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Greater sage-grouse population response to energy development and habitat loss

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Abstract: Modification of landscapes due to energy development may alter both habitat use and vital rates of sensitive wildlife species. Greater sage-grouse (*Centrocercus urophasianus*) in the Powder River Basin (PRB) of Wyoming and Montana have experienced rapid, widespread changes to their habitat due to recent coal-bed natural gas (CBNG) development. We analyzed lek-count, habitat, and infrastructure data to assess how CBNG development and other landscape features influenced trends in the numbers of male sage-grouse observed and persistence of leks in the PRB. From 2001-2005, the number of males observed on leks in CBNG fields declined more rapidly than leks outside of CBNG. Of leks active in 1997 or later, only 38% of 26 leks in CBNG fields remained active by 2004-2005, compared to 84% of 250 leks outside CBNG fields. By 2005, leks in CBNG fields had 46% fewer males per active lek than leks outside of CBNG. Persistence of 110 leks was positively influenced by the proportion of sagebrush habitat within

6.4 km of the lek. After controlling for habitat, we found support for negative effects of CBNG development within 0.8 km and 3.2 km of the lek and for a time lag between CBNG development and lek disappearance. Current lease stipulations that prohibit development within 0.4 km of sage-grouse leks on federal lands are inadequate to ensure lek persistence and may result in impacts to breeding populations over larger areas. Seasonal restrictions on drilling and construction do not address impacts caused by loss of sagebrush and incursion of infrastructure that can affect populations over long periods of time. Regulatory agencies may need to increase spatial restrictions on development, industry may need to rapidly implement more effective mitigation measures, or both, to reduce impacts of CBNG development on sage-grouse populations in the PRB.

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Large-scale modification of habitat associated with energy development may alter habitat use or vital rates of sensitive wildlife species. Populations in developed areas may decline if animals avoid specific features of infrastructure such as roads or power lines (Trombulak and Frissell 2000, Nelleman et al. 2001, 2003) or if energy development negatively affects survival or reproduction (Holloran 2005, Aldridge and Boyce 2007). For example, mortality caused by collisions with vehicles and power lines reduces adult and juvenile survival in a variety of wildlife species (reviewed in Bevanger 1998 and Trombulak and Frissell 2000). Indirect effects of energy development on populations are also possible due to changes in predator or parasite communities (Knight and Kawashima 1993, Steenhof et al. 1993, Daszak et al. 2000) or changes in vegetation structure and composition associated with disturbance (Trombulak and Frissell

2000, Gelbard and Belnap 2003). Negative impacts may be exacerbated if features of development that attract animals (e.g., ponds) simultaneously reduce survival and thereby function as ecological traps (Gates and Gysel 1978).

Rapidly expanding coal-bed natural gas (CBNG) development is a concern for conservation of greater sage-grouse (*Centrocercus urophasianus*) in the Powder River Basin (PRB) of northeastern Wyoming and southeastern Montana. The PRB supports an important regional population, with over 500 leks documented between 1967-2005 (Connelly et al. 2004). In the past decade, the PRB has also experienced rapidly increasing CBNG development, with impacts on wildlife habitat projected to occur over an area of approximately 24,000 km^2 (Bureau of Land Management 2003*a*, *b*). Coal-bed natural gas development typically requires construction of 2-7 km of roads and 7-22 km of power lines per km^2 as well as an extensive network of compressor stations, pipelines, and ponds (Bureau of Land Management 2003*b*). Approximately 10% of surface lands and 75% of mineral reserves in the PRB are federally owned and administered by the Bureau of Land Management (BLM) (Bureau of Land Management 2003*a*, *b*). Over 50,000 CBNG wells have been authorized for development on federal mineral reserves in northeastern Wyoming, at a density of 1 well per 16-32 ha, and as many as 18,000 wells are anticipated in southeastern Montana (Bureau of Land Management 2003*a, b*). According to data from the Wyoming Oil and Gas Conservation Commission and Montana Board of Oil and Gas Conservation, by the beginning of 2005, approximately 28,000 CBNG wells had been drilled on federal (~31%), state (~11%), and private (~58%) mineral holdings in the PRB. Mitigation for sage-grouse on BLM lands typically includes lease stipulations prohibiting surface infrastructure within 0.4 km of sage-grouse leks as well as restrictions on timing of drilling and construction within 3.2 km of documented leks during the

15 March - 15 June breeding season and within crucial winter habitat from 1 December - 31 March (Montana only) (Bureau of Land Management 2003*a*, *b*). These restrictions can be modified or waived by BLM, or additional conditions of approval applied, on a case-by-case basis. In contrast, most state and private minerals have been developed with few or no requirements to mitigate impacts on wildlife.

Coal-bed natural gas development and its associated infrastructure may affect sage-grouse populations via several different mechanisms, and these mechanisms can operate at different scales. For example, 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 during the breeding season (Braun et al. 2002, Holloran 2005, Kaiser 2006). Collisions with nearby power lines and vehicles and increased predation by raptors may also increase mortality of birds at leks (Connelly et al. 2000*a*, 2000*b*). Alternatively, roads and power lines may indirectly affect lek persistence by altering productivity of local populations or survival at other times of the year. For example, sage-grouse mortality associated with power lines and roads occurs year-round (Patterson 1952, Beck et al. 2006, Aldridge and Boyce 2007), and ponds created by CBNG development may increase risk of West Nile virus (WNv) mortality in late summer (Walker et al. 2004, Zou et al. 2006, Walker et al. 2007). Loss and degradation of sagebrush habitat can also reduce carrying capacity of local breeding populations (Swenson et al. 1987, Braun 1998, Connelly et al. 2000*b*, Crawford et al. 2004). Alternatively, birds may simply avoid otherwise suitable habitat as the density of roads, power lines, or energy development increases (Lyon and Anderson 2003, Holloran 2005, Kaiser 2006, Doherty et al. 2008).

97 Understanding how energy development affects sage-grouse populations also requires
98 that we control for other landscape features that affect population size and persistence, including
99 the extent of suitable habitat. Sage-grouse are closely tied to sagebrush habitats throughout their
100 annual cycle, and variation in the amount of sagebrush habitat available for foraging and nesting
101 is likely to influence the size of breeding populations and persistence of leks (Ellis et al. 1989,
102 Swenson et al. 1987, Schroeder et al. 1999, Leonard et al. 2000, Smith et al. 2005). For this
103 reason, it is crucial to quantify and separate the effects of habitat loss from those of energy
104 development.

105 To assess how CBNG development and habitat loss influence sage-grouse populations
106 in the PRB, we conducted 2 analyses based on region-wide lek-count data. Lek counts are
107 widely used for monitoring sage-grouse populations, and at present, are the only data suitable for
108 examining trends in population size and distribution at this scale (Connelly et al. 2003, 2004).
109 First, we analyzed counts of the numbers of males displaying on leks (lek counts) to assess
110 whether trends in the number of males counted and proportion of active and inactive leks
111 differed between areas with and without CBNG development. Second, we used logistic
112 regression to model lek status (i.e., active or inactive) in relation to landscape features
113 hypothesized to influence sage-grouse demographics and habitat use at 3 spatial scales. The
114 objectives of the lek-status analysis were first, to identify the scale at which habitat and non-
115 CBNG landscape features influence lek persistence and second, to evaluate and compare effects
116 of CBNG development at different scales with those of non-CBNG landscape features after
117 controlling for habitat.

