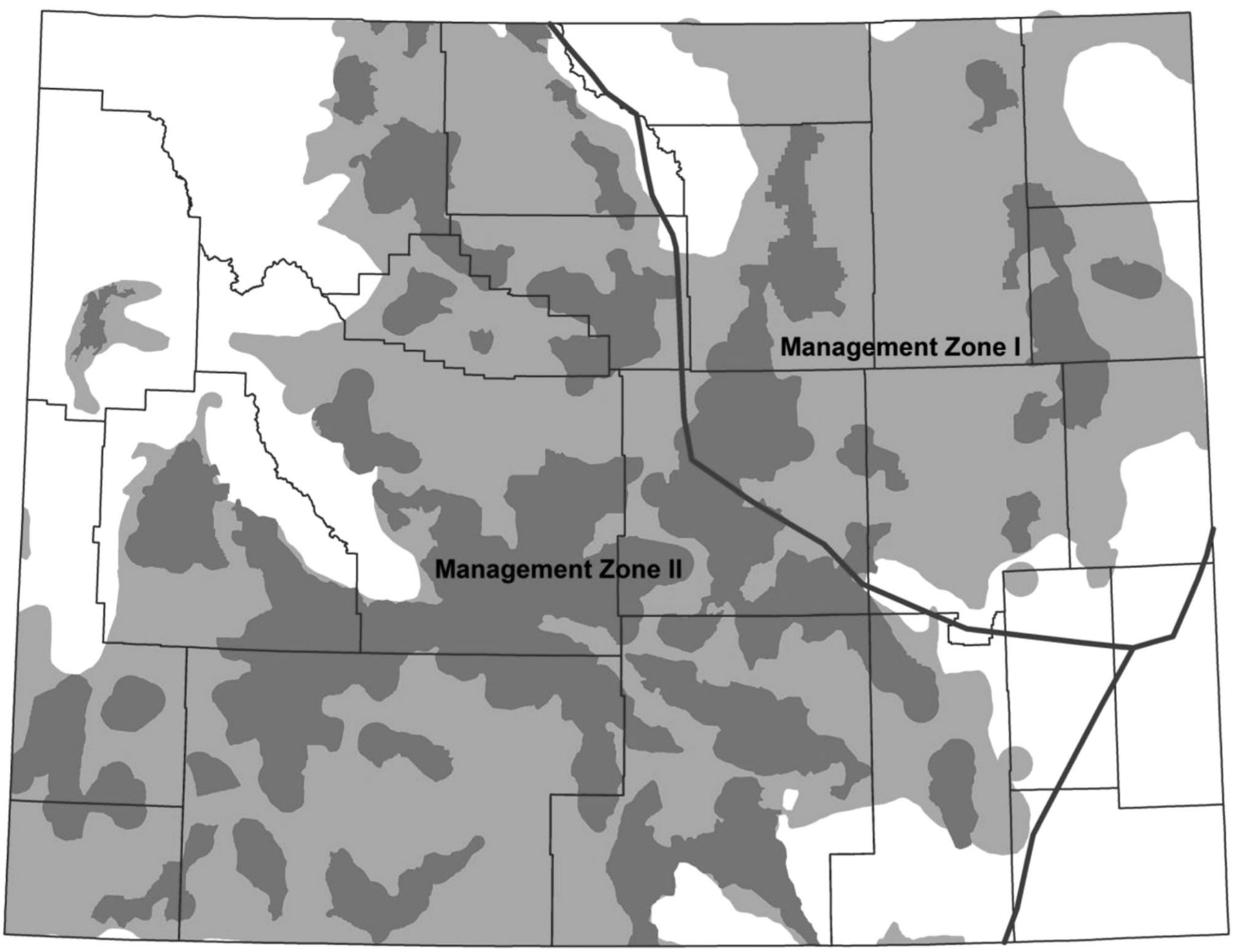


Fig. 1 Location map of 31 core population areas (*dark gray-shaded* areas; *light gray-shaded* areas represent sage-grouse range where non-core sage-grouse populations occur) within current sage-grouse range and Western association of Fish and Wildlife agencies management zones I and II in Wyoming, USA

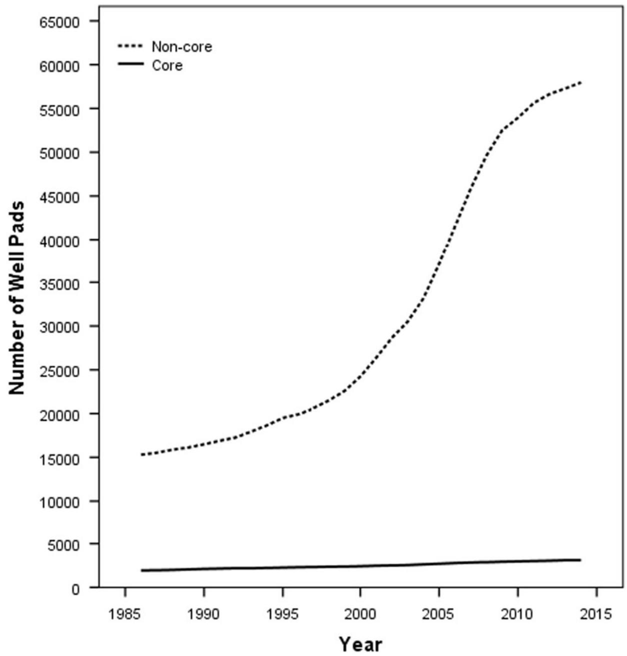


Fig. 2 Number of well pads in core and non-core areas from 1986–2014, Wyoming, USA

defined conservation areas for sage-grouse termed Core Area.

The SGEO, as a state-driven regulatory mechanism, was designed to conserve and maintain sage-grouse populations and habitat through a detailed process of planning and managing energy development and other surface disturbing activities within the boundaries of sage-grouse Core Areas. The goal was to protect two-thirds of the sage-grouse population within the state as identified by peak male lek attendance (B. Budd, Wyoming Sage-Grouse Implementation Team [SGIT], personal communication). This effort assimilated the highest sage-grouse density areas identified by Doherty et al. (2010) as they were identified as the most productive habitats for sage-grouse in Wyoming. In addition, the mapping of Core Areas considered current and potential energy development and encapsulated areas historically low in production (Gamo 2016; Fig. 2). The end result included approximately 82 % of Wyoming's total male sage-grouse population as measured by peak male lek attendance (unpublished data, Wyoming Game and Fish Department [WGFD]). By design, the SGEO process minimizes surface disturbance size and densities at a landscape scale within Core Area boundaries. Policymakers utilized research evaluating the impacts of energy extraction on sage-grouse to develop the specifics of the SGEO. Three parameters were adopted forming the basis for conservation measures within the SGEO: 1) disturbances should not occur within 1 km (0.60 mi) of occupied leks, 2) disturbance density should not exceed 1 per 2.6 km^2 (640 ac) within the analysis area (e.g., Holloran 2005; Doherty 2008), and 3) total disturbance acreage should not exceed 5 % of the analysis area (State of Wyoming 2011). In contrast, sage-grouse populations outside of Core Areas (i.e., non-core areas) are not subject to these conservation measures. Prescribed stipulations for breeding habitat in non-core areas include maintaining a 0.40 km (0.25 mi) buffer of controlled surface use around leks, and a 3.33 km (2.0 mi) buffer with a seasonal timing stipulation (15 Mar-30 Jun) around leks. Both of these stipulations are subject to potential modification or waiver (State of Wyoming 2011).

Wyoming's governor requested a review of the progress and effectiveness of the SGEO to occur every 5 years (State of Wyoming 2011). In addition, the USFWS conducts 5-year status reviews of candidate species including sage-grouse (USFWS 2010). Thus, the State of Wyoming has a need to provide an accurate and accountable examination of the effectiveness of the SGEO in maintaining sage-grouse populations in Wyoming. The effectiveness of the SGEO is dependent upon multiple factors. First, whether the lands encompassed by Core Area benefit sage-grouse. Second, how well have the parameters been applied. This is particularly tenuous as the SGEO is a Governor's order, not a rule of legislated law. And, finally, are the parameters, which are based on science, truly effective when applied at a landscape scale. The success of the SGEO has greater ramifications than just for Wyoming. Other western states are also implementing approaches to sage-grouse conservation within their jurisdictions (e.g., Oregon Department of Fish and Wildlife 2011; State of Idaho 2012a, 2012b; State of Montana 2014; State of Nevada 2014; Stiver 2011). The Bureau of Land Management also recently incorporated additional protections for sage-grouse into their current and updated land management plans (BLM 2012, 2015).

Since it was initiated in 2008, there has not been an evaluation of whether Core Areas designated by the SGEO are effective in conserving sage-grouse in light of continued energy development. The designation of Core Areas is the major component of the SGEO as Core Areas delineate the habitat across the state where SGEO conservation measures are applied. Further, lands encompassed by Core Area likely served as functional Core Area even prior to policy designation as evidenced by historically high densities of sage-grouse (Doherty et al. 2010, WGFD unpublished data) and minimal development through time (Gamo 2016). In addition, disturbance was minimal around Core Area leks prior to 2008 policy implementation. For instance, 4 of 674 (<0.01 %) Core Area leks we evaluated occurred within 1.0 km of a well pad (Gamo, unpublished data). Therefore, the focus of our study was on assessing whether Wyoming Core Areas benefit sage-grouse populations. Our objectives included: (1) evaluating oil and gas well pad development within Core Area, and (2) comparing total peak male sage-grouse lek attendance in Core Area and non-core areas. In line with existing habitat quality at time of SGEO implementation, we predicted that rate of energy development within sage-grouse Core Area would be lower compared to non-core areas. We further predicted oil and gas development in the Core Areas would exhibit less expansion after SGEO implementation compared to non-core area. We also predicted that sage-grouse populations within Core Area would exhibit more robust male lek attendance than non-core area grouse populations. To test these predictions, we evaluated well pad numbers and male sage-grouse lek attendances between core and non-core population areas at statewide and management zone scales. Finally, we provide initial information related to disturbances within Core Area to assess short-term progress of SGEO implementation. Our paper provides an assessment of the measured effectiveness of the Wyoming's Core Area designations for breeding sage-grouse (see Smith et al. 2016 for an evaluation of winter habitat protections afforded by SGEO), which should be of great value to managers and scientists considering implementing other landscape-scale species conservation programs.

