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Author to receive correspondence:

David E. Naugle
Wildlife Biology Program
University of Montana
32 Campus Drive
Missoula, Montana 59812
Phone 406-243-5364
fax 406-243-4557
david.naugle@umontana.edu

Carl D. Marti, Editor
Studies in Avian Biology
1310 E Jefferson St.
Boise, ID 83712 USA
Tel: 208-426-8996
Email: sab@boisestate.edu

ENERGY DEVELOPMENT AND GREATER SAGE-GROUSE

DAVID E. NAUGLE, KEVIN E. DOHERTY, BRETT L. WALKER, MATTHEW J. HOLLORAN, AND HOLLY E. COPELAND

Abstract Rapidly expanding energy development in western North America poses a major new challenge for conservation of Greater Sage-Grouse (*Centrocercus urophasianus*). We reviewed the scientific literature documenting biological responses of sage-grouse to development, quantified changes in landscape features detrimental to sage-grouse that result from development, examined the potential for landscape-level expansion of energy development within sage-grouse range, and outlined recommended landscape-scale conservation strategies. Shrublands developed for energy production contained twice as many roads and power lines, and where ranching, energy development, and tillage agriculture coincided, human features were so dense that every 1 km^2 could be bounded by a road and bisected by a power line. Sage-grouse respond negatively to three different types of development and conventional densities of oil and gas wells far exceed the species' threshold of tolerance. These patterns were consistent among studies regardless of whether they examined lek dynamics or demographic rates of specific cohorts within populations. Severity of current and projected impacts indicates the need to shift from local to landscape conservation. The immediate need is for planning tools that overlay the best remaining areas for sage-grouse with the extent of current and anticipated development. This will allow stakeholders to consider a hierarchy of set-aside areas, lease consolidations, and more effective best-management practices as creative solutions to reduce losses. Multiple stressors including energy development must be managed collectively to maintain sage-grouse populations over time in priority landscapes.

Key Words: *Centrocercus urophasianus*, conservation planning, cumulative impacts, energy development, landscapes, natural gas, oil, sagebrush, sage-grouse, wells.

DESARROLLO ENERGÉTICO Y EL GREATER SAGE-GROUSE

Resumen. Desarrollo energético en rápida expansión en el oeste de Norte America, presenta un nuevo desafío importante para la conservación del Greater Sage-Grouse (*Centrocercus urophasianus*). Revisamos la literatura científica que documenta la respuestas biológica del Greater Sage-Grouse (*Centrocercus urophasianus*) al desarrollo, cuantificamos los cambios en los caracteres del territorio del Greater Sage-Grouse (*Centrocercus urophasianus*)que le son detrimentes, examinamos el potencial de expansión, a nivel de territorio, del desarrollo energético dentro de las extensiones que ocupa el Greater Sage-Grouse (*Centrocercus urophasianus*), y reseñamos las estrategias recomendadas para la conservación del territorio. Los territorios con arbustos desarrollados para la producción de energía contenían el doble de carreteras y líneas de energía, y donde coincidían el desarrollo de ranchos, el desarrollo de energético, y la agricultura tillage, las características humanas eran tan densos que cada 1 km cuadrado puede estar unido por una carretera y ser atravesado por una línea de energía. El Greater Sage-Grouse (*Centrocercus urophasianus*) responde negativamente a tres tipos diferentes de desarrollo y las densidades convencionales de pozos de petróleo y de gas excedían ampliamente los umbrales de tolerancia de la especie. Estas pautas fueron consistentes entre los estudios, independientemente de si examinaron la dinámica del lek o las tasas demográficas de los cohortes específicos al interior de las poblaciones. La severidad de los impactos actual y proyectado indican la necesidad de cambiar de la conservación local a la de territorios. La necesidad inmediata es de herramientas de planeación que cubran las mejores áreas que queden para el Greater Sage-Grouse (*Centrocercus urophasianus*), con el alcance para el desarrollo actual y el esperado. Esto permitirá a las partes interesadas considerer una jerarquía de areas reservadas, consolidación de arrendamientos, y buenas practicas de manejo más efectivas como soluciones creativas que ayude a reducer las pérdidas. Múltiples estresantes, incluyendo el desarrollo energetico, deben ser manejados colectivamente para mantener las poblaciones de Greater Sage Grouse en landscapes con prioridad a lo largo del tiempo.

World demand for energy increased by >50% in the last half-century, and a similar increase is projected between now and 2030 (National Petroleum Council 2007). Fossil fuels will likely remain the largest source of energy worldwide, with oil, natural gas and coal accounting for 83–87% of total world demand. A primary focus of the 2005 amendments to the National Energy Policy and Conservation Act in the US is to expedite the leasing and permitting process on public lands to increase domestic production of fossil fuels (American Gas Association 2005). Of 122,496 federal applications to drill in 13 western states from 1929–2004, 95.7% were authorized, 3.0% were pending, 1.2% were withdrawn and <0.1% were rejected (Connelly et al. 2004, Table 7.18). Projected growth in US energy demand is 0.5–1.3% annually (National Petroleum Council 2007), and trends suggest development of domestic fossil fuel reserves will expand through the first half of the 21st century.

The Greater Sage-Grouse (*Centrocercus urophasianus*; hereafter sage-grouse) is a galliform endemic to western semiarid sagebrush (*Artemisia* spp.) habitats in North America (Schroeder et al. 1999). Previously widespread, loss and degradation of sagebrush habitat have resulted in extirpation of the species from almost half of its original range (Schroeder et al. 2004). Energy development has emerged as a major issue in conservation because areas currently under development contain some of the highest densities of sage-grouse (Connelly et al. 2004) and other sagebrush obligate species in western North America (Knick et al. 2003). An understanding of the biological response of sage-grouse to energy development will inform decision-makers as to whether current lease stipulations are adequate or if landscape conservation is required to maintain populations.

Early studies evaluating potential impacts to sage-grouse are few (Braun 1986, 1987, 1998; Remington and Braun 1991), but interest in research has followed the pace and extent of energy development (Fig. 1). The science is evolving from small-scale (Rost and Bailey 1979, Van Dyke and Klein 1996) reactive studies into broad-scale and comprehensive evaluations of cumulative impacts (Johnson et al. 2005, Sorensen et al. 2008) that use before-after-control-impact designs (Underwood 1997) and viability models capable of quantifying population-level impacts (Haight et al. 2002, Carroll et al. 2003). Past major reviews purport (Schroeder et al. 1999, Connelly et al. 2000, Crawford et al. 2004) and recent studies reaffirm (Holloran and Anderson 2005, Walker et al. 2007a, Doherty et al. 2008) that sage-grouse are landscape specialists that require large and intact sagebrush habitats to maintain populations. Recent studies also show that both direct and indirect impacts can result from synergistic effects of energy development.

Direct impacts result when animals avoid human infrastructure (Sawyer et al. 2006, Doherty et al. 2008) or when development negatively affects survival (Holloran 2005) or reproduction (Aldridge and Boyce 2007). Indirect impacts include changes in habitat quality (Bergquist et al. 2007), predator communities (Hebblewhite et al. 2005), or disease dynamics (Daszak et al. 2000) and can be equally deleterious if cascading effects negatively influence sensitive species.

