

Raptor nest-site use in relation to the proximity of coalbed-methane development

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Abstract

Raptor nest-site use in relation to the proximity of coalbed-methane development. Energy development such as coalbed-methane (CBM) extraction is a major land use with largely unknown consequences for many animal species. Some raptor species may be especially vulnerable to habitat changes due to energy development given their ecological requirements and population trajectories. Using 12,977 observations of 3,074 nests of 12 raptor species across nine years (2003–2011) in the Powder River Basin, Wyoming, USA, we evaluated relationships between raptor nest-site use and CBM development. Our objectives were to determine temporal trends in nest-use rates, and whether nest-site use was related to the proximity of CBM development. Across the study area, nest-use rates varied across species and years in a non-linear fashion. We developed a novel randomization test to assess differences in use between nests at developed and undeveloped sites, while controlling for annual variation in nest-site use. Red-tailed hawks (*Buteo jamaicensis*), burrowing owls (*Athene cunicularia*), and long-eared owls (*Asio otus*) used nests in undeveloped areas more than nests in developed areas (i.e. nests near CBM development). Differences between development groups were equivocal for the remaining nine species; however, we caution that we likely had lower statistical power to detect differences for rarer species. Our findings suggest potential avoidance of nesting in areas near CBM development by some species and reveal that CBM effects may be fairly consistent across distances between 400–2,415 m from wells. Future work should consider habitat preferences and fitness outcomes, and control for other key factors such as local prey availability, raptor densities, and weather.

Key words: Raptors, Coalbed methane, Energy development, Nest-site use, Wildlife conservation, Randomization test

Resumen

Uso de los sitios de nidificación en rapaces en relación con la proximidad de yacimientos de metano en capas de carbón. Las actividades de generación de energía como la extracción de metano en capas de carbón es un uso importante de la tierra que tiene consecuencias prácticamente desconocidas para numerosas especies de animales. Algunas especies de rapaces, dadas de sus necesidades y su evolución demográfica, pueden ser especialmente vulnerables a los cambios en el hábitat provocados por la generación de energía. Utilizando 12.977 observaciones de 3.074 nidos de 12 especies de rapaces durante nueve años (2003–2011) en la cuenca del río Powder, en Wyoming, EE.UU., evaluamos la relación entre el uso de los sitios de nidificación de las rapaces y la extracción de metano en capas de carbón. Nuestros objetivos fueron determinar tendencias temporales en los índices de utilización de nidos y si el uso de los sitios de nidificación estaba relacionado con la proximidad a yacimientos de metano en capas de carbón. En la zona de estudio, los índices de utilización de los nidos variaron en función de la especie y de los años de forma no lineal. Elaboramos una nueva prueba de aleatorización para evaluar las diferencias de uso entre los nidos en zonas extractivas y zonas no extractivas, a la vez que se controlaba la variación anual del uso de los sitios de nidificación. El ratonero de cola roja (*Buteo jamaicensis*), la lechuza madriguera (*Athene cunicularia*) y el búho chico (*Asio otus*) utilizaron nidos en zonas no extractivas más que en zonas extractivas (es decir, nidos cercanos a yacimientos de metano en capas de carbón). Las diferencias entre los grupos fueron ambiguas para las otras nueve especies; no obstante, hemos

de advertir que probablemente teníamos menor potencia estadística para detectar diferencias en especies menos frecuentes. Nuestros resultados sugieren que algunas especies podrían evitar nidificar en zonas cercanas a los yacimientos de metano en capas de carbón y revelan que los efectos de esta sustancia pueden ser relativamente constantes en un radio de entre 400 y 2.415 m de los pozos. En estudios futuros se deberían analizar a las preferencias de hábitat y a la eficacia biológica, y controlar otros factores decisivos como la disponibilidad de presas en el ámbito local, la densidad de rapaces y las condiciones meteorológicas.