Materials and Methods

Study Area

Our study area encompassed the range of sage-grouse across Wyoming. Within this delineated range, 31 Core Areas have been designated and mapped (State of Wyoming 2011; Fig. 2). Core Areas occupy approximately 24 % of the land area of Wyoming and generally reside in the major basins found between mountain ranges including the Wyoming Basins (Rowland and Leu 2011) in the western and central portions of the state and the Powder River Basin in the northeast (Knight et al. (2014). Sage-grouse Core Areas vary in size from a minimum of 41 km^2 to a maximum of 18,587 km^2. The Western Association of Fish and Wildlife Agencies (WAFWA) mapped the entire sage-grouse range into 7 sage-grouse management zones based on ecological conditions (MZ; Stiver et al. 2006). The Great Plains-Management Zone-MZ I and the Wyoming Basin-MZ II occur in Wyoming. The northeastern portion of Wyoming, including the Powder River Basin and the plains extending east and north from the northern Laramie Mountains to the state line bordering South Dakota lie within MZ I. The remainder of the state (excluding the southeastern plains, which are not inhabited by sage-grouse) including the sagebrush dominated basins west of the Laramie and Bighorn Mountain Ranges fall within MZ II (Rowland and Leu 2011). From 2010–2014, MZ II included 36.8 % of range-wide breeding male sage-grouse (compared to 12.4 % in MZ I; Doherty et al. 2015) and the second largest area of suitable habitat range-wide (Wisdom et al. 2011).

Northeastern Wyoming rangelands, including the Powder River Basin, consist of sagebrush dominated shrub steppe integrating with mixed grass prairie toward the South Dakota border (Knight et al. 2014). Sagebrush steppe vegetation consists of Wyoming big sagebrush (*A. tridentata wyomingensis*, silver sagebrush (*A. cana*). and a diverse understory of herbaceous plants. Common native grasses include blue grama (*Bouteloua gracilis*), bluebunch wheatgrass (*Pseudoroegneria spicata*), and non-native grasses include crested wheatgrass (*Agropyron cristatum*) and cheatgrass (*Bromus tectorum*; Thilenius et al. 1994). Rocky Mountain juniper (*Juniperus scopulorum*) and ponderosa pine (*Pinus ponderosa*) occur on rocky uplifts and in river drainages.

The Wyoming Basins in the western part of the state consist of multiple basins between mountain ranges. Major basins include the Bighorn, Great Divide, Green River, and Shirley. Vegetation in these basins is much more dominated by sagebrush than northeast Wyoming and consist of sagebrush steppe dominated by Wyoming big sagebrush with areas of black (*A. nova*) and low sagebrush (*A. arbuscula*; Rowland and Leu 2011; Knight et al. 2014). Common grasses include bluebunch wheatgrass, and needle and thread (*Hesperostipa comata*). Invasive grass species such as cheatgrass are becoming more common in the Wyoming Basins (Knight et al. 2014).

Methods

Wells Pads

We obtained data on numbers of wells from the Wyoming Oil and Gas Conservation Commission (WOGCC) oil and gas well database dating from 1986 through 2014 (WOGCC 2014). Higher well numbers have been previously correlated to higher levels of infrastructure (Walker et al. 2007). Similar to Harju et al. (2010), we used well pads as a more easily measureable surrogate for energy impacts. We tabulated wells located within sage-grouse range and only included active wells; wells that were plugged, abandoned, or not active were removed from further analysis (e.g., Holloran 2005). Wells were also assigned to Core Area or non-core area. We calculated average well pad size based upon the average size of 100 randomly chosen well pads digitized in GIS. Based upon the average well pad size we calculated an average well pad diameter of 120 m. We thus computed the number of well pads by placing a 60 m radius circle around each well head. Using GIS, anywhere a 60 m radius touched or overlapped another 60 m radius that intersection was merged into one well pad. Finally, we determined the number of well pads at a statewide level, within MZ I and II for each year 1986 through 2014.

Male Sage-Grouse Lek Attendance

Our analyses used total (i.e., sum of all lek counts in each analysis scale per year) annual peak male counts, which is the statistic used to monitor sage-grouse populations per the Wyoming SGEO (B. Budd, Wyoming SGIT, personal communication). We calculated annual peak male lek attendance using the WGFD sage-grouse lek count database from 1996 through 2014. Our analyses did not rely on average males per lek, which is a common statistic used to monitor trends in sage-grouse populations (e.g., Walker et al. 2007; Harju et al. 2010; Gregory and Beck 2014). However, for comparison we also calculated and report average males per lek from 1996 through 2014 among our sampled leks. Lek count procedures were standardized in 1996 and protocols consisted of three separate counts for each lek spaced at least 7 days apart from March through May (Connelly et al. 2003, 2004). The peak count was the maximum recorded number of males of the three counts. We only included leks considered active by WGFD definition (e.g., documented attendance of 2 or more individuals within a 10-year timeframe). Leks were identified as Core Area leks or non-core leks according to their location within a Core Area or outside of those areas as described in the SGEO. We evaluated total peak male sage-grouse lek attendance statewide and for WAFWA MZs I and II. These designations were chosen as they correspond to state policy (statewide) and potential regulatory decisions at the federal level (MZs). We summed total peak male lek attendance in Core Area and non-core area at the statewide and WAFWA MZ scales. Statewide estimates included leks aggregated from all 31 individual core population areas.

Recognizing the strong cyclic nature of sage-grouse populations in Wyoming (Fedy and Doherty 2011; Fedy and Aldridge 2011), we chose to evaluate differences between Core Area and non-core area birds separately during periods of population increase (1996–2006) and decline (2006–2013). Core Areas were originally identified based upon high lek densities with abundant grouse populations, high quality habitat (Doherty et al. 2010), and relative exclusion from development (B. Budd, pers. comm., Gamo 2016). Fedy and Aldridge (2011) noted sage-grouse populations in Wyoming experienced a period of increase from 1996 through 2006. Correspondingly, a downward trend was observed from 2006 through 2013 (unpublished data, WGFD, Nielson et al. 2015). Therefore, our evaluation of Core Area influence on grouse includes years prior to the SGEO policy designation and allows the opportunity to evaluate implications of the chosen landscape during both increasing and decreasing phases of a sage-grouse population cycle.

To provide insight on the effectiveness of the Wyoming SGEO policy, we report data provided by the WGFD in response to the 2014 USFWS greater sage-grouse data call as part of their Endangered Species Act listing determination. These data provide a short-term description of SGEO-related features obtained from site-specific impact analyses conducted by development proponents, and state and federal agencies that were reviewed for SGEO policy conformance by the WGFD. Data were available only for the years 2012 through 2014 which correspond to the implementation of a statewide SGEO database system.

Statistical Analysis

We utilized Analysis of Covariance (ANCOVA; PROC REG, SAS 9.4, SAS Institute, Cary, NC) to compare trends in well pad development between Core Area and non-core area at statewide and management zone scales. We compared the main effects of study area (i.e., Core Area or non-core area) with time being the covariate in each ANCOVA. In our design, well pads in Core Area constructed after 2009 constituted the treatment whereas non-core well pads after 2009 served as the control. Well pads within Core Areas from 1986 through 2008 served as before or pre-treatment data. We compared trends in numbers of active well pads between Core Areas and non-core areas (control) from 2009–2014 coinciding with SGEO implementation. We then compared trends in numbers of active well pads from 1986 through 2008 prior to SGEO policy with trends from 2009 through 2014 representing impacts post policy implementation.

We also utilized ANCOVA to evaluate differences in sage-grouse population trends between Core and non-core areas during an increasing population cycle (1996–2006) and a decreasing population cycle (2006–2013) both statewide and within MZs. As some leks occurred within relative close proximity to each other and count data were collected at essentially the same time each year on an annual basis, there was potential for spatial and temporal autocorrelation, respectively, among the data. We tested for temporal autocorrelation among sage-grouse count data using a Durbin-Watson test. If tests for autocorrelation were significant ($\alpha \leq 0.05$), we transformed the data using differencing to remove the temporal autocorrelation prior to employing the regressions within the ANCOVA (Box et al. 1994). Differencing is a technique that simply subtracts the previous year count from the current year count in sequence through the progression of years of data. By doing so, differencing removes the temporal trend but retains the mean across the data.