The potential for energy development to impact sagebrush-obligate species is high (Holloran 2005, Sawyer et al. 2006, Walker et al. 2007a) because the five geologic basins that contain most of the onshore oil and gas reserves in the Intermountain West are within the sagebrush ecosystem (Connelly et al. 2004). Loss and degradation of native sagebrush habitats have already imperiled much of this ecosystem and its associated wildlife (Knick et al. 2003, Connelly et al. 2004, Wisdom et al. 2005). Conservation of public lands is vital because 70% of remaining sagebrush habitat is publicly owned, but almost none of it is protected within a federal reserve system (Knick et al. 2003). Federal policy largely dictates the fate of imperiled species because the Bureau of Land Management (BLM) is both the primary steward of public shrubland and the lead agency responsible for administering the federal mineral estate. Scientific studies that evaluate potential impacts, test sufficiency of mitigation measures, and provide solutions in conservation planning help decision-makers formulate policy that enables the BLM to carry out its multiple use mandate through the Federal Land Policy and Management Act of 1976 (United States Department of the Interior, Bureau of Land Management, and Office of the Solicitor 2001).

Our goal is to synthesize the biological response of sage-grouse to energy development and evaluate whether mitigation at the local scale can sustain populations as cumulative impacts from energy development increase at the landscape scale. We address this question by using coal-bed natural gas development in the Powder River Basin in northeast Wyoming as a case study to quantify changes in landscape features detrimental to sage-grouse that result from energy development. We also provide a critical review of the scientific literature to synthesize the biological response of sage-grouse to energy development. Further, we depict the current extent of development and leasing of the federal mineral estate within the eastern range of the species. Finally, we recommend a paradigm shift from local to landscape conservation and discuss the implications of this change.

ENERGY DEVELOPMENT AND LAND-USE CHANGE

Energy development and its infrastructure may negatively affect sage-grouse populations via several different mechanisms. Mechanisms responsible for cumulative impacts that lead to population declines depend in part on the magnitude and extent of human disturbance. We quantified changes in landscape features detrimental to sage-grouse that result from energy development. Males and females may abandon leks if repeatedly disturbed by raptors perching on power lines near leks (Ellis 1984), by vehicle traffic on nearby roads (Lyon and Anderson 2003), or by noise and human activity associated with energy development (Braun et al. 2002, Holloran 2005, Kaiser 2006). Collisions with power lines and vehicles, and increased predation by raptors may also increase mortality of birds at leks (Connelly et al. 2000, Lammers and Collopy 2007). Roads and power lines may also indirectly affect lek persistence by altering productivity of local populations or survival at other times of the year. Sage-grouse mortality associated with power lines and roads occurs year-round (Aldridge and Boyce 2007), and man-made ponds created by development (Zou et al. 2006) that support breeding mosquitoes known to vector West Nile virus (Walker et al. 2007b) elevate risk of mortality from disease in late summer (Walker and Naugle, *this volume*). Sage-grouse may also avoid otherwise suitable habitat as development increases (Lyon and Anderson 2003, Holloran 2005, Kaiser 2006, Doherty et al. 2008).

METHODS

We quantified changes that accompany ranching, energy development, and tillage agriculture in the Powder River Basin in northeast Wyoming and southeast Montana, a landscape where intensive energy development and irrigated agriculture are intermixed with sagebrush-dominated ranch lands. The traditional land use is cattle and sheep ranching, but tillage agriculture is prevalent with most fields planted to alfalfa. Coal-bed natural gas is the new land use relative to energy development in the Powder River Basin, the largest coal producing basin in the US and one of the largest natural gas fields in North America. Energy development covers much of the basin in northeast Wyoming (Fig. 2) with ~35,000 gas wells drilled since 1997 and 68,000 authorized on public lands. Each additional group of 2–10 wells increases the number of new roads, power lines, man-made ponds, pipelines and compressor stations.

We quantified the cumulative change in human disturbance by classifying land cover using SPOT-5 satellite imagery acquired in 2003 for a 9,081-km^2 area of the Powder River Basin north of Sheridan, Wyoming, near Decker, Montana. Vegetation was predominately Wyoming big sagebrush (*A. tridentata wyomingensis*) intermixed with native bluebunch (*Pseudoroegneria spicata*), western wheatgrass (*Agropyron smithii*), and blue grama (*Bouteloua gracilis*). Rocky mountain juniper (*Juniperus scopulorum*) and ponderosa pine (*Pinus ponderosa*) occurred along slopes and at higher elevations. We used SPOT-5 imagery to classify five cover types as sagebrush, conifer, grassland, riparian, and bare ground. We combined the SPOT-5 panchromatic and multi-spectral images into a single panchromatic, multi-spectral file. We then used the panchromatic 25-m^2-pixel image to perform pan-sharpening to reduce the multi-spectral image pixel size from 100 m^2 to 25 m^2, greatly increasing the resolution of our analysis. Classification accuracy was 83% for sagebrush, 77% for conifer, 76% for grassland, 70% for riparian, and 80% for barren with an overall accuracy of 78% (Doherty et al. 2008).

We overlaid a grid of 9-km^2 cells onto classified land cover and randomly selected 20 cells of each of four land use types: (1) ranch lands, (2) ranch lands with energy development, (3) ranch lands with tillage agriculture, and (4) ranch lands with energy development and tillage agriculture. Cells with >10% of area in crop land defined land use types with tillage agriculture. Cells with ≥4 wells defined land-use types with energy development. We obtained locations of coal-bed natural gas wells from the Montana Board of Oil and Gas Conservation, and Wyoming Oil and Gas Conservation Commission. The three companies that supply electricity to this region provided spatially referenced locations of power lines. Analysts in the Spatial Analysis Laboratory at the University of Montana manually digitized roads and boundaries of tillage agriculture using SPOT-5 imagery and 1-m digital ortho-photography. We also used SPOT-5 imagery to quantify the number of ponds in each 9-km^2 cell. Some ponds were stock water for cattle but most were retention ponds to hold ground water pumped to the surface as part of the energy extraction process. We estimated average density (linear km or number/km^2; ± SE) of each human feature in each of four land use types. We buffered collectively around all human features to estimate the area (%) of the landscape within 50, 100, and 200 m of a road, power line, pond, or tillage agriculture in each of four land use types.

ANALYSIS

Ranching was the most environmentally benign land use that accumulated fewer human features than landscapes that also contained tillage agriculture, energy development, or both (Fig. 3,Table 1; Holechek 2007). A moderate addition of tillage agriculture into ranch lands (5–10% of area tilled in 9-km^2 cells) removed sagebrush habitat and increased densities of roads (33%), power lines (59%), and water sources (167%; Table 1). Ranch lands with tillage agriculture had fewer human features than those with energy development (Table 1), but the area of the landscape juxtaposed to disturbance was similar in both (~70% within 200 m; Fig. 3) because tilled fields resulted in more direct habitat conversion. Ranch lands with energy development contained twice the density of roads (1.57 vs. 3.13 km/km^2) and power lines (0.27 vs. 0.58 km/km^2) and five times as many ponds (0.12 vs. 0.62 per km^2) as those where ranching was the primary land use. Human features had the highest density where ranching, tillage agriculture, and energy development coincided (Table 1). At this intensity of land use, 70% of the landscape was within 100 m and 85% was within 200 m of a human feature (Fig. 3), and densities were sufficiently high that every 1 km^2 of land could be bounded by a road (4.10 km/km^2) and bisected by a power line (0.86 km/km^2).