118 **Study Area**

We analyzed data from sage-grouse leks within an approximately 50,000-km^2 area of northeastern Wyoming and southeastern Montana (Figure 1). This area included all areas with existing or predicted CBNG development in the PRB (Bureau of Land Management 2003*a*, *b*) as well as surrounding areas without CBNG. Land use in this region was primarily cattle ranching with limited dry-land and irrigated tillage agriculture. Natural vegetation consisted of sagebrush-steppe and mixed-grass prairie interspersed with occasional stands of conifers. Sagebrush-steppe was dominated by Wyoming big sagebrush (*Artemisia tridentata wyomingensis*) with an understory of native and non-native grasses and forbs. Plains silver sagebrush (*A. cana cana*) and black greasewood (*Sarcobatus vermiculatus*) co-occurred with Wyoming big sagebrush in drainage bottoms.

Methods

Lek-count trend analyses

Lek-count data. We used sage-grouse lek-count data in public databases maintained by Wyoming Game and Fish Department and Montana Department of Fish, Wildlife, and Parks as the foundation for analyses. We augmented databases with lek counts provided by consultants and by the BLM's Miles City field office for 37 leks (36 in Montana, 1 in Wyoming) known to have been counted but for which data were missing. We checked for and, when possible, corrected errors in the database after consultation with database managers and regional biologists for each state. We excluded records with known errors, surveys in which lek status was not determined, leks without supporting count data, and duplicate leks prior to analysis.

Coal-bed natural gas development. We obtained data on the type, location, status, drilling date, completion date, and abandonment date of wells from public databases maintained by the Wyoming Oil and Gas Conservation Commission and Montana Board of Oil and Gas

142 Conservation. Because wells are highly correlated with other features of development, such as
143 roads, power lines, and ponds (D. E. Naugle, University of Montana, unpublished data), using
144 well locations is a reliable way to map and measure the extent of CBNG development. We
145 retained only those wells that were clearly in the ground, associated with energy development
146 (gas, oil, stratification test, disposal, injection, monitoring, and water source wells), and likely to
147 have infrastructure. We excluded wells that were plugged and abandoned, wells waiting on
148 permit approval, wells drilled or completed in 2005 or later, and those with status reported as dry
149 hole, expired permit, permit denied, unknown, or no report. We included wells in analyses
150 starting in the year in which they were drilled or completed (i.e., started producing). For active
151 wells without drilling or completion dates, we estimated start year based on approval and
152 completion dates of nearby wells and those in the same unit lease. We included wells with status
153 reported as dormant, temporarily abandoned, or permanently abandoned only until the year prior
154 to when they were first reported as abandoned. Because capped wells (also commonly referred
155 to as shut-in wells) may or may not have associated infrastructure, we included them only in
156 years in which they were surrounded by, or within 1 km of, a producing gas field.

157 We estimated the extent of CBNG development around each lek in each year. We first
158 approximated the area affected by CBNG development by creating a 350-m buffer around all
159 well locations using ArcInfo 8.2 (ESRI, Inc., Redlands, CA) and dissolving boundaries where
160 buffers overlapped. We then estimated the proportion of the area within 3.2 km of the lek center
161 that was covered by the buffer around wells. At current well density (1 well per 32-64 ha), a
162 350-m buffer around wells estimates the extent of CBNG development more accurately than
163 larger or smaller buffer sizes. This metric is less sensitive to variation in spacing of wells than

164 measures such as well density and therefore more accurate for estimating the total area affected
165 by CBNG development.

166 *Trends in lek counts.* We examined lek-count data from 1988-2005. In each year, we
167 categorized a lek as in CBNG if ≥40% of the area within 3.2 km was developed or if ≥25%
168 within 3.2 km was developed and ≥1 well was within 350 m of the lek center. We categorized a
169 lek as outside CBNG if <40% of the area within 3.2 km was developed and no wells were within
170 350 m of the lek center. However, because few leks in CBNG were counted in consecutive years
171 prior to 2001, we analyzed trends in lek-counts only from 2001-2005. We calculated the rate of
172 increase in the number of males counted on leks for each year-to-year transition by summing
173 count data across leks within each category (in CBNG vs. outside CBNG) according to their
174 stage of development at the end of the first year of each year-to-year transition (Connelly et al.
175 2004). We summed data across leks to reduce the influence of geographic variation in
176 detectability and used the maximum annual count for each lek to reduce the influence of within-
177 year variation in detectability on the estimated rate of increase. We derived data for each
178 transition only from leks counted in both years and known to be active in at least 1 of the 2 years
179 of the transition. We estimated mean rates of increase in CBNG versus outside CBNG fields
180 based on the slope of a linear regression of interval length versus rate of increase (Morris and
181 Doak 2002). Wells completed between January and March (i.e., before lek counts were
182 conducted) in the second year of each transition may have caused us to underestimate the amount
183 of CBNG development around leks at the time counts were conducted. However, if CBNG
184 development negatively affects populations, this would cause the difference between trends in
185 lek-count data in CBNG and outside CBNG to be underestimated and would produce a
186 conservative estimate of impacts.

187 *Timing of lek disappearance*. If CBNG development negatively affects lek persistence,
188 most leks in CBNG fields that became inactive should have done so following CBNG
189 development. To explore this prediction, we examined the timing of lek disappearance in
190 relation to when a lek was first classified as being in a CBNG field (i.e., ≥40% development
191 within 3.2 km or ≥25% development within 3.2 km and ≥1 well within 350 m of the lek center)
192 for leks confirmed active in 1997 or later.

193 **Lek-status analysis**

194 *Definition of leks*. We defined a lek as a site where multiple males were documented
195 displaying on multiple visits within a single year or over multiple years. We defined a lek
196 complex as multiple leks located <2.5 km from the largest and most regularly attended lek in the
197 complex (Connelly et al. 2004). We defined an initial set of lek complexes based on those
198 known prior to 1990. We considered leks discovered in 1990 or later as separate complexes,
199 even if they occurred <2.5 km from leks discovered in previous years. We did this to avoid
200 problems with the location of already-defined leks and lek complexes shifting as new leks were
201 discovered or if new leks formed in response to nearby CBNG development. We grouped leks
202 discovered within 2.5 km of each other in the same year in the same lek complex. We used lek
203 complexes as the sample unit for calculating proportion of active and inactive leks and in the lek-
204 status analysis, but because the term lek complex can refer either to multiple leks or to a single
205 lek, we refer to both simply as a lek.

206 *Lek status*. We determined the final status of leks by examining count data from 2002-
207 2005. We considered a lek active if ≥ 1 male was counted in 2004 or 2005, whichever was the
208 last year surveyed. To minimize problems with non-detection of males, we considered a lek
209 inactive only if: 1) at least 3 consecutive ground or air visits in the last year surveyed failed to

210 detect males, or 2) if surveys in the last 3 consecutive years the lek was checked (2002-2004 or
211 2003-2005) failed to detect males. We classified the status of leks that were not surveyed or
212 were inadequately surveyed in 2004 or 2005 as unknown. Survey effort in the PRB increased 5-
213 fold from 1997-2005 and included systematic aerial searches for new leks and repeated air and
214 ground counts of known leks within and adjacent to CBNG fields. Therefore, it is unlikely that
215 leks shifted to nearby sites without being detected. Many leks in the PRB disappeared during a
216 region-wide population decline in 1991-1995 (Connelly et al. 2004), well before most CBNG
217 development in the PRB began. To eliminate leks that became inactive for reasons other than
218 CBNG, we calculated proportions of active and inactive leks in CBNG and outside CBNG based
219 only on leks active in 1997 or later.

220 *Scale*. We calculated landscape metrics at 3 distances around each lek: 0.8 km (201 ha),
221 3.2 km (3,217 ha), and 6.4 km (12,868 ha). We selected the 0.8-km scale to represent processes
222 that impact breeding birds at or near leks, while avoiding problems with spatial error in lek
223 locations. We selected the 6.4-km scale to reflect processes that occur at larger scales around the
224 lek, such as loss of nesting habitat, demographic impacts on local breeding populations, or
225 landscape-scale avoidance of CBNG fields. The 3.2-km scale is that at which state and federal
226 agencies apply mitigation for CBNG impacts (e.g., timing restrictions), and it is important to
227 determine the appropriateness of managing at a 3.2-km scale versus at smaller or larger scales.