The ANCOVA procedure we employed used a suite of four models and systematically compared among models to determine the best fit for the comparison among the two trend lines (i.e., core and non-core) from linear regressions (Weisberg 1985). The models were as follows:

Model 1. $\hat{y} = b_{0,1}W_1 + b_{0,2}W_2 + b_{1,1}Z_1 + b_{1,2}Z_2$

Model 2. $\hat{y} = b_{0,1}W_1 + b_{0,2}W_2 + b_1X_1$

Model 3. $\hat{y} = b_0 + b_{1,1}Z_1 + b_{1,2}Z_2$

Model 4. $\hat{y} = b_0 + b_1X$

Where b_0 was the y-intercept, b_1 was the slope estimate, W was a label term, Z was the value associated with the corresponding W, and X was time. We first tested Model 1 against Model 2 to test the null hypothesis that the slopes of Core and non-core area sage-grouse trends were identical vs. the alternate that they were different ($\alpha = 0.05$). If the null hypothesis was accepted, we then tested Model 2 against Model 4 to test the null hypothesis that the slopes were identical between core and non-core areas as well as the y-intercepts being identical between the two areas vs. the alternate that the slopes were identical but the y-intercepts were different. In addition, if upon visual inspection of the plots of the compared slopes, the y-intercepts were clearly distinct we first tested model 1 against model 3 to test the null hypothesis that the y-intercepts were identical between core and non-core areas vs. the alternate that they were different. If the null hypothesis was accepted, we then tested model 3 against model 4 to test the null hypothesis that the y-intercepts were identical between Core and non-core areas as well as the slopes being identical between the two areas vs. the alternate that the y-intercepts were identical but the slopes were different. We tested for normal probabilities and used Ordinary Least Squares assuming residuals were normally distributed. Model significance testing was accomplished using an F-test.

We calculated coefficients of variation (CV) for each year's average peak male lek attendance by MZ and statewide to obtain a measure of the variation around the mean of each year's lek attendance. We considered populations that exhibited smaller CVs to be more stable and resilient to changing environmental conditions (Harrison 1979).

Results

Well Pads

Well pads within statewide sage-grouse range increased from 1946 in Core Area and 15,304 in non-core area in 1986 to 3112 and 57,970, respectively, in 2014 (Table 1). Well pads in MZ I increased from 866 in Core and 8244 in non-core in 1986 to 1174 in Core and 34,178 in non-core in 2014 (Table 1). During this same time frame, well pads in MZ II increased from 1080 in core and 7060 in non-core to 1938 in core and 23,792 in non-core in 2014. Comparing non-core to Core Area at the statewide scale, well pads increased at a ratio of 29 to 1 per year, 48 to 1 in MZ I, and 15 to 1 in MZ II (Table 1).

Core Area vs. Non-core Population Areas (2009–2014: post SGEO policy implementation)

Rate of increase in active well pads differed ($F_{1,8} = 97.77$, $p < 0.01$, $r^2 = 1.00$; Fig. 3a) as Core ($\hat{\beta}_1 = 37.43$,

Table 1 Numbers of well pads by year statewide and within Western association of fish and wildlife agencies management zones I and II (MZ I and MZ II) in Wyoming, USA, 1986–2014

Year	Number of active well pads					
	Statewide		MZ I		MZ II	
	Core	Non-core	Core	Non-core	Core	Non-core
1986	1946	15,304	866	8244	1080	7060
1987	1958	15,538	870	8386	1088	7152
1988	2000	15,878	880	8562	1120	7316
1989	2052	16,128	904	8646	1148	7482
1990	2102	16,498	922	8746	1180	7752
1991	2152	16,900	938	8874	1214	8026
1992	2178	17,270	946	8988	1232	8282
1993	2194	17,952	950	9096	1244	8856
1994	2228	18,664	956	9258	1272	9406
1995	2266	19,508	958	9428	1308	10,080
1996	2300	19,918	966	9494	1334	10,424
1997	2324	20,614	970	9688	1354	10,926
1998	2364	21,510	974	9968	1390	11,542
1999	2386	22,588	976	10,406	1410	12,182
2000	2420	24,234	980	11,446	1440	12,788
2001	2466	26,366	994	12,772	1472	13,594
2002	2510	28,656	1002	14,096	1508	14,560
2003	2550	30,500	1004	15,234	1546	15,266
2004	2622	33,158	1016	16,936	1606	16,222
2005	2708	37,142	1032	19,822	1676	17,320
2006	2774	41,490	1056	23,074	1718	18,416
2007	2836	45,846	1074	26,134	1762	19,712
2008	2878	49,624	1086	28,590	1792	21,034
2009	2940	52,514	1096	30,352	1844	22,162
2010	2964	53,944	1102	31,316	1862	22,628
2011	3014	55,614	1120	32,558	1894	23,056
2012	3050	56,646	1132	33,240	1918	23,406
2013	3102	57,276	1160	33,686	1942	23,590
2014	3112	57,970	1174	34,178	1938	23,792

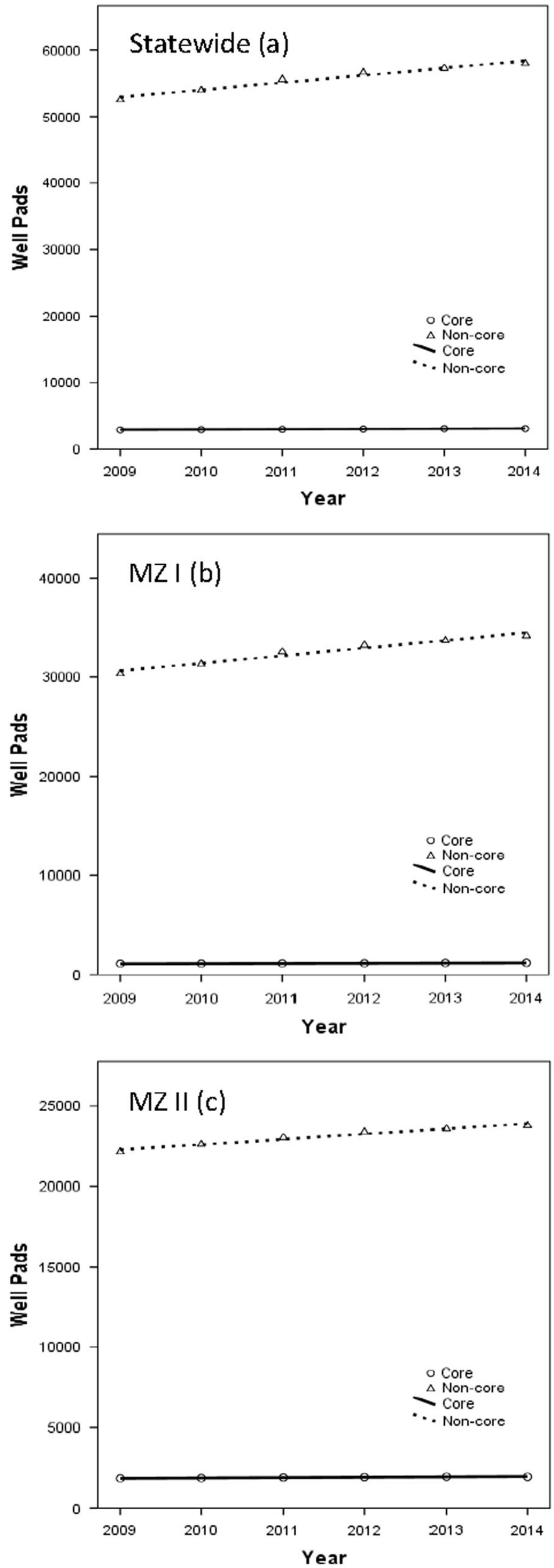


Fig. 3 Well pad comparison between core and non-core areas in Wyoming, USA, 2009–2014. Data are reported at statewide **a** and management zone (MZ I **b** and MZ II **c**) scales

SE = 75.59, $DF_{error} = 8$, $p = 0.63$) was less compared to non-core ($\hat{\beta}_1 = 1094.51$, SE = 75.59, $DF_{error} = 8$, $p < 0.01$) areas at the statewide level. Within MZ I, rate of increase of well pads differed ($F_{1,8} = 95.16$, $p < 0.01$, $r^2 = 1.00$; Fig. 3b) as Core ($\hat{\beta}_1 = 16.46$, SE = 54.56, $DF_{error} = 8$, $p = 0.77$) was less than in non-core areas ($\hat{\beta}_1 = 769.2$, SE = 54.56, $DF_{error} = 8$, $p < 0.01$). Rate of increase in active well pads differed ($F_{1,8} = 99.13$, $p < 0.01$, $r^2 = 1.00$;Fig. 3c) in MZ II as Core ($\hat{\beta}_1 = 20.97$, SE = 21.61, $DF_{error} = 8$, $p = 0.36$) was lower compared to non-core ($\hat{\beta}_1 = 325.31$, SE = 21.61, $DF_{error} = 8$, $p < 0.01$) sage-grouse population areas.