Quantitative analyses provide the baseline for describing the magnitude and extent of change that accompanies energy development. Impacts of energy development have been documented for a few species in sagebrush ecosystems including mule deer (*Odocoileus hemionus*) that avoided otherwise suitable habitats within 2.7–3.7 km of gas wells (Sawyer et al. 2006), Brewer's Sparrow (*Spizella breweri*), and Sage Sparrow (*Amphispiza belli*) for which breeding densities declined 36–57% within 100-m of roads in gas fields (Ingelfinger and Anderson 2004). Until energy-specific research is available for more species, the magnitude and extent of change can be used in land-use planning to anticipate thresholds of disturbance that trigger biological responses in species such as elk (*Cervus elaphus*) that either alter their habitat use (Hurley and Sargeant 1991), avoid roads altogether (Lyon 1979, Frair et al. 2007, Sawyer et al. 2007), or are affected by increased rates of poaching or legal harvest (Leptich and Zager 1991, Unsworth and Kuck 1991). Most new research on this topic has focused on sage-grouse in particular and we further evaluate the importance of cumulative impacts by synthesizing the biological response of sage-grouse to energy development.

BIOLOGICAL RESPONSE OF SAGE-GROUSE TO ENERGY DEVELOPMENT

METHODS

We conducted a literature review (Pullin and Stewart 2006) for studies that investigated relationships between sage-grouse and energy development by searching from 1980 to present in the data bases of ISI Web of Science, Google Scholar, Agricola, Biological Abstracts, CAB Abstracts, CSA Biological Sciences, Wildlife and Ecology Studies Worldwide, Dissertation Abstracts, and Zoological Record. We searched data bases using combinations of keywords: sage-grouse, sage grouse, *Centrocercus* *urophasianus,* sagebrush, habitat, land use change, resource selection function, energy development, oil development, gas development, coal-bed natural gas development, four seasons in the life cycle of a sage-grouse (breeding, brood-rearing, fall, and winter), six states, Montana, North and South Dakota, Wyoming, Colorado, and Utah, and two Canadian provinces, Alberta and Saskatchewan. Annotation for each citation used in the synthesis indicates the study length and location, rigor of peer-review, scientific outlet, general research design, presence of pretreatment or control data and sample size (Table 2). We provide context by describing each of the three oil or gas fields studied, status of their associated sage-grouse populations (Table 3), and by summarizing how leasing of the federal mineral estate works (Appendix 1).

ANALYSIS

The search yielded 32 documents for screening from which we identified seven scientific investigations that form the foundation for this review (Table 2). Four investigations are published in peer-reviewed journals and three are available as a dissertation, thesis, or an agency report from the US Geological Survey (Table 2). Nine additional documents excluded from further review include either cautionary statements regarding the potential for impacts (Braun 1987, Remington and Braun 1991, Braun 1998, Connelly et al. 2000, Crompton and Mitchell 2005, Hanson and Wright 2006) or anecdotal evidence of lek abandonment following development (Braun 1986, Braun et al. 2002, Aldridge and Brigham 2003). The remaining 18 documents were mostly state and federal management plans that discuss sage-grouse and energy development but included no new or additional research.

Seven studies (Table 2) reported negative impacts of energy development on sage-grouse. No study reported any positive influence of development on populations or habitats. Findings suggested that development in excess of one pad/2.6 km^2 resulted in impacts to breeding populations (Holloran 2005) and impacts at conventional well densities—eight pads/2.6 km^2—exceeded the species' threshold of tolerance (Holloran 2005, Walker et al. 2007a, Doherty et al. 2008). Negative impacts are known for three different sage-grouse populations in three different types of development (Table 3) including shallow coal-bed natural gas in the Powder River Basin of northeast Wyoming and extreme southeast Montana (Walker et al. 2007a, Doherty et al. 2008), deep gas in the Pinedale Anticline Project Area in southwest Wyoming (Lyon and Anderson 2003, Holloran 2005, Kaiser 2006, Holloran et al. 2007), and oil extraction in the Manyberries Oil Field in southeast Alberta (Aldridge and Boyce 2007). Population trends in the Powder River Basin indicated that from 2001–2005, lek-count indices inside gas fields declined by 82%, whereas indices outside development declined by 12% (Fig. 4). By 2004–2005, 38% of leks inside gas fields remained active whereas 84% of leks outside of development remained active (Walker et al. 2007a). Male lek attendance in the Pinedale Anticline decreased with distance to the nearest active drilling rig (Fig. 5), producing gas well, and main haul road, and declines were most severe (40–100%) at breeding sites within 5 km of an active drilling rig or within 3 km of a producing gas well or main haul road (Holloran 2005). In an endangered population in Alberta, Canada, where low chick survival (12% to 56 days) limits population growth, risk of chick mortality in the Manyberries Oil Field was 1.5 times higher for each additional well site visible within 1 km of a brood location (Aldridge and Boyce 2007).

Studies also have quantified the distance from leks at which impacts of development become negligible and have assessed the efficacy of the current BLM stipulation of no surface infrastructure within 0.4 km of a lek (United States Department of the Interior 1992, 1994, 2004). Impacts to leks from energy development were most severe near the lek, remained discernable out to distances >6 km (Holloran 2005, Walker et al. 2007a), and have resulted in the extirpation of leks within gas fields (Holloran 2005, Walker et al. 2007a). Curvilinear relationships in Holloran (2005) showed that lek counts decreased with distance to the nearest active drilling rig, producing well, or main haul road, and that development influenced counts of displaying males to a distance of between 4.7 and 6.2 km (Fig. 5). All well-supported models in Walker et al. (2007a) indicated a strong negative effect of energy development, estimated as proportion of development within either 0.8 km or 3.2 km, on lek persistence. Models with development at 6.4 km had considerably less support (5–7 ΔAIC_c units lower), but the regression coefficient ($\beta = -5.11$, SE = 2.04) indicated that negative impacts were still apparent out to 6.4 km. Walker et al. (2007a) used the resulting model to demonstrate the 0.4-km lease stipulation (Table 3) was insufficient to conserve breeding sage-grouse populations in fully developed gas fields because this buffer distance leaves 98% of the landscape within 3.2 km open to full-scale development. Full-field development of 98% of the landscape within 3.2 km of leks in a typical landscape in the Powder River Basin reduced the average probability of lek persistence from 87% to 5% (Walker et al. 2007a).

Negative responses of sage-grouse to energy development were consistent among studies regardless of whether they examined lek dynamics or demographic rates of specific cohorts within populations. Recent research demonstrated that sage-grouse populations declined when birds behaviorally avoid infrastructure in one or more seasons (Doherty et al. 2008), when cumulative impacts of development negatively affect reproduction or survival (Aldridge and Boyce 2007) or both (Lyon and Anderson 2003, Holloran 2005, Kaiser 2006, Holloran et al. 2007). Avoidance of energy development reduces the distribution of sage-grouse and may result in population declines if density-dependence, competition or displacement into poor-quality habitats lowers survival or reproduction among displaced birds (Holloran and Anderson 2005, Aldridge and Boyce 2007). Sage-grouse in the Powder River Basin were 1.3 times less likely to use otherwise suitable winter habitats that have been developed for energy (12 wells/4 km^2), and avoidance was most pronounced in high quality winter habitat with abundant sagebrush (Doherty et al. 2008).

These studies provide compelling evidence of impacts, and long-term studies in the Pinedale Anticline Project Area in southwest Wyoming (Table 3) present the most complete picture of cumulative impacts of energy development to sage-grouse populations. Lyon and Anderson (2003) showed that early in the development process, nest sites were farther from disturbed leks than from undisturbed leks, that nest initiation rate for females from disturbed leks was 24% lower than for birds breeding on undisturbed leks, and that 26% fewer females from disturbed leks initiated nests in consecutive years. As development of the anticline progressed, Holloran (2005) reported that adult female sage-grouse remained in traditional nesting areas regardless of increasing levels of development, but yearling females that had not yet imprinted on habitats inside the gas field avoided development by nesting farther from main haul roads. Kaiser (2006) and Holloran et al. (2007) later confirmed that yearling females avoided infrastructure when selecting nest sites and that yearling males that avoided leks inside of development were displaced to the periphery of the gas field. Recruitment of males to leks also declined as distance within the external limit of development increased, indicating the likelihood of lek loss near the center of development.