228 *Habitat variables*. Each model represented a distinct hypothesis, or combination of
229 hypotheses, regarding how landscape features influence lek persistence. We included 2 types of
230 habitat variables in the analysis, the proportion of sagebrush habitat and the proportion of tillage
231 agriculture in the landscape around each lek. Because the scale at which habitat most strongly
232 influenced lek persistence was unknown, we considered habitat variables at all 3 scales. We

233 calculated the amount of sagebrush habitat and tillage agriculture around each lek at each scale
234 using ArcInfo 8.2 based on classified SPOT-5 satellite imagery taken in August 2003 over an
235 approximately 15,700 km^2 area of the PRB. We restricted the lek-status analysis to leks within
236 the SPOT-5 satellite imagery because the only other type of classified imagery available for this
237 region (Thematic Mapper at 30-m resolution) is unreliable for measuring the extent of sagebrush
238 habitat (Moynahan 2004). We visually identified and manually digitized areas with tillage
239 agriculture from the imagery. Classification accuracy was 83% for sagebrush habitat (i.e.,
240 sagebrush-steppe and sagebrush-dominated grassland). We excluded 20 leks for which >10% of
241 classified habitat data were unavailable due to cloud cover or proximity to the edge of the
242 imagery.

243 *Road, power line, and CBNG variables.* We hypothesized that infrastructure can affect
244 lek persistence in 3 ways and included different variables to examine each hypothesis. Roads,
245 power lines, and CBNG development may affect lek persistence in proportion to their extent on
246 the landscape. Alternatively, the effects of roads and power lines may depend their distance
247 from the lek, in which case they are expected to drop off rapidly as distance increases. Coal-bed
248 natural gas development may also influence lek status depending on how long the lek has been in
249 a CBNG field. If CBNG increases mortality, it may be several years before local breeding
250 populations are reduced to the point that males no longer attend the lek (Holloran 2005).
251 Avoidance of leks in CBNG fields by young birds (Kaiser 2006) combined with site fidelity of
252 adults to breeding areas (Schroeder et al. 1999) would also result in a time lag between CBNG
253 development and lek disappearance.

254 We used TIGER/Line® 1995 public-domain road layers for Wyoming and Montana (U.S.
255 Census Bureau 1995) to estimate the proportion of each buffer around each lek within 350 m of a

road at each of the 3 scales. We used 1995 data, rather than a more recent version, to represent roads that existed on the landscape prior to CBNG development. We obtained autumn 2005 GIS coverages of power lines directly from utility companies and used this layer to estimate the proportion of each buffer around each lek within 350 m of a power line at each scale. Year-specific power line coverages were not available, so this variable includes both CBNG and non-CNBG power lines. We estimated the extent of CBNG development around each lek at each scale by calculating the proportion of the total buffer area around the lek center covered by a dissolved 350-m buffer around well locations. If a lek was a complex, we first placed a buffer around all lek centers in the complex then dissolved the intersections to create a single buffer. We selected a 350-m buffer around roads, power lines, and CBNG wells for 2 reasons. First, quantitative estimates of the distance at which infrastructure affects habitat use or vital rates of sage-grouse were not available, and 350 m is a reasonable distance over which to expect impacts to occur, such as increased risk of predation near power lines or increased risk of vehicle collisions near roads. Second, we also wished to maintain a consistent relationship between well, road, and power line variables and the amount of area affected by each feature. We measured how long a lek was in a CBNG field as the number of years prior to 2005 during which the lek had ≥40% CBNG development within 3.2 km (or ≥25% CBNG within 3.2 km and ≥ 1 well within 350 m of the lek center).

Analyses. We used a hierarchical analysis framework to evaluate how landscape features influenced lek status (i.e., active or inactive). Our first goal was to identify the scale at which habitat, roads, and power lines affected lek persistence. Our second goal was to evaluate and compare effects of CBNG development at different scales with those of roads and power lines after controlling for habitat. In both cases, we used an information-theoretic approach (Burnham

279 and Anderson 2002) to select the most parsimonious model from a set of plausible candidate
280 models. We conducted all analyses using logistic regression in R (version 2.3.1, R Development
281 Core Team 2006). We used a logit-link function to bound persistence estimates within a (0,1)
282 interval. Almost all CBNG development within the extent of the SPOT-5 imagery occurred after
283 1997, so we restricted our analysis to leks known to have been active in 1997 or later to
284 eliminate those that disappeared for reasons other than CBNG development. We also excluded 4
285 leks known to have been destroyed by coal mining.

286 To identify the most relevant scale(s) for each landscape variable, we first allowed
287 univariate models at different scales to compete. Variables assessed for scale effects included:
288 (1) proportion sagebrush habitat, (2) proportion tillage agriculture, (3) proportion area affected
289 by power lines, and (4) proportion area affected by non-CBNG roads. We then used the scale for
290 each variable that best predicted lek status to construct the final set of candidate models. We
291 also included models with squared distance to nearest road and squared distance to nearest power
292 line in the final model set. To assess different possible mechanisms of CBNG impacts, we
293 evaluated models with the extent of CBNG development or the number of years since the lek
294 was classified as in a CBNG field. To assess the scale at which CBNG impacts occur, we
295 included models with the extent of CBNG effects at all 3 scales. We also included models with
296 interactions between habitat and CBNG metrics to evaluate whether effects of CBNG
297 development are amelioriated by the amount of sagebrush habitat around the lek. To avoid
298 problems with multicollinearity, we did not allow models with correlated variables (i.e., $r > |0.7|$)
299 in the final model set.

300 We judged models based on Akaike's Information Criterion adjusted for small sample
301 size (AIC_c) and examined beta coefficients and associated standard errors in all models to

302 determine the direction and magnitude of effects. We estimated overdispersion by dividing the
303 deviance of the global model by the deviance degrees of freedom. We conducted goodness-of-fit
304 testing in R following methods described in Hosmer et al. (1997). We used parametric
305 bootstrapping (Efron and Tibshirani 1993) to obtain means, standard errors, and 95% confidence
306 limits for persistence estimates because coefficients of variation for most beta estimates were
307 large (Zhou 2002). Due to model uncertainty, we used model averaging to obtain unconditional
308 parameter estimates and variances (Burnham and Anderson 2002). We compared the relative
309 importance of habitat, CBNG, and infrastructure in determining lek persistence by summing
310 Akaike weights across all models containing each class of variable (Burnham and Anderson
311 2002). We also calculated evidence ratios to compare the likelihood of the best approximating
312 habitat-plus-CBNG model versus the best approximating habitat-plus-infrastructure and habitat-
313 only models.

314 To assess whether a known West Nile virus outbreak or habitat loss associated with
315 tillage agriculture disproportionately influenced model selection and interpretation, we also
316 reanalyzed the dataset after removing specific leks. The first analysis excluded 4 leks near
317 Spotted Horse, Wyoming known to have disappeared after 2003 likely due to WNv-related
318 mortality (Walker et al. 2004). The second analysis excluded 20 leks that had ≥5% agriculture at
319 1 or more of the 3 scales examined.

320 To evaluate the effectiveness of the stipulation for no surface infrastructure within 0.4 km
321 of a lek, we examined the estimated probability of lek persistence without development versus
322 that under full CBNG development with a 0.4-km buffer.

323 **Results**

Trends in lek counts. From 2001-2005, lek-count indices in CBNG fields declined by 82%, at a rate of 35% per year (mean rate of increase in CBNG = 0.65, 95% CI: 0.34-1.25) whereas indices outside CBNG declined by 12%, at a rate of 3% per year (mean rate of increase outside CBNG = 0.97, 95% CI: 0.50-1.87) (Figure 2). The mean number of males per active lek was similar for leks in CBNG and outside CBNG in 2001, but averaged 45% ± 8% (mean ± SE; range 33-55%) lower for leks in CBNG from 2002-2005 (Figure 3).