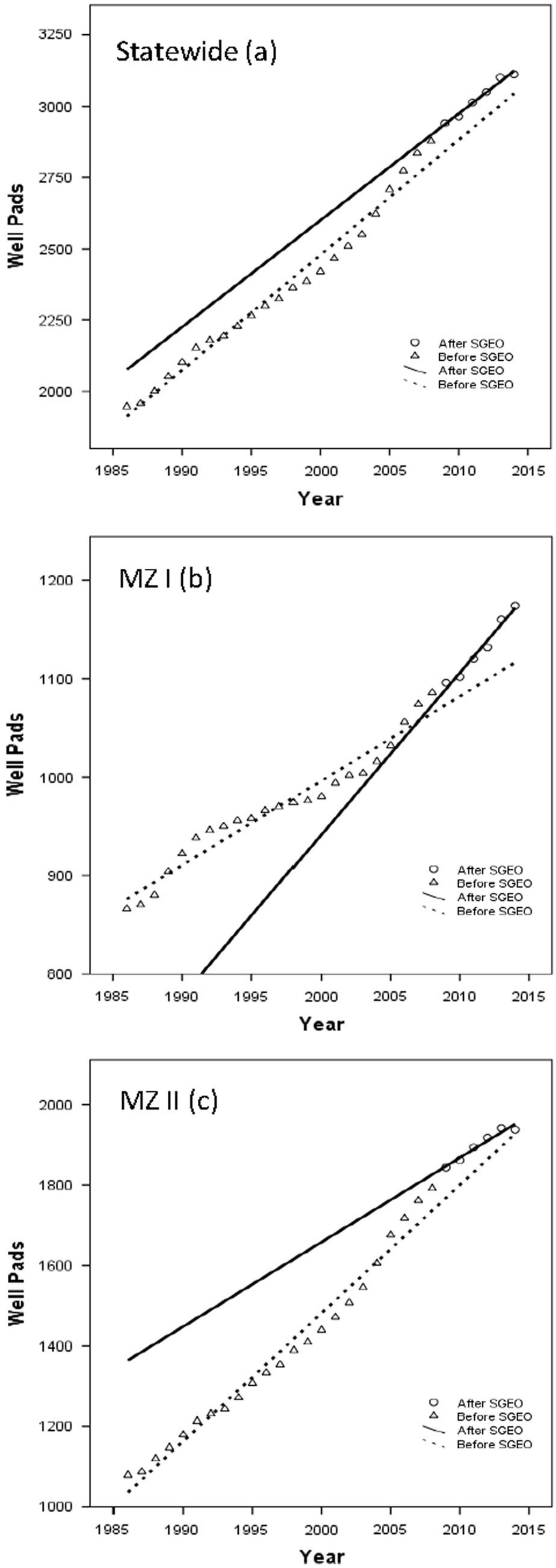
Before (1986–2008)–After (2009–2014) Impact (SGEO Policy Implementation)

Trends in the rate of increase of number of active well pads were the same ($F_{1,25} = 0.11$, $p = 0.75$, $r^2 = 1.00$) within Core Area before (1986–2008; $\hat{\beta}_1 = 40.42$, SE = 1.20, $DF_{error} = 25$, $p < 0.01$) and after (2009–2014; $\hat{\beta}_1 = 37.42$, SE = 9.13, $DF_{error} = 25$, $p < 0.01$; Fig. 4a) Core Area designation at the statewide level. In MZ I, the rate of increase in the number of active well pads differed ($F_{1,25} = 6.8$, $p < 0.02$, $r^2 = 1.00$) as the rate before ($\hat{\beta}_1 = 8.59$, SE = 0.39, $DF_{error} = 25$, $p = 0.01$) was less than after ($\hat{\beta}_1 = 16.45$, SE = 2.99, $DF_{error} = 25$, $p < 0.01$) Core Area designation (Fig. 4b). In MZ II, the rate of increase in the number of active well pads in Core Areas was similar ($F_{1,25} = 2.09$, $p = 0.16$, $r^2 = 1.00$) before ($\hat{\beta}_1 = 31.83$, SE = 0.98, $DF_{error} = 251$, $p = 0.0$) and after ($\hat{\beta}_1 = 20.97$, SE = 7.44, $DF_{error} = 25$, $p < 0.01$) Core Area designation (Fig. 4c).

Male Sage-Grouse Lek Attendance

We identified 958 active leks (674 Core Area leks and 284 non-core leks) statewide that were consistently surveyed each year from 1996 through 2014. Surveyed leks in MZ I and II included 63 and 611 in Core Areas, and 110 and 174 in non-core areas, respectively. Lek counts increased from 1996 through 2006 and decreased from 2006 through 2013 (Table 2).

Male lek attendance for Core Area grouse populations exhibited smaller CVs as compared to non-core CVs (Table 3). Specifically, both MZ II and statewide CVs were consistently lower in Core than in non-core population areas across years. For MZ I, CVs were also lower in Core than in non-core population areas except in 1998 and 2004, when they were higher in Core. In addition, CVs in MZ II Core Area were lower than CVs in MZ I Core Area in 16 out of 18 years (Table 3).



◀ **Fig. 4** Oil and gas well pad comparison between before (1986–2008) and after (2009–2014) SGEO implementation in core areas in Wyoming, USA. Data are reported at statewide **a** and management zone (MZ I **a** and MZ II **c**) scales. Extended linear trend lines (solid *black* lines) for after SGEO implementation (2009–2014) are provided for slope comparisons among landscape scales

Table 2 Peak male sage-grouse counted from annual lek counts statewide and within Western association of fish and wildlife agencies management zones I and II (MZ I and MZ II) based on 958 active leks in Wyoming, USA, with consistent lek counts, 1996–2013

Year	Peak total male sage-grouse counted					
	Statewide		MZ I		MZ II	
	Core	Non-core	Core	Non-core	Core	Non-core
Period of increase						
1996	3516	784	204	150	3312	634
1997	4103	1096	185	212	3918	884
1998	6384	1386	288	335	6096	1051
1999	9127	1861	558	288	8569	1573
2000	11,068	2475	842	658	10,226	1817
2001	9021	1976	520	497	8501	1479
2002	8062	1639	367	248	7695	1391
2003	9709	1765	555	320	9154	1445
2004	10,715	1518	508	265	10,207	1253
2005	17,686	2728	1177	503	16,509	2225
2006	20,893	2763	1364	588	19,529	2175
Period of decrease						
2006	20,893	2763	1364	588	19,529	2175
2007	18,544	2496	1137	608	17,407	1888
2008	14,613	2379	853	473	13,760	1906
2009	13,444	1993	550	367	12,894	1626
2010	10,966	1761	647	297	10,319	1464
2011	8621	1275	463	210	8158	1065
2012	7684	1299	379	204	7305	1095
2013	6526	1520	283	148	6243	1372

Note: 2006 lek attendance is reported for periods of increase and decrease because these data were used in calculations for each period

Period of Increase (1996–2006)

During the 1996–2006 population increase, average lek size (males per lek) in Core Areas was 14.9 (range: 5.2–31.0) statewide, 9.5 (range: 2.9–21.7) in MZ I, and 15.4 (range: 5.4–32.0) in MZ II (Table 4). Non-core lek averages during 1996–2006 were 6.4 (range: 2.8–9.7) statewide, 3.4 (range: 1.4–6.0) in MZ I, and 8.3 (range: 3.6–12.8) in MZ II (Table 4). Our 1996–2006 ANCOVA models considered an average of 10,259 (range: 3516–20,893) peak male sage-grouse in Core Areas and 1817 (range: 784–2763) peak males in non-core areas at the statewide scale (Table 2). Our

Table 3 Coefficients of variation for core and non-core peak male populations in Western association of fish and wildlife agencies management zones I and II (MZ I and MZ II), and statewide in Wyoming, USA, 1997–2014

Year	Coefficient of variation					
	Statewide		MZ I		MZ II	
	Core	Non-core	Core	Non-core	Core	Non-core
Period of increase						
1997	219.3	272.6	252.7	321.6	214.9	243.5
1998	202.7	242.4	263.9	259.5	197.7	225.8
1999	173.5	233.2	183.0	301.5	171.7	199.9
2000	155.2	199.4	174.0	229.2	153.6	183.7
2001	162.1	206.7	164.3	212.8	160.3	194.7
2002	157.0	258.2	185.3	242.9	153.3	227.7
2003	145.4	211.7	199.4	241.0	141.4	186.9
2004	157.8	232.8	218.4	210.0	153.3	209.8
2005	152.4	226.8	175.4	229.1	150.2	204.1
2006	143.0	222.2	178.9	218.6	140.1	205.2
Period of decrease						
2006	143.0	222.2	178.9	218.6	140.1	205.2
2007	137.9	225.6	153.6	211.3	135.9	215.4
2008	156.8	227.6	162.0	219.7	155.0	208.4
2009	149.7	235.7	179.7	207.8	145.6	214.8
2010	142.7	218.3	168.3	278.5	140.1	188.5
2011	156.2	239.2	158.8	277.0	154.1	209.3
2012	163.0	238.8	154.5	263.9	160.7	208.7
2013	163.2	227.1	161.5	326.6	159.9	185.1
2014	170.3	232.5	143.9	361.4	167.6	189.1

ANCOVA models also considered an average of 597 (range: 204–1364) peak male sage-grouse in Core Areas and 369 (range: 150–658) in non-core areas in MZ I and 9429 (range: 3312–19,529) and 1448 (range: 634–2225) males in Core and non-core areas, respectively in MZ II (Table 2).

Our test for autocorrelation confirmed sage-grouse count data were temporally correlated ($p < 0.001$) so we transformed these data using the differencing technique and utilized the transformed count data (BIRDTRANS) for analysis. Differencing sacrifices the first year of data (1996) so transformed analyses began with 1997. At the statewide scale, trends in BIRDTRANS differed ($F_{1,17} = 5.29$, $p = 0.034$, $r^2 = 0.27$) as the rate in Core ($\hat{\beta}_1 = 284.06$, SE = 146.68, $DF_{error} = 17$, $p = 0.07$) was greater than non-core ($\hat{\beta}_1 = 0.58$, SE = 146.68, $DF_{error} = 17$, $p = 0.99$) population areas during 1997–2006 (Fig. 5a). In MZ I, trends in BIRDTRANS were not different ($F_{1,17} = 0.46$, $p = 0.37$, $r^2 = 0.18$) between Core ($\hat{\beta}_1 = -0.06$, SE = 26.47, $DF_{error} = 18$, $p = 0.99$) and non-core ($\hat{\beta}_1 = 24.92$, SE = 24.47, $DF_{error} = 18$, $p = 0.36$) population areas during 1997–2006 (Fig. 5b). In MZ II, trends in BIRDTRANS differed ($F_{1,17} = 6.04$, $p = 0.03$, $r^2 = 0.30$) as the rate in Core ($\hat{\beta}_1 = 263.79$, SE = 129.68, $DF_{error} = 17$, $p = 0.06$) was greater than non-core ($\hat{\beta}_1 = -4.01$, SE = 129.68, $DF_{error} = 17$, $p = 0.98$) areas during 1997–2006 (Fig. 5c).