Perhaps the most important finding from studies in the Pinedale Anticline was that sage-grouse declines are at least partially explained by lower annual survival of female sage-grouse, and that impacts to survival resulted in a population-level decline (Holloran 2005). The population decline observed in sage-grouse is similar to that observed in Kansas for the Lesser Prairie-Chicken (*Tympanuchus pallidicinctus*; Hagen 2003), a federally threatened species that also avoided otherwise suitable sand-sagebrush (*Artemisia filifolia*) habitats proximal to oil and gas development (Pitman et al. 2005, Johnson et al. 2006). High site fidelity but low survival of adult sage-grouse combined with lek avoidance by younger birds (Kaiser 2006, Holloran et al. 2007) resulted in a time lag of 3–4 yr between the onset of development activities and lek loss (Holloran 2005). The time lag observed by Holloran (2005) in the Anticline matched that for leks that became inactive 3–4 yr following intensive coal-bed natural gas development in the Powder River Basin (Walker et al. 2007a).

The scientific evidence from 1998 to the present that energy development is impacting sage-grouse populations has become apparent. However, questions remain concerning the exact mechanisms responsible for population declines, and manipulative experiments are needed to test the efficacy of mitigation policies and practices (Table 3). Burying power lines (Connelly et al. 2000), minimizing road and well pad construction, vehicle traffic, and industrial noise (Lyon and Anderson 2003, Holloran 2005), and managing produced water to prevent the spread of West Nile virus (Zou et al. 2006, Walker et al. 2007b) may reduce impacts. Rigorous testing is needed to know whether these or other modifications will allow sage-grouse to persist in developed areas. The severity of population-level impacts is a major concern because attempts to translocate birds for reintroduction or to supplement existing populations are rarely successful (Reese and Connelly 1997, Baxter et al. 2008).

CURRENT AND POTENTIAL EXTENT OF DEVELOPMENT

The pace and extent of oil and gas development has emerged as a major issue because areas being developed in southwest Wyoming and northwest Colorado are some of the largest and most ecologically intact sagebrush landscapes with the highest densities of sage-grouse remaining in North America (Connelly et al. 2004). Documented negative impacts suggest the pace and extent of future development will have a large role in the future status of region-wide sage-grouse populations. The current pace (Fig. 1) and extent (Fig. 2) of drilling in sagebrush habitats, and continued leasing of the federal mineral estate (Appendix 1) with inadequate stipulations for conservation of wildlife (Table 3) increases risk of further declines in sage-grouse distribution and abundance. We depict the extent of existing development and uncertainty about the scale of future development, demonstrating the need for a fundamental shift from local to landscape conservation.

METHODS

Most current energy exploration and development occurs within the remaining eastern range of sage-grouse (Fig. 2). IHS Incorporated provided geo-referenced data layers depicting locations of producing oil and gas wells as of 1 September 2007 on public and private lands in Montana, North Dakota, South Dakota, Wyoming, Colorado, and Utah. State offices of the BLM provided information on the extent of the federal mineral estate and locations of authorized leases within these states. Leases were authorized for exploration and development on or before 1 June 2007 for all states except Utah (1 May 2007). We acquired from Saskatchewan Industry and Resources via the Geological Atlas of Saskatchewan, locations of producing oil and gas wells on or before August 2007; data on authorized leases on crown lands were obtained from the same source on or before 29 January 2008. Producing well data for Alberta were acquired from the Resource Data Branch through IHS Energy (Canada) Limited; Alberta Energy provided data on leases authorized on or before 4 April 2008.

We overlaid locations of producing wells within the range of sage-grouse (Schroeder et al. 2004) in sage-grouse management zones I and II (Stiver et al. 2006) to illustrate the scope of energy development within sage-grouse habitats. We then overlaid authorized leases within the same geographic areas to quantify the proportion of the federal mineral estate that has been authorized for future oil and gas exploration, and potential development. We overlaid wells within authorized leases to estimate the proportion of leases that contain ≥1 producing wells and to estimate the proportion of leases that are held by production (Appendix 1). We excluded federally protected national parks and wilderness areas from calculations; lands with other federal designations that might exclude oil and gas development—wilderness study areas and areas of critical environmental concern—were included in our analysis.

ANALYSIS

The number of producing wells has tripled from 11,231 in the 1980s to 33,280 in 2007 within the eastern range of sage-grouse in the US (Fig. 1). The US government has authorized exploration and development (Appendix 1) in 7,000,000 of 16,000,000 ha (44%) of the federal mineral estate within the range of sage-grouse in management zones I and II (Table 4; Fig. 2). Almost two-thirds of the federal mineral estate in management zones I and II are within Wyoming (Table 4). Wyoming also has the highest proportion of federal leases (52%) authorized for exploration and development (Table 4). Lease sales are conducted under a market-driven process whereby most lands offered for lease are nominated by industry (Appendix 1). Opportunities for conservation remain because 4.3 million ha of authorized leases have not yet been developed, but options are limited once leases are authorized (Appendix 1) and no comprehensive plan is in place to reduce impacts to sage-grouse populations. To date, 25% of the 7,000,000 ha of authorized leases contain ≥1 producing wells and 39% are held by production. The proportion of authorized leases that will be developed remains uncertain.

CONSERVATION IMPLICATIONS

Severity of impacts and continued leasing of the public mineral estate dictate the need to shift from local to landscape conservation. The scientific basis of this shift should transcend state and other political boundaries to develop and implement a plan for conservation of sage-grouse populations across the western US and Canada. The immediate need is for planning tools that overlay the best existing areas for sage-grouse with the extent of current and projected development for all of sage-grouse management zones I and II (Stiver et al. 2006). Maps that depict locations of the best remaining sage-grouse populations and their relative risk of loss will provide decision-makers with the information they need to implement a conservation strategy (Doherty et al. *this volume*). Following initial implementation, site-specific information including that of seasonal habitat use will be necessary to test and refine the strategy. Ultimately, multiple stressors—not just energy development—must be managed collectively to maintain populations over time in priority landscapes. Integrated analyses should consider how additional stressors such as habitat loss (Knick et al. 2003), restoration (Wisdom et al. 2002), range management (Crawford et al. 2004), disease (Naugle et al. 2004), invasive weeds (Bergquist et al. 2007), and other ecological threats such as climate change will cumulatively affect sage-grouse populations over time.

A scientifically defensible strategy can be constructed, and the most reliable measure of success will be long-term maintenance of sage-grouse populations in their natural habitats. The challenge will be for federal and state governments and industries to implement solutions at a sufficiently large scale across multiple jurisdictions to meet the biological requirements of sage-grouse. One approach to conserve large populations may be to forego development in priority landscapes until new best-management practices that safeguard populations are implemented. New best-management practices can be applied and rigorously tested in landscapes less critical to conservation. Practices to reduce impacts may include a combination of unitization, phased development, consolidation of well pads per unit area, and remote instrumentation to reduce traffic volume. Accelerated restoration programs may increase the probability of re-establishing populations in landscapes that are developed for energy production. We have the capability and opportunity to reduce future losses, but time is becoming critical and the need for inter-jurisdictional cooperation is paramount.

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Table 1. Density (linear kilometer or number/kilometer^2; ± SE) of human features in sagebrush landscapes where the primary land use is livestock grazing with or without agricultural tillage or coal-bed natural gas development. Estimates based on a sample of 80 9-km^2 cells stratified by status of agricultural and energy development (N = 20 cells in each category), Powder River Basin, Wyoming and Montana.