Lek status. Among leks active in 1997 or later, fewer leks remained active by 2004-2005 in CBNG fields (38%) than outside CBNG fields (84%) (Table 1). Of the 10 remaining active leks in CBNG fields, all were classified as being in CBNG in 2000 or later.

Timing of lek disappearance. Of 12 leks in CBNG fields monitored intensively enough to determine the year when they disappeared, 12 became inactive after or in the same year that development occurred (Figure 4). The average time between CBNG development and lek disappearance for these leks was 4.1 ± 0.9 years (mean ± SE).

Lek-status analysis. We analyzed data from 110 leks of known status within the SPOT-5 imagery that were confirmed active in 1997 or later. Proportion sagebrush habitat and proportion tillage agriculture best explained lek persistence at the 6.4-km scale (Table 2). Proportion power lines also best explained lek persistence at the 6.4-km scale (although power line effects at the 3.2-km scale were also supported), whereas proportion roads best explained lek persistence at the 3.2-km scale.

The final model set consisted of 19 models: 2 models based on habitat only (i.e., sagebrush, sagebrush plus tillage agriculture), 4 models with habitat plus power line variables, 4 models with habitat plus road variables, and 9 models with habitat plus CBNG variables (Table 3). Goodness-of-fit testing using the global model revealed no evidence of lack of fit (P = 0.49).

347 Our estimate of the variance inflation factor based on the global model ($\hat{c}$ = 0.96) indicated no
348 evidence of overdispersion, so we based model selection on AIC_c values (Burnham and
349 Anderson 2002).

350 Despite substantial model uncertainty, the top 8 of 19 models all included a moderate to
351 strong positive effect of sagebrush habitat on lek persistence and a strong negative effect of
352 CBNG development, measured either as proportion CBNG development within 0.8 km,
353 proportion CBNG development within 3.2 km, or number of years in a CBNG field. These 8
354 models were well supported, with a combined Akaike weight of 0.96. Five of the 8 models were
355 within 2 ΔAIC_c units of the best approximating model, whereas all habitat-plus-infrastructure
356 and habitat-only models showed considerably less support (> 6 ΔAIC_c units lower). Evidence
357 ratios indicate that the best habitat-plus-CBNG model was 28 times more likely to explain
358 patterns of lek persistence than the best habitat-plus-infrastructure model and 50 times more
359 likely than the best habitat-only model. Models 1 and 2 both included a negative effect of
360 proportion CBNG development within 0.8 km. Models with a negative effect of number of years
361 in CBNG (model 3) or proportion CBNG development within 3.2 km (model 4) also had
362 considerable support. Although regression coefficients suggested that CBNG within 6.4 km also
363 had a negative impact on lek persistence (Table 4), models with CBNG at 6.4 km showed
364 considerably less support (~5-7 ΔAIC_c units lower). Tillage agriculture appeared in 1 well-
365 supported model (model 2), and the coefficient suggested that tillage agriculture had a strong
366 negative effect on lek persistence. However, this effect was poorly estimated, and the same
367 model without tillage agriculture (model 1) was more parsimonious. Regression coefficients
368 suggested negative effects of proximity to power lines and of proportion power line development
369 within 6.4 km (Table 4), but models with power line effects were only weakly supported (~6-8

370 ΔAIC_c units lower) (Table 3). Models containing effects of roads unrelated to CBNG
371 development received little or no support. Coefficients for interaction terms did not support an
372 interaction between habitat and CBNG variables. The best approximating model accurately
373 predicted the status of 79% of 79 active leks and 47% of 31 inactive leks. The summed Akaike
374 weight for CBNG variables (0.97) was almost as large as that of sagebrush habitat (1.00) and
375 greater than that for the effects of tillage agriculture (0.26), power lines (0.02) or non-CBNG
376 roads (0.01). Unconditional, model-averaged estimates and 95% confidence limits for beta
377 estimates and odds ratios show that loss of sagebrush habitat and addition of CBNG development
378 around leks had effects of similar magnitude (Table 4).

379 The model-averaged estimate for the effect of CBNG within 0.8 km was close to that of
380 the best approximating model (model 1, $\beta_{CBNG\ 0.8\ km} = -3.91 \pm 1.11$ SE) (Table 4). Thus, we
381 illustrate the effects CBNG within 0.8 km on lek persistence using estimates from that model
382 (Figure 5a). We also illustrate results from model 3, which indicated that leks disappeared, on
383 average, within 3-4 years of CBNG development (Figure 5b).

384 The current 0.4-km stipulation for no surface infrastructure leaves 75% of the landscape
385 within 0.8 km and 98% of the landscape within 3.2 km open to CBNG development. In an
386 average landscape around a lek (i.e., 74% sagebrush habitat, 26% other land cover types), 75%
387 CBNG development within 0.8 km would drop the probability of lek persistence from 86% to
388 24% (Figure 5a). Similarly, 98% CBNG development within 3.2 km would drop the average
389 probability of lek persistence from 87% to 5%.

390 *Secondary analyses.* Analysis of reduced datasets did not meaningfully change model fit,
391 model selection, or interpretation, nor did it alter the magnitude or direction of estimated CBNG
392 effects. After excluding leks affected by WNv, the top 8 of 19 models and all 3 models within 2

393 ΔAIC_c units included a positive effect of sagebrush within 6.4 km and a negative effect of
394 CBNG development. Model-averaged estimates of CBNG effects were similar to those from the
395 original analysis ($\beta_{Sagebrush\ 6.4\ km} = 3.96 \pm 1.97$ SE; $\beta_{CBNG\ 0.8\ km} = -3.48 \pm 1.15$ SE; $\beta_{CBNG\ 3.2\ km} = -$
396 4.39 ± 1.52 SE; $\beta_{CBNG\ 6.4\ km} = -4.57 \pm 2.06$ SE; $\beta_{Years\ in\ CBNG} = -1.30 \pm 0.61$ SE). After excluding
397 leks with ≥5% tillage agriculture, the top 4 of 11 models and 4 of 5 models within 2 ΔAIC_c units
398 included a positive effect of sagebrush within 6.4 km and a negative effect of CBNG
399 development. Estimates of CBNG effects were again similar to the original model-averaged
400 values ($\beta_{Sagebrush\ 6.4\ km} = 4.03 \pm 2.29$ SE; $\beta_{CBNG\ 0.8\ km} = -3.34 \pm 1.41$ SE; $\beta_{CBNG\ 3.2\ km} = -4.83 \pm 2.06$
401 SE; $\beta_{CBNG\ 6.4\ km} = -4.76 \pm 3.21$ SE; $\beta_{Years\ in\ CBNG} = -2.44 \pm 1.25$ SE).

402 **Discussion**

403 Coal-bed natural gas development appeared to have substantial negative effects on sage-
404 grouse breeding populations as indexed by male lek attendance and lek persistence. Although
405 the small number of transitions (n = 4) in the trend analysis limited our ability to detect
406 differences between trends, effect sizes were nonetheless large and suggest more rapidly
407 declining breeding populations in CBNG fields. Effects of CBNG development explained lek
408 persistence better than effects of power lines, pre-existing roads, WNv mortality, or tillage
409 agriculture, even after controlling for availability of sagebrush habitat. Strong support for
410 models with negative effects of CBNG at both the 0.8-km and 3.2-km scales indicate that the
411 current restriction on surface infrastructure within 0.4 km is insufficient to protect breeding
412 populations. Moreover, support for a lag time between CBNG development and lek
413 disappearance suggests that monitoring effects of a landscape-level change like CBNG may
414 require several years before changes in lek status are detected.