Table 4 Average annual peak per lek attendance of male sage-grouse obtained from annual lek counts statewide and within Western association of fish and wildlife agencies management zones I and II (MZ I and MZ II) based on 958 active leks with consistent counts in Wyoming, USA, 1996–2013

Year	Average peak male sage-grouse per lek					
	Statewide		MZ I		MZ II	
	Core	Non-core	Core	Non-core	Core	Non-core
Period of increase						
1996	5.2	2.8	3.2	1.4	5.4	3.6
1997	6.1	3.9	2.9	1.9	6.4	5.1
1998	9.5	4.9	4.6	3.1	10.0	6.0
1999	13.5	6.6	8.9	2.6	14.0	9.0
2000	16.4	8.7	13.4	6.0	16.7	10.4
2001	13.4	7.0	8.3	4.5	13.9	8.5
2002	12.0	5.8	5.8	2.3	12.6	8.0
2003	14.4	6.2	8.8	2.9	15.0	8.3
2004	15.9	5.4	8.1	2.4	16.7	7.2
2005	26.2	9.6	18.7	4.6	27.0	12.8
2006	31.0	9.7	21.7	5.4	32.0	12.5
Period of decrease						
2006	31.0	9.7	21.7	5.4	32.0	12.5
2007	27.5	8.8	18.1	5.5	28.5	10.9
2008	25.5	8.4	13.5	4.3	22.5	11.0
2009	20.0	7.0	8.7	3.3	21.1	9.3
2010	16.3	6.2	10.3	2.7	16.9	8.4
2011	12.8	4.5	7.4	1.9	13.4	6.1
2012	11.4	4.6	6.0	1.9	12.0	6.3
2013	9.7	5.4	4.5	1.4	10.2	7.9

Note: 2006 lek attendance is reported for periods of increase and decrease because these data were used in calculations for each period

Period of Decrease (2006–2013)

During the 2006–2013 population decrease, average lek size in Core Area was 19.3 (range: 9.7–31.0) statewide, 11.3 (range: 4.5–21.7) in MZ I, and 19.6 (range: 10.2–32.0) in MZ II (Table 4). Non-core lek size during 2006–2013 averaged 6.8 (range: 4.5–9.7) statewide, 3.3 (range: 1.4–5.5) in MZ I, and 9.0 (range: 6.1–12.5) in MZ II (Table 4).

Our ANCOVA models during 2006–2013 at the statewide scale considered average peak males in Core Area of 12,661 (range: 6526–20,893), and 1936 (range: 1275–2763) in non-core areas (Table 2). Peak males considered in MZ I averaged 710 (283–1363) and 362 (range: 148–608) in Core

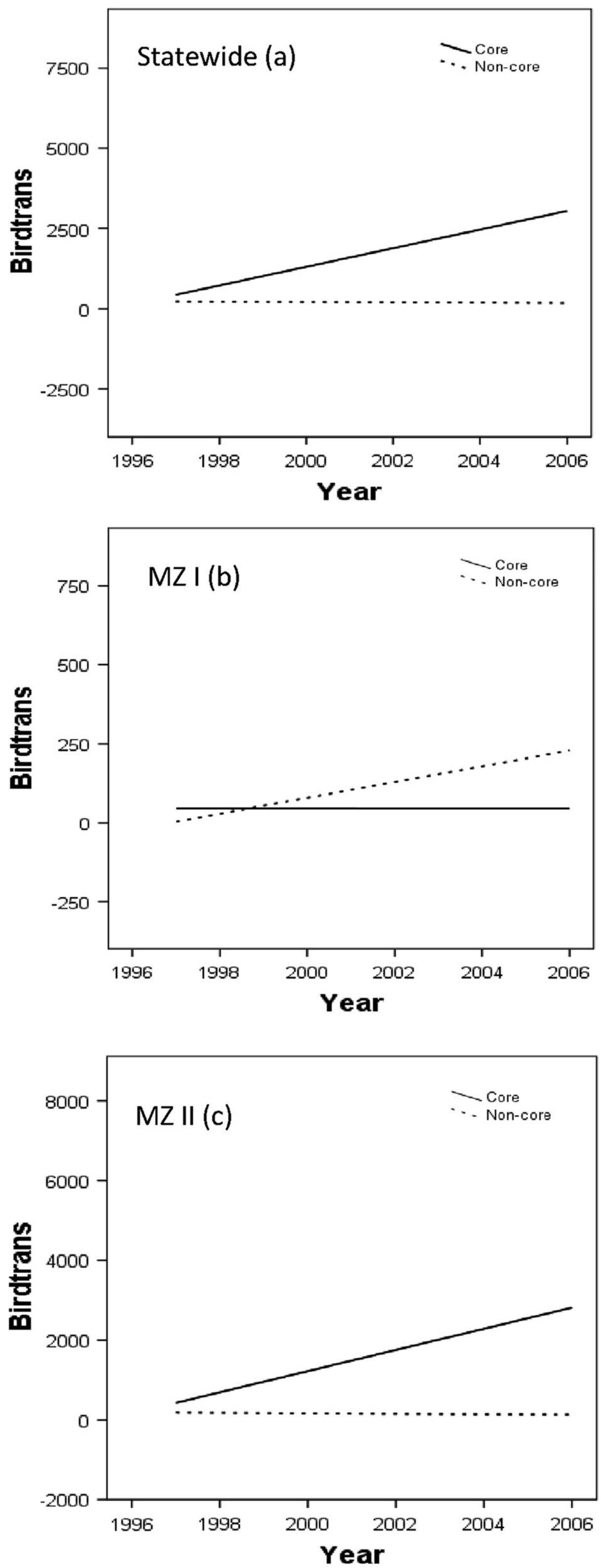


Fig. 5 Linear trend comparison of BIRDTRANS (differenced peak male sage-grouse numbers) between core and non-core areas in Wyoming, USA during period of population increase (1997–2006; *note—differencing removed the year 1996*). Data are reported at statewide **a** and management zone (MZ I **b** and MZ II **c**) scales

and non-core areas, respectively. Peak males considered in MZ II averaged 11,952 (range: 6243–19,529) and 1574 (range: 1065–2175) in Core and non-core population areas, respectively (Table 2).

Trends in BIRDTRANS were not different ($F_{1,12} = 3.42$, $p = 0.09$, $r^2 = 0.23$) between statewide Core ($\hat{\beta}_1 = -245.13$, $\mathrm{SE} = 178.64$, $\mathrm{DF}_{\mathrm{error}} = 13$, $p = 0.19$) and non-core ($\hat{\beta}_1 = -27.95$, $\mathrm{SE} = 178.64$, $\mathrm{DF}_{\mathrm{error}} = 12$, $p = 0.88$) population areas during 2006–2013 (Fig. 6a). In MZ I, trends in differenced transformed counts did not differ ($F_{1,12} = 0.02$, $p = 0.89$, $r^2 = 0.33$) between Core ($\hat{\beta}_1 = -11.15$, $\mathrm{SE} = 15.07$, $\mathrm{DF}_{\mathrm{error}} = 12$, $p = 0.62$) and non-core ($\hat{\beta}_1 = -6.74$, $\mathrm{SE} = 15.07$, $\mathrm{DF}_{\mathrm{error}} = 12$, $p = 0.77$) population areas. In MZ II, trends in BIRDTRANS were not statistically different ($F_{1,13} = 3.54$, $p = 0.08$, $r^2 = 0.24$) between Core ($\hat{\beta}_1 = -230.69$, $\mathrm{SE} = 168.43$, $\mathrm{DF}_{\mathrm{error}} = 13$, $p = 0.19$) and non-core ($\hat{\beta}_1 = 31.41$, $\mathrm{SE} = 168.43$, $\mathrm{DF}_{\mathrm{error}} = 13$, $p = 0.85$) population areas during 2006–2013 (Fig. 6c).

Policy Application

We found from 2012 through 2014, the average level of surface disturbance incurred from projects ranged from 0.7 to 18.7 % per analysis area within a Core Area (Table 5). Project densities averaged 0.0 per 2.6 km^2 (640 ac)–1.65 per 2.6 km^2. During this period, 174 projects occurred in Core Area with 126 (72.4 %) initially conforming to SGEO stipulations. The remaining 27.6 % of projects went through further review and mitigation practices including co-location on previously disturbed sites, site-specific avoidance of sage-grouse habitat, habitat restoration and reclamation projects, and creation of habitat management plans to minimize disturbance and provide consistency with the SGEO (WGFD 2014). There were 26 (15 %) instances where disturbances exceeded the 5 % threshold. These exceedances were resultant of landscapes that included existing permit rights prior to 2008 (WGFD 2014). Such existing rights are recognized in the SGEO and are not subject to thresholds, but are considered disturbance in some situations whether developed or not (State of Wyoming 2011).