	Land Use			
Density of human feature	Ranch land	Ranch land with tillage	Ranch land with energy	Ranch land with tillage with energy
Number of wells	0.04 ± 0.02	0.02 ± 0.01	2.82 ± 0.58	4.82 ± 0.73
Kilometers of roads	1.57 ± 0.15	2.10 ± 0.16	3.13 ± 0.29	4.10 ± 0.36
Kilometers of power lines	0.27 ± 0.08	0.43 ± 0.09	0.58 ± 0.09	0.86 0.08
Number of ponds	0.12 ± 0.04	0.32 ± 0.12	0.51 ± 0.09	0.62 0.09

Table 2. Research citations on effects of energy development (oil and gas) to Greater Sage-Grouse.

Citation and study location	Research outlet	Pretreatment design	Length or control	Years	Sample size
Walker et al. (2007a), Powder River Basin, NE Wyoming and SE Montana	Scientific journal	Correlative	Y/Y	8	97–154 leks/year for trends, 276 leks in status analysis
Doherty et al. (2008), Powder River Basin, NE Wyoming and SE Montana	Scientific Journal	Correlative	N/N	4	435 locations to build model, 74 new locations from different years to test it
Aldridge and Boyce (2007), SE Alberta, Canada	Scientific journal	Correlative	N/N	4	113 nests, 669 locations on 35 broods, 41 chicks from 22 broods
Lyon and Anderson (2003), Pinedale Mesa, SW Wyoming	Scientific journal	Observational	N/Y	2	48 females from 6 leks
Holloran (2005), Pinedale Anticline Project Area and Jonah II gas field,	Ph.D. dissertation	Correlative and observational	N/Y	7	Counts of 21 leks, 209 females from 14 leks, 162 nests SW Wyoming

Kaiser (2006) Pinedale Anticline Project Area and Jonah II gas field, SW Wyoming	M.S. thesis	Correlative and observational	N/Y	1	18 leks, 83 females (23 yearlings), plus 20 yearling males
Holloran et al. (2007), Pinedale Anticline Project Area and Jonah II gas field, SW Wyoming	US Geological Survey	Correlative and observational	N/Y	2	86 yearlings (52 females), 23 yearlings (17 females) with known maternity

Table 3. Characteristics of oil and gas fields where research was conducted to evaluate response of Greater Sage-Grouse to energy development.

	Study areas		
Description	Powder River Basin	Pinedale Anticline Project area	Manyberries oil field
Location	A 24,000-km^2 area (1,230 m elevation) of the basin in northeast Wyoming-southeast Montana (44° 13´ 46 N”, 106° 6´ 21” W). Part of largest coal producing basin in US and one of the largest gas fields in North America.	A 2,550-km^2 area located within a high-desert ecosystem (2,100–2,350 m elevation) near the town of Pinedale in southwest Wyoming (42° 37´ 33” N, 109° 53´ 7” W). Pinedale is 120 km south of Jackson Hole in the northern reach of the Green River Basin, an area rich in oil and gas resources.	A 150-km^2 area in southeast Alberta (49° 23´ 60” N, 110° 42´ 1” W) just outside the hamlet of Manyberries (903 m elevation) and 85 km south of Medicine Hat. This field lies within the northwest quarter of remaining occupied range of sage-grouse in the province[b].
Development	Coal-bed natural gas is most recent and extensive development. First wells drilled in 1990s with	Natural gas wells were first drilled near Pinedale in 1930s, but activity was limited until 1990s when renewed	Renewed interest in fluid minerals in the late 1970s resulted in increased oil drilling in southern

	rapid expansion in 1997. By 2007, 35,000 producing wells had been drilled. 68,000 wells are authorized for development on federal lands in Wyoming (50,000) and Montana. All but 3% of federal leases have been authorized for development.	interest was prompted by production in nearby Jonah Gas Field. Existing development is 700 producing well pads with 645 km of pipeline and 445 km of road. Development is expected for ≥10 yr. Life of field is 50–100 yr. On federal lands, an anticipated 242 new wells will be drilled annually from 2001–2020, of which 60% will be in the Anticline and Jonah field.	Alberta. About 1,500 wells have been drilled in and around this field, of which 30% are still producing[c].
Ownership	Mix of federal, state and private land in split estate where subsurface mineral rights have legal precedence over surface rights. Most of surface is privately owned (85%), but 75% of mineral	Ownership in the Anticline is straightforward when compared to the Anticline, the BLM owns surface and mineral rights, administers permits to drill, and approves construction.	Mix of public and private land Powder River Basin. In the but heavily weighted to provincial surface ownership. Like the US, mineral rights in Canada hold legal precedence over surface

	rights and 10% of surface are federally owned and administered by Bureau of Land Management (BLM). Producing wells are on federal (30%), state (10%), and private (60%) holdings.		rights. Mineral rights are leased to industry by the province.
Stipulations and restrictions	Drilling authorized at 1 well/32 ha on federal lands. Federal lease stipulations prohibit surface infrastructure within 0.4 km of lek and restrict timing of drilling and construction activities within 3.2 km of documented lek during the breeding season (15 March–15 June) and within crucial winter habitat (1 Dec–31	Drilling authorized at 1 pad/16 ha. Federal stipulations prohibit surface disturbance with 0.4 km of lek, no activity within 0.8-km radius of active lek between 0000–0900 H in breeding season, and no construction or drilling during breeding within 1.6 km of active lek. BLM restricts construction activities in breeding and nesting seasons in suitable habitat within 3.2 km of active	Few limitations are placed on spacing or density of wells in Alberta. Alberta Fish and Wildlife Division provides a set of voluntary guidelines that recommend timing and setback distances around leks, but no provincial or federal legislation commits Alberta Public Lands or Alberta Energy Utility Board to implement

	March; Montana only). Restrictions (excludes operational phase),can be modified or waived, or other conditions of approval applied, on a case-by-case basis. Private and state minerals are largely developed with no restrictions.	only apply during initial construction lek. Suitable habitat designation requires that an active nest be located during on-site review. No additional restrictions placed on well field activities in operational phase.	recommendations.
Population status	Component of larger Wyoming Basin population that represents 25% of sage-grouse in species' range[a]. Supports an important regional population, with >500 known leks since 2005[a] and is a link to fringe populations in	Population stronghold for sage-grouse with some of the highest densities of males per km^2 anywhere in remaining range of species. Component of larger Wyoming Basin population that represents 25% of sage-grouse in species' range. Part of southwest Wyoming-northwest	Endangered status since 2003 under Canadian Species at Risk Act. Extirpated from British Columbia, sage-grouse remain in Alberta and Saskatchewan but occupy 6% of former range, and constitute <1% of range-wide population[d].

	eastern Wyoming and western South Dakota and between the Wyoming Basin and central Montana.	Colorado sub-population with >800 known leks[a].	Population in Canada which totals <700 individuals declined 82–92% in <20 yr[e]. Population in Alberta declined 77–84% since 1968 and was estimated at 285–422 birds in 2005.

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[a] Aldridge and Boyce (2007).

[b] Braun et al. (2002).

[c] Connelly et al. (2004).

[d] Aldridge and Brigham (2003).

[e] Lungle and Pruss (2007).

TABLE 4. PROPORTION OF AUTHORIZED LEASES FOR THE FEDERAL MINERAL ESTATE WITHIN THE RANGE OF GREATER SAGE-GROUSE (SCHROEDER ET AL. 2004; GRAY SHADED AREA IN FIG. 2) IN SAGE-GROUSE MANAGEMENT ZONES I AND II (CONNELLY ET AL. 2004).