415 Although CBNG development was clearly associated with population declines, the
416 relative contribution of different components of infrastructure to overall population impacts
417 remains unclear. Models with power line effects were weakly supported compared to models
418 with CBNG, but coefficients nonetheless suggested that power lines (including those associated
419 with CBNG) had a negative effect on lek persistence. In our study, non-CBNG roads did not
420 appear to influence lek persistence, even though collisions with vehicles and disturbance of leks
421 near roads can have negative impacts on sage-grouse (Lyon and Anderson 2003, Holloran 2005).
422 This may be because most roads in sage-grouse habitat in the PRB prior to CBNG development
423 were rarely-traveled dirt tracks rather than the more heavily traveled, all-weather roads
424 associated with CBNG development. West Nile virus has also contributed to local lek
425 extirpations in the PRB (Walker et al. 2004). However, unless CBNG development facilitates
426 the spread of WNv into sage-grouse habitat, impacts of the virus should be similar in areas with
427 and without CBNG. Thus, the impact of WNv by itself cannot explain declining breeding
428 populations in CBNG. Rather, increased WNv-related mortality may be an indirect effect of
429 CBNG development (Zou et al. 2006). Other indirect effects, such as changes in livestock
430 grazing due to newly-available CBNG water, or changes in predator abundance caused by
431 addition of ponds or power lines, may also contribute to the cumulative effect of CBNG
432 development on sage-grouse populations.

433 Although CBNG development and loss of sagebrush habitat both contributed to declines
434 in lek persistence, more of the landscape in the PRB has potential for CBNG than for tillage
435 agriculture, which suggests that CBNG may eventually have a greater impact on region-wide
436 populations. In our analyses, we were unable to distinguish between conversion of sagebrush to
437 cropland that would have occurred without CBNG development and that which occurred because

438 CBNG water became available for irrigation following development. Although sage-grouse
439 sometimes use agricultural fields during brood-rearing (Schroeder et al. 1999, Connelly et al.
440 2000*b*), conversion of sagebrush habitat to irrigated cropland in conjunction with CBNG
441 development may be detrimental (Swenson et al. 1987, Leonard et al. 2000, Smith et al. 2005),
442 particularly if birds in agricultural areas experience elevated mortality due to mowing, pesticides,
443 or WNv (Patterson 1952, Connelly et al. 2000*b*, Naugle et al. 2004).

444 Accumulated evidence across studies suggests that sage-grouse populations typically
445 decline following energy development (Braun 1986, Remington and Braun 1991, Braun et al.
446 2002, Holloran 2005), but our study is the first to quantify and separate effects of energy
447 development from those of habitat loss. Our results are similar to those of Holloran (2005:49),
448 who found that "natural gas field development within 3-5 km of an active greater sage-grouse lek
449 will lead to dramatic declines in breeding populations," leks heavily impacted by development
450 typically became inactive within 3-4 years, and energy development within 6.2 km of leks
451 decreased male attendance. As in other parts of their range, sage-grouse populations in the PRB
452 likely have declined due to cumulative impacts of habitat loss combined with numerous other
453 known and unknown stressors. New threats, such as WNv, have also emerged (Naugle et al.
454 2004, Walker et al. 2007). Nonetheless, our analysis indicates that energy development has
455 contributed to recent localized population declines in the PRB. More importantly, the scale of
456 future development in the PRB suggests that, without more effective mitigation, CBNG will
457 continue to impact populations over an even larger area.

458 It is unclear whether declines in lek attendance within CBNG fields were caused by
459 impacts to breeding birds at the lek, reduced survival or productivity of birds in the surrounding
460 area, avoidance of developed areas, or some combination thereof. We simultaneously observed

461 less support for models with CBNG effects and increasing magnitude of those effects at larger
462 scales around leks, but model uncertainty precluded identification of a specific mechanism
463 underlying impacts. Experimental research using a before-after, control-impact design with
464 radio-marked birds would be required to rigorously evaluate these hypotheses. Although this
465 would allow us to identify mechanisms underlying declines, based on our findings and those of
466 others (e.g., Holloran 2005, Aldridge and Boyce 2007, Doherty et al. 2008), such an experiment
467 would likely be detrimental to the affected populations. Nonetheless, ongoing development
468 provides an opportunity to test mitigation measures in an adaptive management framework, with
469 the ultimate goal of determining how to maintain robust sage-grouse populations in areas with
470 CBNG development.

471 **Management implications**

472 Our analysis indicates that maintaining extensive stands of sagebrush habitat over large
473 areas (6.4 km or more) around leks is required for sage-grouse breeding populations to persist.
474 This recommendation matches those of all major reviews of sage-grouse habitat requirements
475 (Schroeder et al. 1999, Connelly et al. 2000*b*, Connelly et al. 2004, Crawford et al. 2004,
476 Rowland 2004). Our findings also refute the idea that prohibiting surface infrastructure within
477 0.4 km of the lek is sufficient to protect breeding populations and indicate that increasing the size
478 of no-development zones around leks would increase the probability of lek persistence. The
479 buffer size required would depend on the amount of suitable habitat around the lek and the level
480 of population impact deemed acceptable. Timing restrictions on construction and drilling during
481 the breeding season do not prevent impacts of infrastructure (e.g., avoidance, collisions, raptor
482 predation) at other times of the year, during the production phase (which may last a decade or
483 more), or in other seasonal habitats that may be crucial for population persistence (e.g., winter).

484 Previous research suggests that a more effective mitigation strategy would also include, at
485 minimum, burying power lines (Connelly et al. 2000*b*), minimizing road and well pad
486 construction, vehicle traffic, and industrial noise (Lyon and Anderson 2003, Holloran 2005), and
487 managing water produced by CBNG to prevent the spread of mosquitos that vector WNv in
488 sage-grouse habitat (Zou et al. 2006, Walker et al. 2007). The current pace and scale of CBNG
489 development suggest that effective mitigation measures should be implemented quickly to
490 prevent impacts from becoming more widespread.

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628 sensing and GIS: implications of coal-bed methane development and West Nile virus.
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Pre-Print Uncorrected

632 Figure 1. Distribution and status of active, inactive, and destroyed greater sage-grouse leks, coal-
633 bed natural gas wells, and major highways in the Powder River Basin, Montana and Wyoming,
634 U.S.A. The dashed line shows the extent of SPOT-5 satellite imagery. This map excludes leks
635 that became inactive or were destroyed prior to 1997 and leks whose status in 2004-2005 was
636 unknown. The status of leks within a lek complex are depicted separately. Dot sizes of active
637 leks represent the final count of displaying males in 2004 or 2005, whichever was the last year
638 surveyed: small = 1-25 males, medium = 26-50 males, large = 51-75 males.
639
640 Figure 2. Population indices based on male lek attendance for greater sage-grouse in the Powder
641 River Basin, Montana and Wyoming, U.S.A., 2001-2005 for leks categorized as in coal-bed
642 natural gas fields or outside coal-bed natural gas fields on a year-by-year basis. Sample sizes in
643 parentheses next to each year-to-year transition indicate the number of leks available for
644 calculating rates of increase for that transition.
645
646 Figure 3. Number of male sage-grouse per active lek in coal-bed natural gas (CBNG) fields
647 (gray) and outside (black) CBNG fields in the Powder River Basin, Montana and Wyoming,
648 U.S.A., 2001-2005. Error bars represent 95% confidence intervals (error bars for leks outside
649 CBNG are too small to be visible). Sample sizes in parentheses above each index indicate the
650 number of active leks available for calculating males per active lek in each year.
651
652 Figure 4. Timing of greater sage-grouse lek disappearance relative to coal-bed natural gas
653 development in the Powder River Basin for leks confirmed active in 1997 or later. Leks above
654 the diagonal line became inactive after CBNG development reached ≥40% within 3.2 km (or