Discussion

An important aspect of implementing natural resource policy is determining whether it is effective in achieving the desired outcome. In the case of Wyoming's SGEO, Core Areas as identified in the policy were intended to provide for the maintenance or increase of sage-grouse populations across the state (State of Wyoming 2008, 2011). We predicted a lesser rate of development within sage-grouse Core Area compared to non-core areas. Well pads did increase at a lesser rate statewide and in MZ's I and II post SGEO

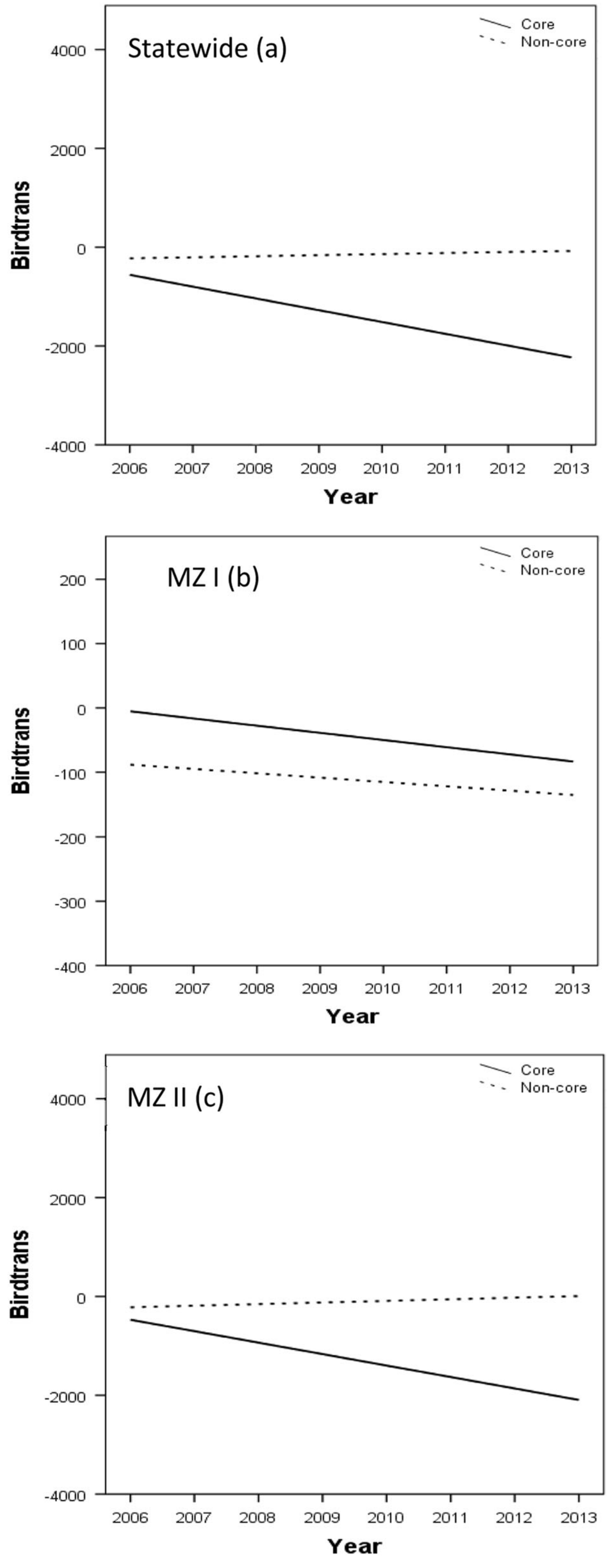


Fig. 6 Linear trend comparison of BIRDTRANS (differenced peak male sage-grouse numbers) comparison between core and non-core areas in Wyoming, USA during period of population decrease (2006–2013; *note—differencing removed the year 2005*). Data are reported at statewide **a** and management zone (MZ I **b** and MZ II **c**) scales

implementation (2009–2014) in Core Area as compared to non-core areas. This finding was not surprising as well pad development has historically been higher in non-core areas. In addition, during the mapping of Core Area, locations of existing development influenced placement of Core Area boundaries as policymakers constrained boundaries to avoid heavily developed areas and protect undeveloped areas (B. Budd, Wyoming SGIT, personal communication). Nonetheless, our analysis showed well pads in non-core area continued to increase at a higher rate than in Core Area. Although not definitive, these findings suggest the implementation of the Core Area policy pertaining to oil and gas development was being met during the timeframe we analyzed.

Our before-after SGEO policy comparisons provide further evidence of the role Core Area plays within the SGEO policy in relation to development statewide and in MZ II. In both instances, the rate of development remained the same throughout 1986–2014. Thus, the SGEO may have been influential at maintaining the slow pace of development that has historically occurred in areas now designated as Core Area. Alternatively, the slow development pace may simply be the result of continued low interest in resource development within areas mapped as Core Area. Interestingly, we did not find this in MZ I. Rather, the rate of development in Core Areas in MZ I actually was higher post SGEO implementation compared to long-term development. This trend began around the early 2000s. We suspect this trend may be at least in part due to coalbed methane gas development (Stilwell et al. 2012) and the more recent interest in oil production maintaining well pad development in the area as evidenced by an increase in WOGCC permits since a low in 2009 (Applegate and Owens 2014).

We predicted male sage-grouse lek attendance would be higher in Core Areas before and after implementation of the SGEO. We found mixed results in male lek attendance, depending on the spatial scale and timeframe. Total male sage-grouse lek attendance was greater in Core Area compared to non-core area at the statewide scale and in MZ II, but not in MZ I, during 1996–2006, when sage-grouse populations in Wyoming were notably increasing. Trends in male sage-grouse lek attendance did not differ between Core and non-core population areas statewide, in MZ I, or MZ II during 2006–2013, when sage-grouse were declining across Wyoming. However, from a biologically significant standpoint, Core Area populations in MZ II appeared to decrease at a greater rate than non-core area birds during the period of decline. This decline was likely mathematically related to loss of relatively more males from Core Areas, which had higher absolute numbers of grouse prior to the period of decline compared to non-core leks. Our findings on trends and numbers of well pads, and male lek

Table 5 Average surface disturbance and density of projects within Wyoming's 31 Sage-grouse core areas including core area size, percentage surface disturbance, and disturbance density (No./2.66 km^2), 2012–2014 (WGFD 2014)

Core area	MZ	km^2	Percentage disturbance (range)		No./2.66 km^2 (range)	
Buffalo	I	1974	4.1	(1.5–6.8)	0.2	(0.1–0.3)
Douglas	I	356	18.7	(4.1–42.9)	0.6	(0.3–0.8)
North Gillette	I	493	3.1	(2.4–3.9)	0.4	(0.1–0.7)
Newcastle	I	481	7.0	(2.5–10.2)	1.1	(0.6–1.3)
North Glenrock	I	556	11.2	(N/A)	0.8	(N/A)
North Laramie	I	890	4.3	(2.8–5. 8)	0.1	(0.0–0.1)
Thunder Basin	I	3119	4.9	(0.9–25.7)	0.2	(0.1–1.0)
Natrona	I, II	10,011	5.3	(0.5–11.9)	0.2	(0.1–1.5)
Black's Fork	II	753	n/a		n/a	
Continental Divide	II	697	1.4	(1.3–1.6)	0.3	(0.3–0.3)
Crowheart	II	1259	10.6	n/a	1.7	n/a
Daniel	II	2069	1.9	(1.7–2.2)	0.0	(0.0–0.0)
Elk Basin East	II	144	No projects		No projects	
Elk Basin West	II	41	No projects		No projects	
Fontenelle	II	608	No Projects		No projects	
Grass Creek	II	660	No projects		No projects	
Greater South Pass	II	18,587	4.6	(0.2–53.4)	0.0	(0.0–2.1)
Hanna	II	2958	5.6	(0.6–12.5)	0.1	(0.0–0.3)
Heart Mountain	II	487	No projects		No projects	
Hyattville	II	585	No projects		No projects	
Jackson	II	342	No projects		No projects	
Little Mountain	II	199	No projects		No projects	
Oregon Basin	II	2462	11.5	(3.6–26.1)	0.2	(0.0–0.5)
Sage	II	2566	1.2	(0.8–1.8)	0.0	(0.0–0.0)
Salt Wells	II	1595	No projects		No projects	
Seedskadee	II	352	4.6	(2.1–9.3)	0.4	(0.1–0.7)
Shell	II	147	No projects		No projects	
South Rawlins	II	3694	14.6	(0.4–31.4)	0.2	(0.0–1.3)
Thermopolis	II	105	No projects		No projects	
Uinta	II	950	5.5	(1.5–16.8)	0.1	(0.0–0.1)
Washakie	II	2599	0.7	(0.6–0.9)	0.1	(0.0–0.1)

attendance suggest that Core Areas in general were well delineated to capture productive sage-grouse populations in areas of less energy disturbance.

When conditions are favorable, sage-grouse populations can increase after a period of decrease (Garton et al. 2011). During the 1996 through 2006 recent peak, our data, in agreement with Fedy and Aldridge (2011), demonstrated Wyoming sage-grouse populations increased dramatically both in Core and non-core areas statewide and in MZ II. And, within these area designations, we found increases within Core Area were significantly higher than those observed in non-core area. We also found population variation was less in MZ II Core than in non-core areas indicating stability and resilience within Core Area sage-grouse populations in this management zone. Populations exhibiting higher variability may be more prone to significant decline as opposed to those with lower variability (Pimm 1991; Vucetich et al. 2000). Thus, in Core Area in MZ II, it appears that trends in sage-grouse populations here were able to remain more consistent due to slow rate of energy development likely combined with favorable habitats. Comparatively, in MZ I, while total male lek attendance also increased during population increase, increases in Core did not out pace those in non-core. Conditions within Core Area in MZ I, may not be more favorable to sage-grouse populations than those in non-core areas or certainly not to the degree found in MZ II. This result may be due a combination of factors including degree of development, habitat condition, or relative lower population levels.