State	Proportion authorized	Area of federal mineral estate (1,000 ha)
Wyoming	52%	10,600
Colorado	50%	915
Montana	27%	3,700
Utah	25%	405
Dakotas	14%	365
Totals	44%	15,985

APPENDIX 1. LAWS AND PROCESSES GOVERNING MINERAL LEASING WITH THE US FEDERAL GOVERNMENT.

Regulations governing leasing are in Title 43, Part 3100 of the Code of Federal Regulations. The Mineral Leasing Act of 1920 and the Mineral Leasing Act for Acquired Lands of 1947 give the Bureau of Land Management (BLM) leasing authority on 230,000,000 ha of BLM, National Forest, other federal lands, and on private lands where mineral rights are retained by the federal government. Qualifications to hold a Federal lease are identified in 43 CFR 3102. Leases can be held by U.S. citizens, associations, municipalities, and companies that are incorporated in the U.S. The Federal Onshore Oil and Gas Leasing Reform Act of 1987 stipulates that publicly owned lands available for leasing first be offered by competitive leasing. If no bid is received on a parcel at the competitive sale, lands are available for filing of a noncompetitive offer for 2 yr. Maximum lease sizes are 1,032 ha for competitive (except Alaska) and 4,129 ha for noncompetitive parcels. Before land can be offered for leasing, it must be identified in a land-use plan as suitable. Title 43 Section 1712 of the Federal Land Policy and Management Act stipulates the Secretary of the Interior shall for land use plans use a systematic and interdisciplinary approach to achieve integrated consideration of physical, biological, economic, and other sciences, and give priority to the designation and protection of areas of critical environmental concern. The Reform Act requires BLM to hold a minimum of four oral auctions annually and, because the leasing process is market driven, most lands offered for lease are nominated by industry. Values of leases vary and are determined by marketplace at auction. BLM does not make a separate evaluation for oil and gas potential. A notice of competitive lease sale is posted for at least 45 d prior to the auction date. Leases grant lessees rights to explore and drill for, extract, remove, and dispose of oil and gas deposits found in leased lands. Granted rights are subject to terms of lease, stipulations attached to lease, applicable laws, Secretary of the Interior's regulations, and formal orders in effect as of lease issuance and to regulations and formal orders subsequently placed into effect that are not inconsistent with specific lease provisions. Mitigation measures identified in the planning document are attached to leases. Typical mitigation measures for sage-grouse are described (Table 3). Lessees submit application to BLM for a permit to drill, at which time restrictions can be modified or waived by BLM, or additional conditions of approval applied, on a site-by-site basis. Most state and private minerals are developed with few or no requirements to mitigate impacts to wildlife. Prior to approval of a drilling permit, bonding must be filed. Minimum amounts for drilling bonds are found in 43 CFR 3104. The Energy Policy Act of 1992 directs competitive and noncompetitive leases to be issued for a 10-yr period. Annual rental rates for leases paid to the Federal Minerals Management Service are $3.75/ha or fraction thereof the first 5 yr and $5.00/ha each year thereafter. For leases issued under the 1987 Reform Act, royalty rate for produced oil or gas is 12.5% and payable to the Minerals Management Service. Leases are subject to extension privileges outlined in 43 CFR 3107 and may be held by production as long as there is oil or gas being produced in paying quantities on the lease or within a unit agreement (e.g., communitization) to which the lease is committed. Lessee may surrender a lease in whole or part by filing a written relinquishment with the BLM.

Figure captions

Figure 1. Number of producing and non-producing oil and gas wells through time on public and private lands within the range of Greater Sage-Grouse (Schroeder et al. 2004; gray shaded area in Fig. 2) within the US portion of sage-grouse management zones I and II (Connelly et al. 2004). Number of wells in each time interval is based on the decade that permit to drill was issued.

Figure 2. (A). Locations of producing oil and gas wells within sage-grouse management zones I and II (Connelly et al. 2004). Range of Greater Sage-Grouse (Schroeder et al. 2004) within management zones is shown in gray. (B). Federal mineral estate is shown in gray. Authorized leases from the federal mineral estate in the US and Canada are shaded black. Leases were authorized for exploration and development on or before 1 June 2007 for each state except Utah (1 May 2007). Leases in Canada were authorized for development on or before 29 January 2008 in Saskatchewan and 4 April 2008 in Alberta. A swath of authorized leases across southern Wyoming appears lighter in color because mineral ownership is mixed.

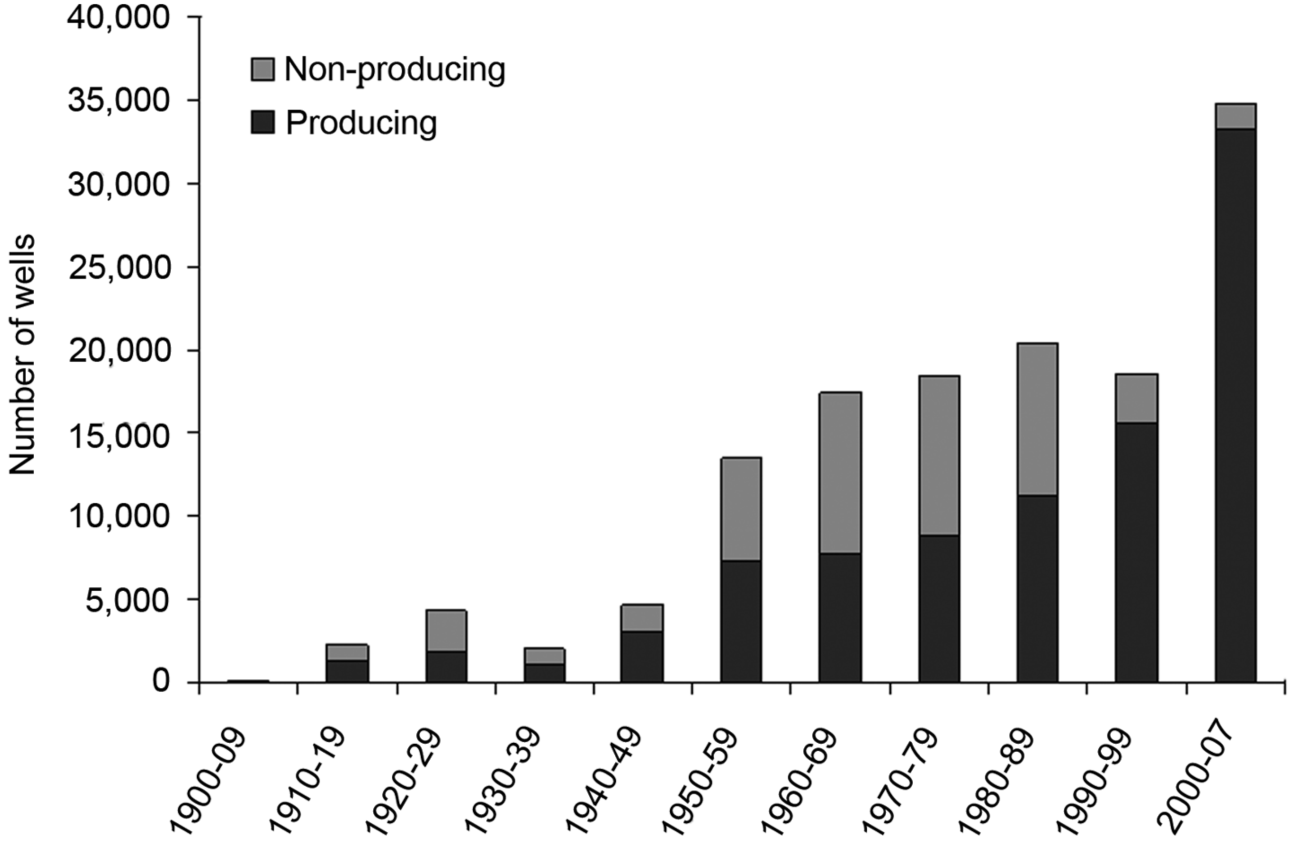
Figure. 3. Percent area of a 9-km^2 landscape (N = 20 each category) within 50, 100, and 200 m of a road, power line, man-made pond, or agricultural tillage. Estimates of area (%) calculated for sagebrush landscapes where primary use is ranch land either with or without agricultural tillage or energy development. Error bars represent 95% CIs.