655 >25% development within 3.2 km and ≥1 well within 350 m of the lek center). Small dot = 1
656 lek, medium dot = 2 leks, large dot = 3 leks.
657
658 Figure 5. Estimated lek persistence as a function of proportion sagebrush habitat within 6.4 km
659 and either (a) proportion coal-bed natural gas (CBNG) development within 0.8 km or (b) number
660 of years within a CBNG field for greater sage-grouse leks in the Powder River Basin, Montana
661 and Wyoming, U.S.A., 1997-2005. Means and 95% confidence intervals (dashed lines) are
662 based on parametric bootstrapping. In (a), black lines are estimated lek persistence with no
663 CBNG development, and gray lines are estimated lek persistence with 75% CBNG development
664 within 0.8 km. Seventy-five percent CBNG development within 0.8 km is equivalent to full
665 development under the Bureau of Land Management's current restriction on surface
666 infrastructure within 0.4 km of active sage-grouse leks. In (b), black lines are estimated lek
667 persistence prior to CBNG development, and gray lines are estimated lek persistence after 3
668 years in a developed CBNG field (i.e., ≥40% CBNG within 3.2 km or ≥25% CBNG within 3.2
669 km and ≥1 well within 350 m of the lek center).
670
671

Preliminary

672 Table 1. Status of greater sage-grouse leks in the Powder River Basin, Montana and Wyoming,
673 U.S.A as of 2004-2005, including only leks confirmed active in 1997 or later.

	In CBNG[a]		Outside CBNG[a]	
Lek status[a]	No.	%[b]	No.	%[b]
Active	10	38	211	84
Inactive	16	62	39	16
Unknown	1		43	
Total active + inactive	26		250	

674 [a] See text for definitions of active and inactive leks and for how we catgorized leks as in coal-
675 bed natural gas development (In CBNG) vs. outside coal-bed natural gas (Outside CBNG). Each
676 lek complex counted as one lek.

677 [b] We calculated percentages based only on the total number of active and inactive leks.

Proposed Findings

678 Table 2. Univariate model selection summary for different classes of landscape variables
679 influencing greater sage-grouse lek persistence in the Powder River Basin, Montana and
680 Wyoming, U.S.A., 1997-2005.[a]

Model	LL	K	n	ΔAIC_c	w_i	β	SE
Sagebrush							
6.4 km	-60.05	2	110	0.00	0.70	5.20	1.68
3.2 km	-60.95	2	110	1.81	0.28	4.38	1.53
0.8 km	-63.43	2	110	6.77	0.02	2.26	1.15
Tillage agriculture							
6.4 km	-55.52	2	110	0.00	0.79	-20.98	6.02
3.2 km	-56.83	2	110	2.63	0.21	-19.31	6.30
0.8 km	-60.92	2	110	10.81	0.00	-10.44	4.59
Power lines							
6.4 km	-58.69	2	110	0.00	0.52	-6.06	1.76
3.2 km	-58.81	2	110	0.24	0.46	-4.92	1.43
0.8 km	-62.12	2	110	6.84	0.02	-2.51	0.99
Roads							
3.2 km	-64.59	2	110	0.00	0.50	-2.50	1.99
6.4 km	-65.20	2	110	1.21	0.27	-1.52	2.35
0.8 km	-65.41	2	110	1.63	0.22	-0.08	0.87

681 [a] We present maximum log-likelihood (LL), number of parameters (K), sample size (n), ΔAIC_c
682 values, AIC_c weights (w_i), estimated regression coefficients (β), and standard errors (SE) for each
683 model in each class in order of decreasing maximum log-likelihood. AIC_c = Akaike's

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684 Information Criterion adjusted for small sample size.

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685 Table 3. Model selection summary for hypotheses to explain greater sage-grouse lek persistence
686 in the Powder River Basin, Montana and Wyoming, U.S.A., 1997-2005.[a]

No.	Model[b]	LL	K	n	ΔAIC_c[c]	w_i
1	Sagebrush 6.4 + CBNG 0.8	-51.16	3	110	0.00	0.24
2	Sagebrush 6.4 + Agriculture 6.4 + CBNG 0.8	-50.48	4	110	0.80	0.16
3	Sagebrush 6.4 + Years in CBNG	-51.56	3	110	0.80	0.16
4	Sagebrush 6.4 + CBNG 3.2	-51.70	3	110	1.09	0.14
5	Sagebrush 6.4 * CBNG 0.8	-50.98	4	110	1.81	0.10
6	Sagebrush 6.4 * Years in CBNG	-51.32	4	110	2.48	0.07
7	Sagebrush 6.4 + Agriculture 6.4 + CBNG 3.2	-51.52	4	110	2.88	0.06
8	Sagebrush 6.4 + CBNG 6.4	-53.69	3	110	5.07	0.02
9	Sagebrush 6.4 + Agriculture 6.4 + Dist. power line^2	-53.39	4	110	6.63	0.01
10	Sagebrush 6.4 + Agriculture 6.4 + CBNG 6.4	-53.48	4	110	6.81	0.01
11	Sagebrush 6.4 + Agriculture 6.4	-55.08	3	110	7.84	0.00
12	Sagebrush 6.4 + Power lines 6.4	-55.08	3	110	7.84	0.00
13	Sagebrush 6.4 + Agriculture 6.4 + Power lines 6.4	-54.07	4	110	7.99	0.00
14	Sagebrush 6.4 + Agriculture 6.4 + Dist. road^2	-54.47	4	110	8.78	0.00
15	Sagebrush 6.4 + Agriculture 6.4 + Roads 3.2	-54.49	4	110	8.83	0.00
16	Sagebrush 6.4 + Dist. power line^2	-57.36	3	110	12.41	0.00
17	Sagebrush 6.4	-60.05	2	110	15.67	0.00
18	Sagebrush 6.4 + Roads 3.2	-59.39	3	110	16.46	0.00
19	Sagebrush 6.4 + Dist. road^2	-59.46	3	110	16.62	0.00