Regardless of timeframe, we found no statistical differences between total male lek attendance in Core and non-core populations in MZ I. However, CVs indicated population numbers were more stable in Core Area vs. non-core in MZ I for most years (Harrison 1979). Regardless, MZ I habitats have been described as being less favorable to sage-grouse, in general, as MZ I includes the interface of sagebrush with the Great Plains (Knight et al. 2014) resulting in patchier sagebrush habitats across only 14 % of the area compared to 45 % in MZ II (Knick 2011). In addition, the region encompassed in MZ I has experienced historical land treatments aimed at reducing or removing sagebrush, further exacerbating the fragmentation of naturally occurring vegetation (BLM 2010). From a development perspective, MZ I experienced tremendous growth from natural gas development (primarily coalbed methane) during the 1990s through the early 2000s (Stilwell et al. 2012) and our well pad data reflect this. One study conducted in MZ I found that by 2005, male lek attendance within coalbed methane fields was 46 % less than at leks outside of these areas (Walker et al. 2007). Doherty et al. (2008) also found sage-grouse were 1.3 times more likely to occupy winter habitats that had not been developed for energy. They found a density of well spacing at12.3 well pads per 4 km^2 resulted in a decrease in odds of sage-grouse use by 0.30 compared to the average landscape (odds 0.57 vs. 0.87) in MZ I. In addition, lower numbers of males attending leks in MZ I compared to MZ II suggest MZ I leks have difficulty in recovering from energy development impacts, which occur immediately (1 year) after development in MZ I (Gregory and Beck 2014). Disease also likely contributed negatively to sage-grouse populations in MZ I. For example, Taylor et al. (2013) found after West Nile virus outbreaks in 2003 and 2007, lek inactivity rates in MZ I doubled. All of these factors likely contributed to Core Area performance not exceeding non-core in MZ I.

The majority of project development from 2012–2014 within Core Area fell within the 5 % surface disturbance thresholds of the SGEO. Yet, over 25 % of the projects did not initially meet all of the threshold requirements. It is our understanding the impacts associated with these remaining projects were minimized through further guidance with the WGFD and land management agencies (WGFD 2014). An unquantifiable aspect of the SGEO is the effort and practice of agencies applying the components of the SGEO across the Core Areas.

Conclusion

While difficult to ascertain the effects of the Wyoming SGEO policy so soon after implementation, it appears Core Area designations combined higher quality habitats with low paced levels of oil and gas development, which contribute to conserving sage-grouse. We suggest these areas contributed to the sustainability of sage-grouse populations at the statewide level and within MZ II enabling sage-grouse to continue to fluctuate and exhibit population cycles. However, despite implementation of the SGEO, we are concerned with the relatively poorer performance of sage-grouse populations in MZ I. Garton et al. (2011) developed a predictive model suggesting continued declines in MZ I potentially leading to extinction in 2107 if projected trends continue. Perhaps the current slowdown in natural gas development and increased use of horizontal drilling, which places multiple wells per pad (Applegate and Owens 2014), concurrently reducing numbers of well pads, combined with increased reclamation, restoration, and protection of habitats through easement (Copeland et al. 2013) may help provide conditions for birds to respond more favorably. In addition, a recent study reported nesting success in MZ I was higher in areas with fewer reservoirs and higher sagebrush cover, suggesting two critical issues to focus energy development mitigation in this management zone to benefit sage-grouse (Kirol et al. 2015b). Perhaps greater focus on future mitigation efforts will improve sage-grouse population response during periods of decline. Success may ultimately rest on whether the state of Wyoming maintains the political fortitude to keep this experiment in landscape conservation operating into the future.

Acknowledgments Our research would not have been possible without the efforts of biologists from Wyoming Game and Fish Department (WGFD), USDI-Bureau of Land Management, other agencies, and consulting firms in collecting lek attendance data we used to frame our analyses. The authors thank Tom Christiansen from WGFD for providing access to the Wyoming sage-grouse lek database. The authors especially acknowledge David Legg, University of Wyoming, for his critical assistance with statistical analyses. Matthew Kauffman, Roger Coupal, and Peter Stahl, University of Wyoming, and Joshua Millspaugh, University of Missouri-Columbia, all provided helpful insights in regard to study design and analyses. They also thank Mary Flanderka, John Emmerich, John Kennedy, and Troy Gerhardt from WGFD for their insights. Mark Rumble, U.S. Forest Service Research Ecologist, provided an outside review of an earlier draft, and Brian Brokling processed spatial data for use in analyses. The authors' research was supported by WGFD Grant Number 0020011.

Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no competing interests.

References

Aldridge CL, Boyce MS (2007) Linking occurrence and fitness to persistence: habitat-based approach for endangered greater sage-grouse. Ecol Appl 117:508–526

Applegate DH, Owens NL (2014) Oil and gas impacts on Wyoming's sage-grouse: summarizing the past and predicting the foreseeable future. Hum Wildlife Interact 8:284–290

Box GEP, Jenkins GM, Reinsel GC (1994) Time Series Analysis, Forecasting and Control, 3rd edn. Prentice Hall, Englewood Cliffs, NJ

Braun CE, Oedekoven OO, Aldridge CL (2002) Oil and gas development in western North America: effects on sagebrush steppe avifauna with particular emphasis on sage-grouse. Transactions of the North American Wildlife and Natural Resources Conference 67:337–349

Bureau of Land Management (2010) Draft Resource Management Plan and Final Environmental Impact Statement for the Buffalo Field Office Planning Area. U.S. Department of the Interior, Bureau of Land Management, Wyoming State Office, Cheyenne, WY

Bureau of Land Management (2012) Greater sage-grouse habitat management policy on Wyoming Bureau of Land Management (BLM) administered public lands including the Federal Mineral Estate. Instruction Memorandum No. WY-2012-019, Cheyenne, WY

Bureau of Land Management (2015) Record of Decision and Approved Resource Management Plan Amendments for the Rocky Mountain Region, Including the Greater Sage-Grouse Sub-Regions of Lewistown, North Dakota, Northwest Colorado, Wyoming, and the Approved Resource Management Plans for Billings, Buffalo, Cody, HiLine, Miles City, Pompeys Pillar National Monument, South Dakota, Worland. US Department of the Interior, Bureau of Land Management, Washington, DC

Carpenter J, Aldridge CL, Boyce MS (2010) Sage-grouse habitat selection during winter in Alberta. J Wildl Manage 74:1806–1814

Connelly JW, Knick ST, Schroeder MA, Stiver SJ (2004) Conservation assessment of greater sage-grouse and sagebrush habitats. Western Association of Fish and Wildlife Agencies, Cheyenne, WY

Connelly JW, Reese KP, Schroeder MA (2003) Monitoring of greater sage-grouse habitats and populations. College of Natural Resources Experiment Station Bulletin, Vol. 80, Moscow, ID

Copeland HE, Pocewicz A, Naugle DE, Griffiths T, Keinath D, Evans J, Platt J (2013) Measuring the effectiveness of conservation: a novel framework to quantify the benefits of sage-grouse conservation policy and easements in Wyoming. PLoS ONE 8(6): e67261. doi:10.1371/journal.pone.0067261

Dinkins JB, Conover MR, Kirol CP, Beck JL, Frey SN (2014a) Greater sage-grouse hen survival: effects of raptors, anthropogenic and landscape features, and hen behavior. Can J Zool 92:319–330

Dinkins JB, Conover MR, Kirol CP, Beck JL, Frey SN (2014b) Greater sage-grouse (*Centrocercus urophasianus*) select habitat based on avian predators, landscape composition, and anthropogenic features. The Condor 116:629–642

Doherty KE (2008) Sage-grouse and energy development: integrating science with conservation planning to reduce impacts. Dissertation, University of Montana, Missoula

Doherty KE, Evans JS, Coates PS, Juliusson L, Fedy BC (2015) Importance of regional variation in conservation planning and defining thresholds for a declining species: A range-wide example of the Greater Sage-grouse. USGS, Technical Report, p 51

Doherty KE, Naugle DE, Copeland HE, Pocewicz A, Kiesecker JM (2011) Energy development and conservation trade-offs: systematic planning for greater sage-grouse in their eastern range. In: Knick ST, Connelly JW (eds) Greater sage-grouse: ecology and conservation of a landscape species and its habitats. Studies in Avian Biology 38, University of California Press, Berkeley, CA, pp 505–516

Doherty KE, Naugle DE, Walker BL, Graham JM (2008) Greater sage-grouse winter habitat selection and energy development. J Wildl Manage 72:187–195

Doherty KE, Tack JD, Evans JS, Naugle DE (2010) Breeding densities of greater sage grouse: a tool for range wide conservation. BLM Completion Report: Interagency Agreement No. L10PG00911, p 30

Dzialak MR, Olson CV, Harju SM, Webb SL, Mudd JP, Winstead JB, Hayden-Wing LD (2011) Identifying and prioritizing greater sage-grouse nesting and brood-rearing habitat for conservation in human-modified landscapes. PLoS ONE 6:e26273

Dzialak MR, Webb SL, Harju SM, Olson CV, Winstead JB, Hayden-Wing LD (2013) Greater sage-grouse and severe winter conditions: Identifying habitat for conservation. Rangeland Ecol and Manage 66:10–18