Figure 4. Population indices based on male lek attendance for sage-grouse in the Powder River Basin (PRB), Montana and Wyoming, 2001–2005 for leks categorized as inside or outside of

coal-bed natural gas fields on a year-by-year basis (modified from Walker et al. [2007a]). Leks in gas fields had ≥40% energy development within 3.2 km or >25% development within 3.2 km and ≥1 well within 350 m of the lek center. Number of producing gas wells in the PRB documents the overall increase in development coincident with declines in sage-grouse population indices.

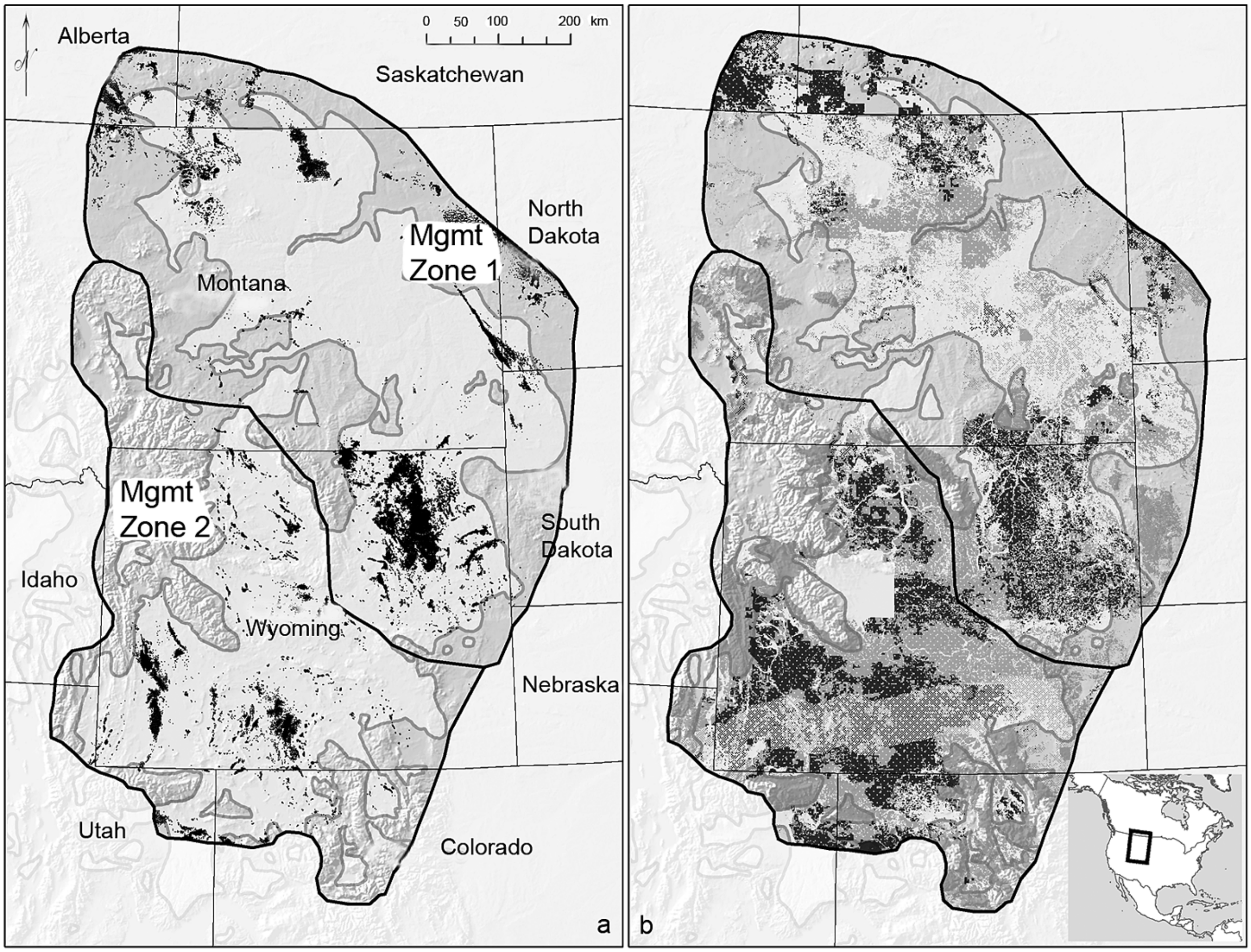
Figure 5. Relationship between number of male sage-grouse attending leks and average distance from leks to closest active drilling rig, Pinedale Anticline Project Area, southwest Wyoming, 1998–2004 (modified from Holloran [2005]). Each point along the regression line represents one lek (N = 21).

Figure 1.



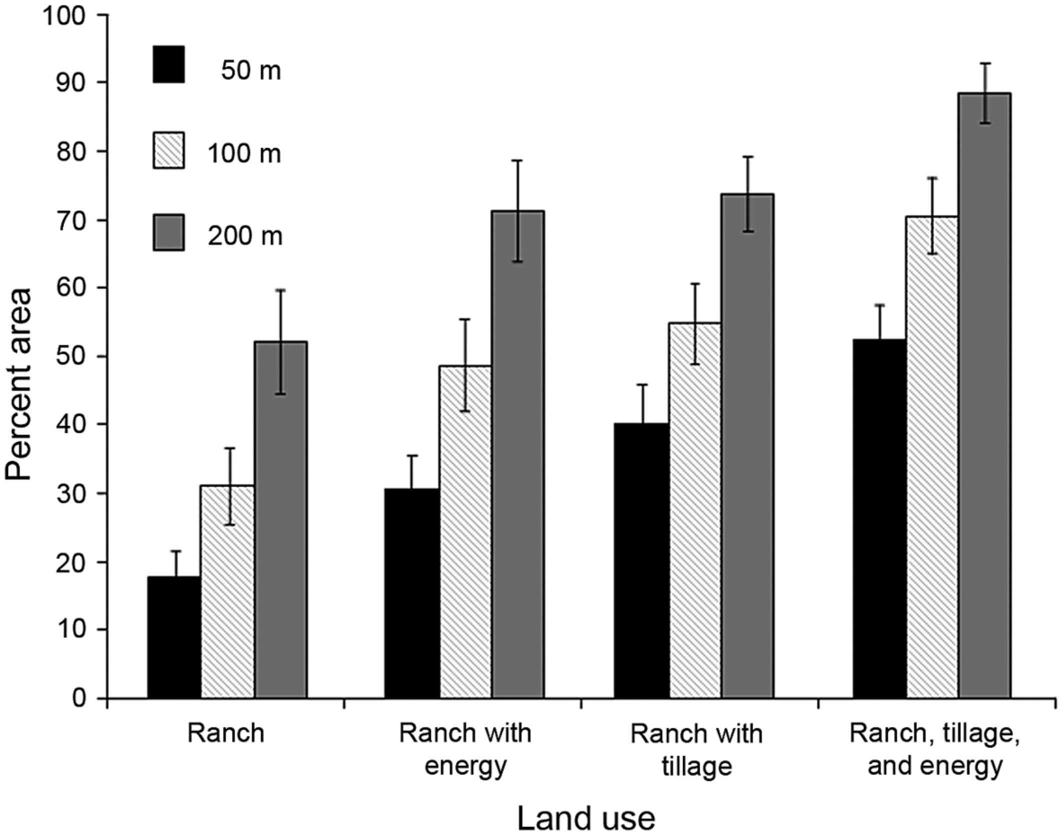
40,000
35,000
30,000
25,000
20,000
15,000
10,000
5,000
0
Number of wells
Non-producing
Producing
1900-09
1910-19
1920-29
1930-39
1940-49
1950-59
1960-69
1970-79
1980-89
1990-99
2000-07

Figure 2.