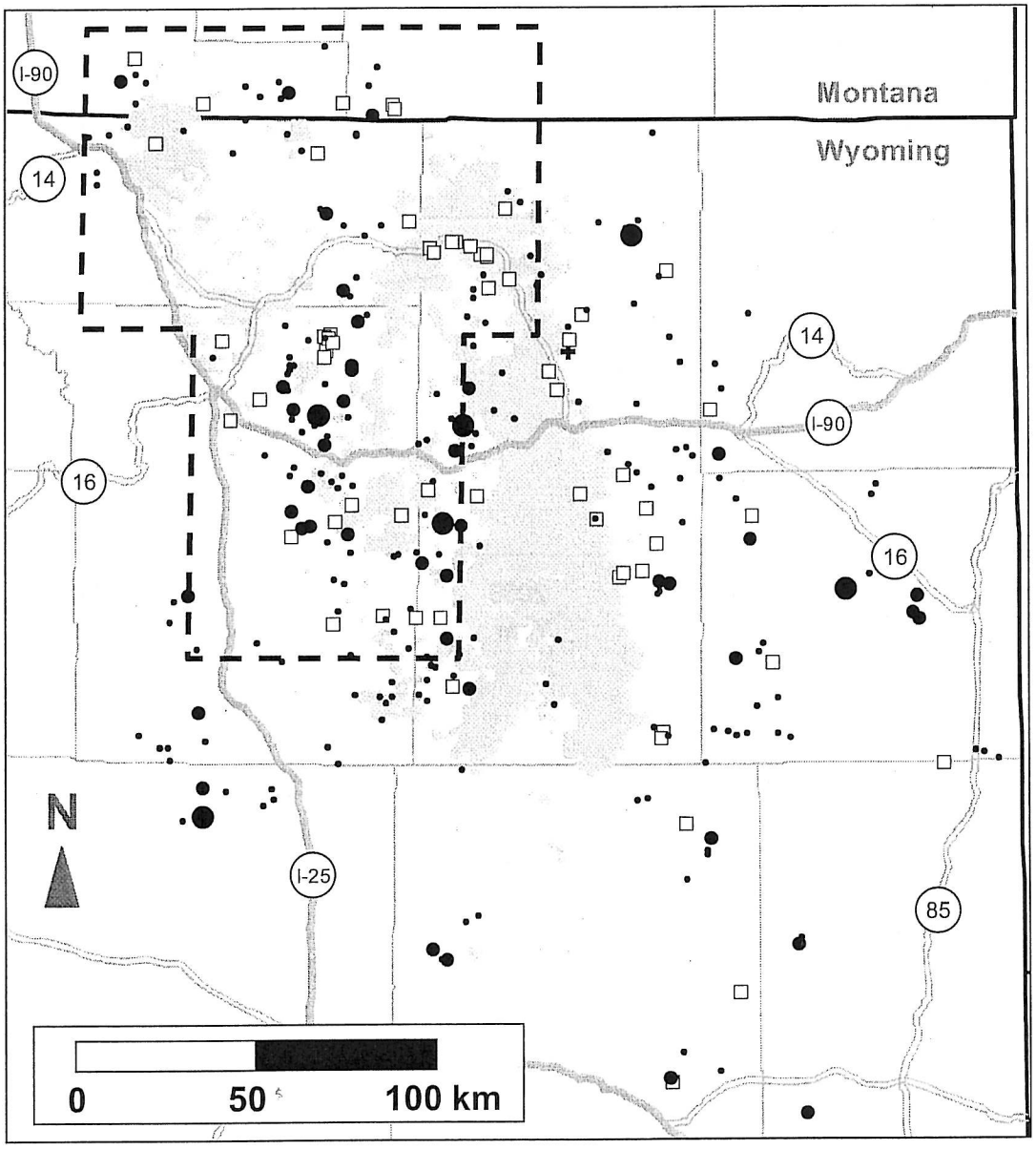
687 [a] We present maximum log-likelihood (LL), number of parameters (K), sample size (n), ΔAIC_c
688 values, and AIC_c weights (w_i) for each model in order of increasing ΔAIC_c units, starting with
689 the best approximating model. AIC_c = Akaike's Information Criterion adjusted for small sample
690 size.
691 [b] CBNG = coal-bed natural gas development. Numbers refer to the radius (km) around the lek
692 at which the variable was measured.
693 [c] The AIC_c value of the best approximating model in the analysis was 108.54.

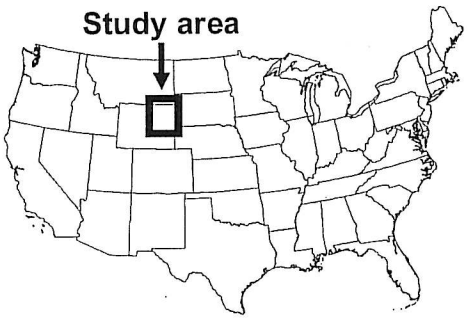
Pre-Print In-Press

694 Table 4. Model-averaged estimates of regression coefficients (β) and standard errors (SE), odds
695 ratios, and lower and upper 95% confidence limits on odds ratios for effects of landscape
696 variables on greater sage-grouse lek persistence in the Powder River Basin, Montana and
697 Wyoming, U.S.A., 1997-2005.

Variable[a]	β	SE	Odds Ratio	Lower CL	Upper CL
Intercept	-1.25	1.40			
Sagebrush	4.06	2.03	58.241	1.083	3131.682
Agriculture	-8.76	8.73	1.57×10^{-4}	5.81×10^{-12}	4.22×10^{3}
Dist. power line[2]	1.72	1.27	5.603	0.462	67.925
Power lines	-4.52	2.40	0.011	0.0001	1.203
Dist. road[2]	0.62	0.67	1.86	0.505	6.859
Roads	-2.38	2.23	0.092	0.001	7.331
CBNG 0.8 km	-3.67	1. 18	0.026	0.003	0.257
CBNG 3.2 km	-4.72	1.50	0.009	0.001	0.169
CBNG 6.4 km	-5.11	2.04	0.006	0.0001	0.328
Years in CBNG	-1.41	0.58	0.244	0.078	0.761

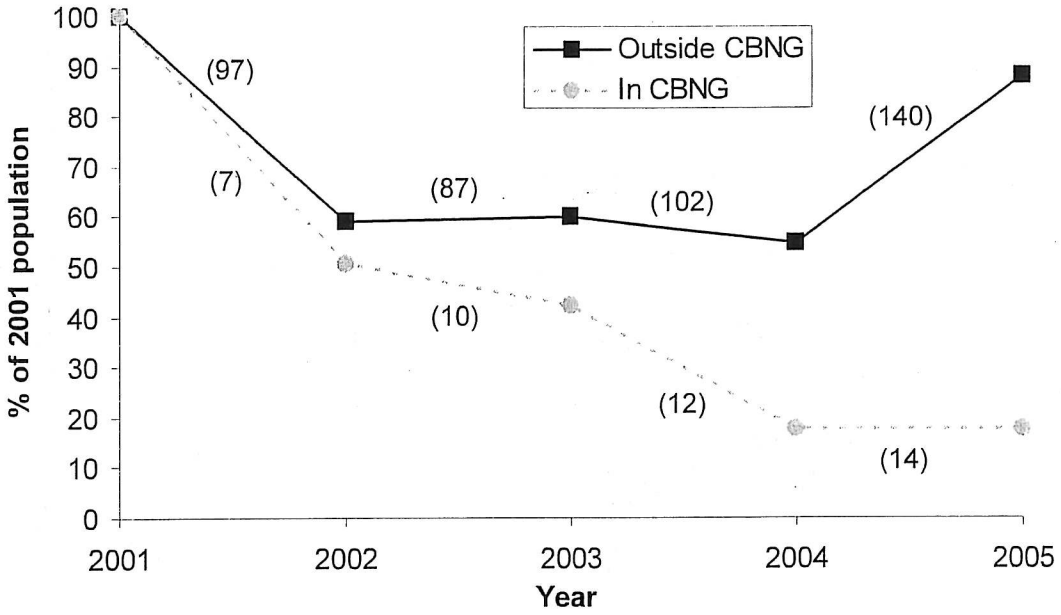
698 [a] CBNG = coal-bed natural gas development. The estimated regression coefficient for Years in
699 CBNG could only be derived from 1 model.





Boundary of SPOT-5 satellite imagery
Coal-bed natural gas wells
Inactive lek
Destroyed lek
Active lek:
- Small (1-25 males)
- Medium (26-50 males)
- Large (51-75 males)