Fedy BC, Aldridge CL (2011) The importance of within-year repeated counts and the influence of scale on long-term monitoring of sage-grouse. J Wildl Manage 75:1022–1033

Fedy BC, Doherty KE (2011) Population cycles are highly correlated over long time series and large spatial scales in two unrelated species: greater sage-grouse and cottontail rabbits. Oecologia 165:915–924

Fedy BC, Doherty KE, Aldridge CL, O'Donnell M, Beck JL, Bedrosian B, Holloran MJ, Johnson GD, Kaczor NW, Kirol CP, Mandich CA, Marshall D, McKee G, Olson C, Pratt AC, Swanson CC, Walker BL (2014) Habitat prioritization across large landscapes, multiple seasons, and novel areas: an example using greater sage-grouse in Wyoming. Wildl Monographs 190:1–39

Gamo RS (2016) Effectiveness of Wyoming's sage-grouse core areas in conserving greater sage-grouse and mule deer and influence of energy development on big game harvest. Dissertation, University of Wyoming, Laramie, WY

Garton EO, Connelly JW, Horne JS, Hagen CA, Moser A, Schroeder MA (2011) Greater sage-grouse population dynamics and probability of persistence. In: Knick ST, Connelly JW (eds) Greater Sage-Grouse: ecology and conservation of a landscape species and its habitats. Studies in Avian Biology 38, University of California Press, Berkeley, CA, pp 293–382

Garton EO, Wells AG, Baumgardt JA, Connelly JW (2015) Greater sage-grouse population dynamics and probability of persistence. Final Report to The Pew Charitable Trusts, Washington, DC

Gregory AJ, Beck JL (2014) Spatial heterogeneity in response of male greater sage-grouse lek attendance to energy development. PLoS ONE 9(6):e97132

Harju SM, Dzialak MR, Taylor RC, Hayden-Wing LD, Winstead JB (2010) Thresholds and time lags in effects of energy development on greater sage-grouse populations. J Wildl Manage 74:437–448

Harrison GW (1979) Stability under environmental-stress—resistance, resilience, persistence, and variability. Am Nat 113:659–669

Hess JE, Beck JL (2012) Disturbance factors influencing greater sage-grouse lek abandonment in north-central, Wyoming. J Wildl Manage 76:1625–1634

Holloran MJ (2005) Greater sage-grouse (*Centrocercus urophasianus*) population response to natural gas field development in western Wyoming. Dissertation, University of Wyoming, Laramie, WY

Holloran, MJ, SH Anderson SH (2005) Greater sage-grouse population response to natural gas development in western Wyoming: are regional populations affected by relatively localized disturbances. Trans North American Wildl and Nat Res Conf 70:160–170

Holloran MJ, Fedy BC, Dahlke J (2015) Winter habitat use of greater sage-grouse relative to activity levels at natural gas well pads. J Wildl Manage 79:630–640

Holloran MJ, Kaiser RC, Hubert WA (2010) Yearling greater sage grouse response to energy development in Wyoming. J Wildl Manage 74:65–72

Kirol CP, Beck JL, Huzurbazar SV, Holloran MJ, Miller SN (2015a) Identifying greater sage-grouse source and sink habitats for conservation planning in an energy development landscape. Ecol Apps 25:968–990

Kirol CP, Sutphin AL, Bond L, Fuller MR, Maechtle TL (2015b) Mitigation effectiveness for improving nesting success of greater sage-grouse influenced by energy development. Wildl Biol 21:98–109

Knick ST (2011) Historical development, principal federal legislation, and current management of sagebrush habitats. In: Knick ST, Connelly JW (eds) Greater Sage-Grouse: ecology and conservation of a landscape species and its habitats. Studies in Avian Biology 38, University of California Press, Berkeley, CA, pp 13–31

Knight DH, Jones GP, Reiners WA, Romme WH (2014) Mountains and plains: the ecology of Wyoming landscapes, 2nd edn. Yale University Press, New Haven, CT

LeBeau CW, Beck JL, Johnson GD, Holloran MJ (2014) Short-term impacts of wind energy development on greater sage-grouse fitness. J Wildl Manage 78:522–530

Lyon AG, Anderson SH (2003) Potential gas development impacts on sage grouse nest initiation and movement. Wildl Soc Bull 31:486–491

Nielson RM, McDonald LL, Mitchell J, Howlin S, LeBeau C (2015) Analysis of greater sage-grouse lek data: Trends in peak male counts 1965-2015. West. EcoSys. Tech., Inc., Cheyenne, WY

Oregon Department of Fish and Wildlife (2011) Greater sage-grouse conservation assessment and strategy for Oregon: a plan to maintain and enhance populations and habitat, p 221

Pimm SL (1991) The balance of nature. University of Chicago Press, Chicago, IL

Rowland MM, Leu M (2011) Study area description. In: Hanser SE, Leu M, Knick ST, Aldridge CL (eds) Sagebrush ecosystem conservation and management: Ecoregional assessment tools and models for the Wyoming Basins. Allen Press, Lawrence, KS, pp 10–45

Schroeder MA, Aldridge CL, Apa AD, Bohne JR, Braun CE, Bunnell SD, Connelly JW, Deibert PA, Gardner SC, Hilliard MA, Kobriger GD, McAdam SM, McCarthey CW, McCarthy JJ, Mitchell DL, Rickerson EV, Stiver SJ (2004) Distribution of sage-grouse in North America. Condor 106:363–376

Smith KT, Beck JL, Pratt AC (2016) Does Wyoming's core area policy protect winter habitats for greater sage-grouse? Environ Manage 58:585–596

Smith KT, Kirol CP, Beck JL, Blomquist FC (2014) Prioritizing winter habitat quality for greater sage-grouse in a landscape influenced by energy development. Ecosphere 5:15

State of Idaho (2012a) Governor C. L. Butch Otter. Establishing the Governor's sage-grouse task force. Executive Order 2012–02

State of Idaho (2012b) Federal alternative of Governor C. L. Butch Otter for greater sage-grouse management in Idaho, p 54

State of Montana (2014) Office of Steve Bullock. State of Montana Executive Order No. 10-2014. Executive Order Creating the Sage Grouse Oversight Team and the Montana Sage Grouse Habitat Conservation Plan, p 29

State of Nevada (2014) Nevada greater sage-grouse conservation plan. Sagebrush Ecosystem Program, Carson City, NV, p 214

State of Wyoming (2008) Office of Governor Freudenthal. State of Wyoming Executive Department Executive Order. Greater Sage Grouse Area Protection, 2008–02

State of Wyoming (2011) Office of Governor Mead. State of Wyoming Executive Department Executive Order. Greater Sage Grouse Area Protection, 2011–05

Stilwell DP, Elser AM, Crockett FJ (2012) Reasonable Foreseeable Development Scenario for Oil and Gas Buffalo Field Office Planning Area, Wyoming. U.S. Department of the Interior, Bureau of Land Management, Buffalo, WY

Stiver SJ, Apa AD, Bohne JR, Bunnell SD, Deibert PA, Gardner SC, Hilliard MA, McCarthy CW, Schroeder MA (2006) Greater sage-grouse: comprehensive conservation strategy. Western Association of Fish and Wildlife Agencies, Cheyenne, WY, USA

Stiver SJ (2011) The legal status of greater sage-grouse: organizational structure of planning efforts. In: Knick ST, Connelly JW (eds) Greater Sage-Grouse: ecology and conservation of a landscape species and its habitats. Studies in Avian Biology 38, University of California Press, Berkeley, CA, pp 33–52

Taylor RL, Tack JD, Naugle DE, Mills LS (2013) Combined effects of energy development and disease on greater sage-grouse. PLoS ONE 8(8):e71256

Thilenius JF, Brown GR, Medina AL (1994) Vegetation on semi-arid rangelands, Cheyenne River Basin, Wyoming. General Technical Report RM-GTR-263. Fort Collins, CO. U. S. Dept. of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station, p 60

U. S. Fish and Wildlife Service [USFWS] (2010) Endangered and Threatened Wildlife and Plants; 12-month findings for petitions to list the greater sage-grouse (*Centrocercus urophasianus*) as threatened or endangered. Fed Reg 75:13909–14014

U.S. Fish and Wildlife Service [USFWS] (2015) Endangered and Threatened Wildlife and Plants; 12-Month Finding on a Petition to list Greater Sage-Grouse (*Centrocercus urophasianus*) as an Endangered or Threatened Species; Proposed Rule. Fed Reg 80:59858–59942

Vucetich JA, Waite TA, Qvarnemark L, Ibarguen S (2000) Population variability and extinction risk. Cons Biol 14:1704–1714

Walker BL, Naugle DE, Doherty KE (2007) Greater sage-grouse population response to energy development and habitat loss. J Wildl Manage 71:2644–2654

Weisberg S (1985) Applied linear regression. John Wiley and Sons, New York and Chichester, UK

Wisdom MJ, Meinke CW, Knick ST, Schroeder MA (2011) Factors associated with extirpation of sage-grouse. In: Knick ST, Connelly JW (eds) Greater Sage-Grouse: ecology and conservation of a landscape species and its habitats. Studies in Avian Biology 38, University of California Press, Berkeley, CA, pp 451–474

Wyoming Game and Fish [WGFD] (2014) US Fish and Wildlife Service Greater Sage-Grouse (*Centrocercus urophasianus*) 2014 Data Call. Wyoming Game and Fish Department October 31, p 258

Wyoming Oil and Gas Conservation Commission (2014) WOGCC homepage. http://www.wogcc.wyo.gov/ Accessed Dec 2014