Alberta
0 50 100 200 km
Saskatchewan
North Dakota
Mgmt Zone 1
Montana
Mgmt Zone 2
South Dakota
Idaho
Wyoming
Nebraska
Utah
Colorado
a
b

Figure 3.



100
90
80
70
60
50
40
30
20
10
0
Percent area
50 m
100 m
200 m
Ranch
Ranch with energy
Ranch with tillage
Ranch, tillage, and energy
Land use

Figure 4.

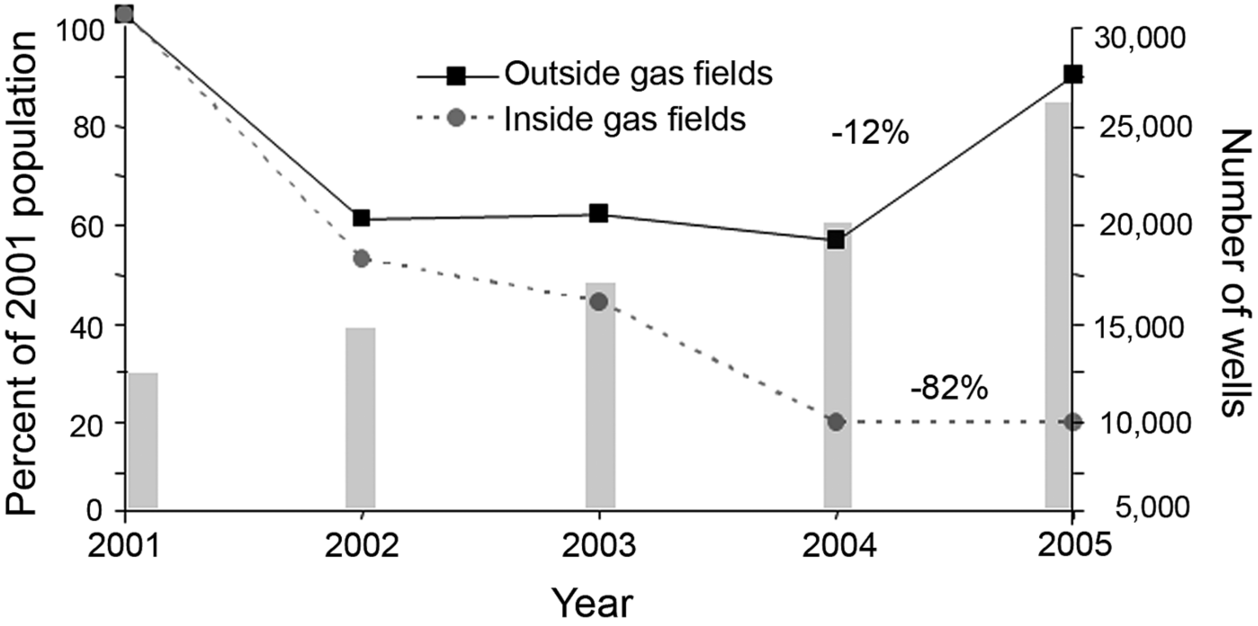
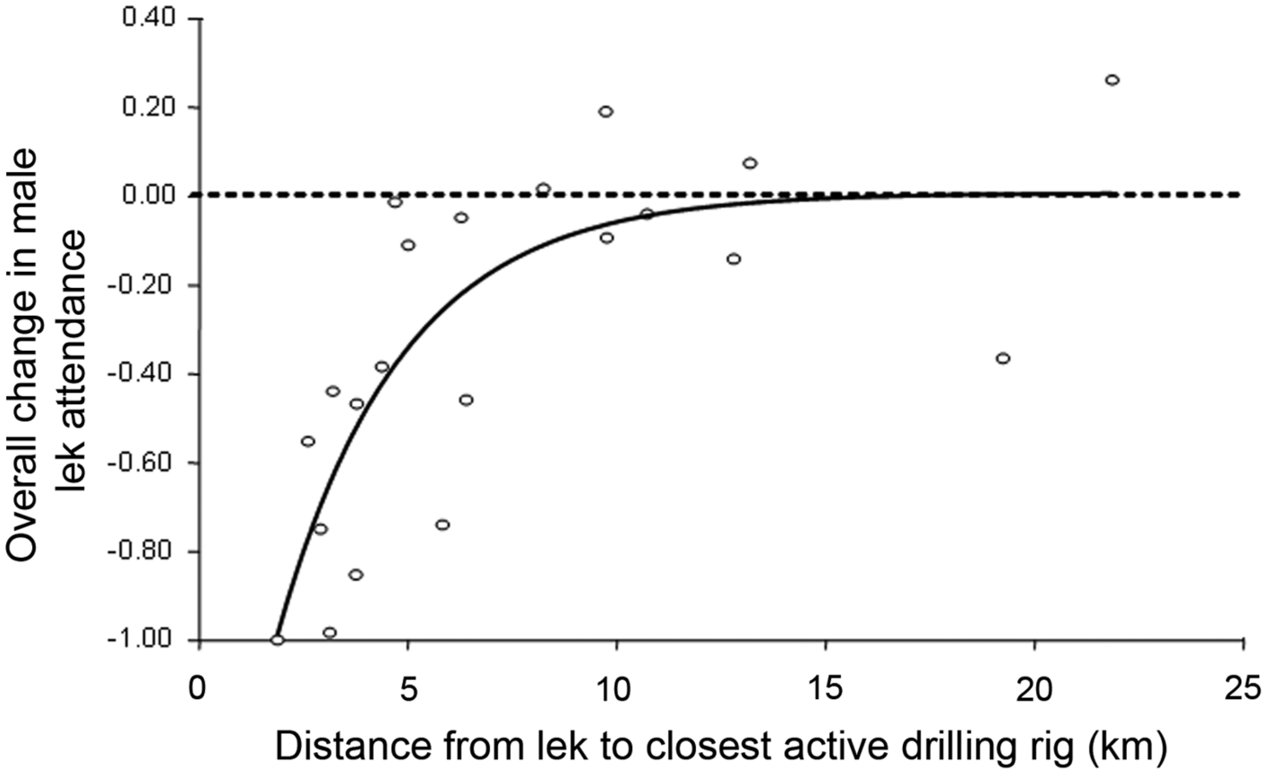

Percent of 2001 population
100
80
60
40
20
0
Outside gas fields
Inside gas fields
-12%
-82%
30,000
25,000
20,000
15,000
10,000
5,000
Number of wells
2001
2002
2003
2004
2005
Year

Figure 5.


0.40
0.20
0.00
-0.20
-0.40
-0.60
-0.80
-1.00
0
5
10
15
20
25
Overall change in male lek attendance
Distance from lek to closest active drilling rig (km)