Figure 2



Pre-Print

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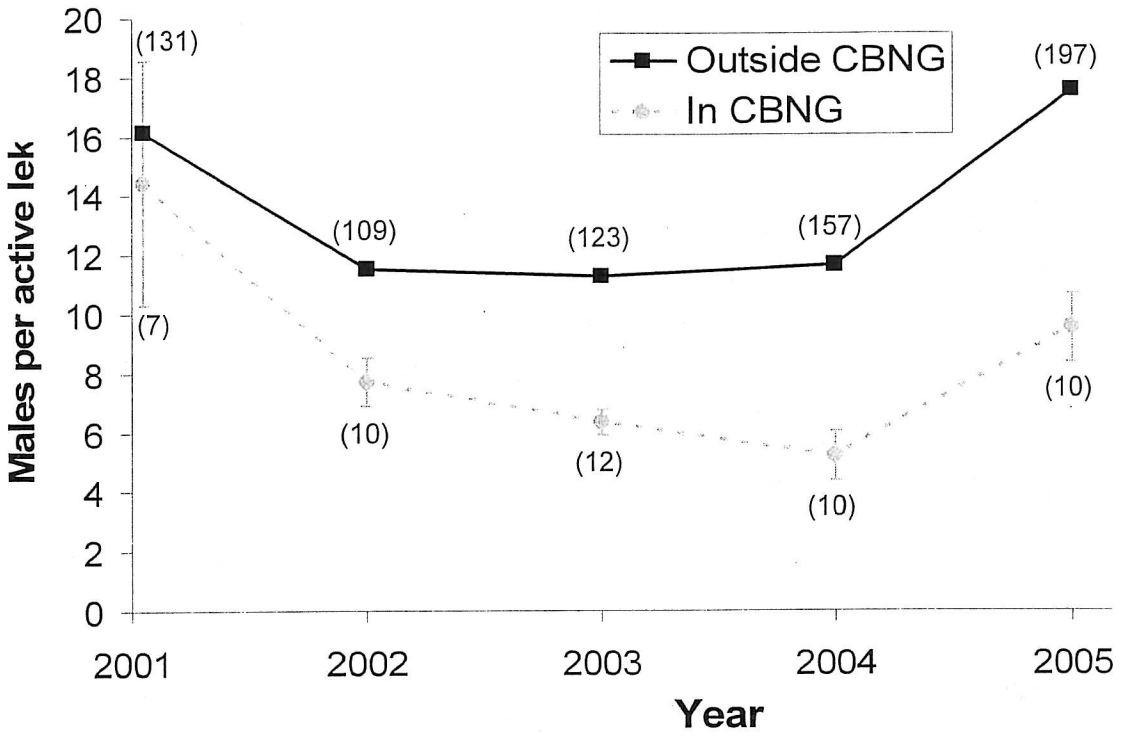
Figure 3



Preprint

Walker et al.

Figure 4

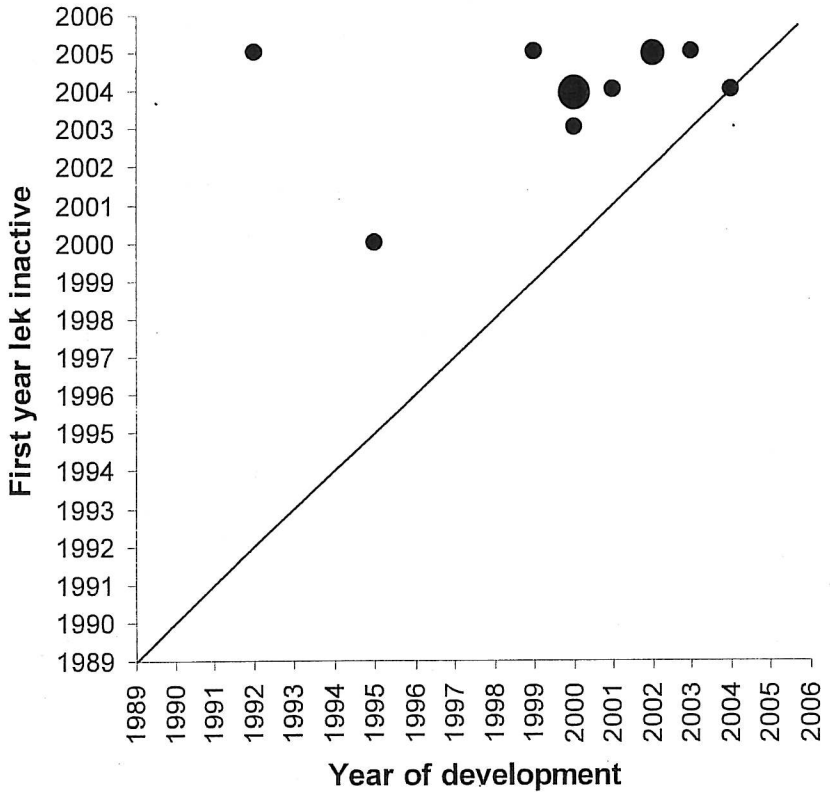


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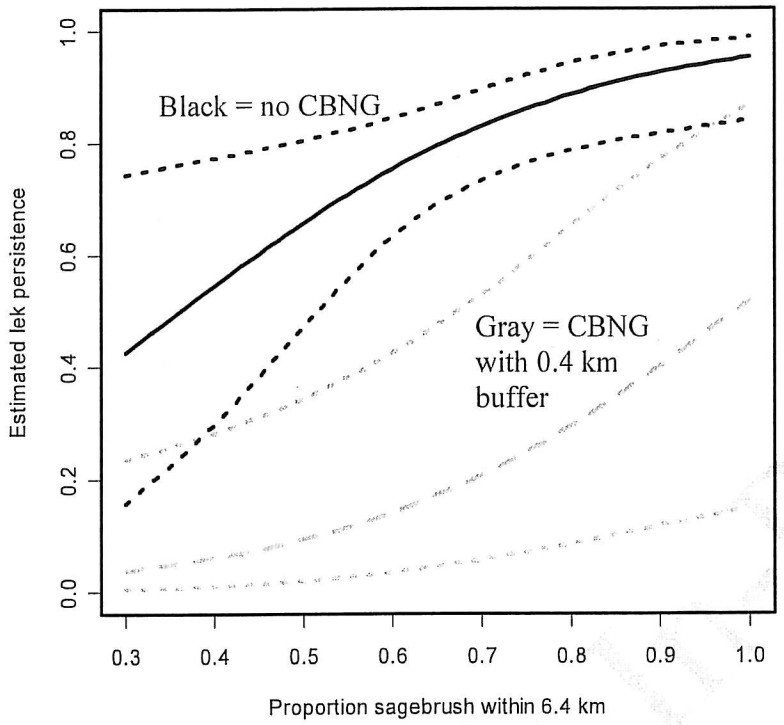
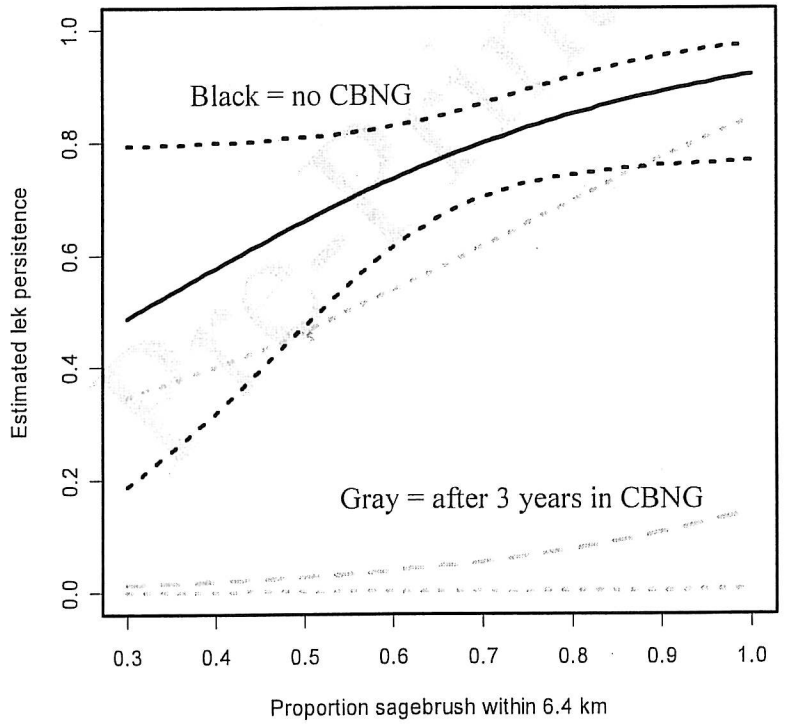
Figure 5

a



b