Palabras clave: Rapaces, Metano en capas de carbón, Generación de energía, Uso de sitios de nidificación, Conservación de la fauna silvestre, Prueba de aleatorización

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Introduction

Human-induced habitat changes can alter the ability of landscapes to support wildlife populations (Munns, 2006) via behavioral avoidance of disturbed areas (Frid and Dill, 2002; Blumstein, 2006; Sih, 2013), loss of critical habitat elements (Cristine and Kerr, 2011), and/or fitness consequences (i.e. decreased survival and/or reproduction; Acevedo-Whitehouse and Duffus, 2009; Kociolek et al., 2011). Energy development (i.e. oil, natural gas, coal, solar and wind) continues to increase as a global land use and a ubiquitous form of human-induced habitat change (U.S. Energy Information Administration, 2013; Allred et al., 2015; Jones et al., 2015), with largely unknown consequences for wildlife (Gilbert and Chalfoun, 2011; Garvin et al., 2011; Northrup and Wittemyer, 2013;). Coalbed natural gas, also known as coalbed methane (hereafter, CBM), has emerged in recent decades as an alternative source of natural gas extracted from coal beds (U.S. Geological Survey, 2000). CBM development can influence wildlife habitat, demographic rates, and population persistence (Walker et al., 2007; Doherty et al., 2008; Buchanan et al., 2014). Identifying patterns of habitat use over time in relation to human activity such as CBM development is a critical first step in assessing development-related effects on wildlife (Kennedy et al., 2014).

Birds of prey, including members of the orders Accipitriformes (e.g., hawks, eagles, harriers, and vultures), Falconiformes (e.g., falcons), and Strigiformes (e.g., owls), (hereafter, raptors) play important roles in their ecological communities, can serve as indicators of biodiversity and/or environmental degradation, and often have a high profile in the public eye and in conservation strategies (Sergio et al., 2005; Bart et al., 2006; Burgas et al., 2014; Donazar et al., 2016). Concomitant with expanded energy development worldwide, raptors have garnered increased conservation attention as a result of regional population declines (Woffinden and Murphy, 1989; Kochert and Steenhof, 2002) and demonstrated sensitivity to habitat change (Krüger, 2002; Brown et al., 2014; Coates et al., 2014) and human activities (Suter and Jones, 1981; Martínez-Abraín et al., 2010). Furthermore, federal laws and international treaties applicable in many parts of the world have been established to protect raptor species (e.g., Migratory Bird Treaty Act, Bald and Golden Eagle Protection Act, Endangered Species Act, Birds Directive, and Berne Convention; Romin and Muck, 2002; Stroud, 2003), making the assessment and monitoring of impacts from anthropogenic activities a primary concern for many government agencies.

For birds, including raptors, the nesting period is a critical life history stage in terms of fitness and population viability (Stahl and Oli, 2006). Human activities such as energy development that encroach upon historic nesting habitats may elicit behavioral avoidance (Krüger, 2002; Coates et al., 2014; Johnston et al., 2014) or indirectly affect nesting success (Hethcoat and Chalfoun, 2015a). Because raptors tend to exhibit high fidelity to nesting areas (Newton, 1979; Millsap et al., 2015) and often reuse the same nests, changes in

nest-site use over time could signal the existence of one or both of the aforementioned effects and warrant further examination. Monitoring activities that identify potential changes in raptor nesting habitat use with respect to energy development will be particularly important for management prescriptions geared towards maintaining sustainable raptor populations.

Our main objective was to determine whether the proximity of CBM development influenced raptor nest-use rates. Determining the risks that wildlife face from anthropogenic stressors such as energy development is often difficult because individual species may react to stressors differently, the appropriate scale of analysis can be unclear, and available datasets are typically limited (Munns, 2006). Here, we leverage a large, long-term dataset that overcomes these challenges by including multiple species, spatially-explicit data analyzed at multiple spatial scales, and several thousand observations spanning nearly a decade. Our specific objectives were to (1) determine temporal trends in raptor nest-use rates, by species; (2) examine whether nest-use rates were related to the proximity of the nest to CBM development; and (3) investigate whether effects were consistent across multiple distance-to-development thresholds.

Material and methods

Study area

Data for our study were collected in the Powder River Basin (PRB), one of the region's key raptor areas (Olendorff and Kochert, 1992). The PRB includes ~29,800 km², overlapping Campbell, Johnson, and Sheridan counties in northeast Wyoming, USA (44.2° N, 106.15° W; fig. 1). The PRB (excluding the Bighorn Mountains on the PRB's western border) is characterized by a mixture of lowlands, rugged badlands, and steep buttes ranging in elevation from ~1,000–1,600 m (Knight, 1994). The climate is semi-arid, with average annual precipitation of ~25–40 cm (Knight, 1994). The dominant land cover types (Homer et al., 2015) within the study area were grasslands (54.8 % of land area), shrublands (30.2%), and forests (10.3 %, primarily concentrated in the Bighorn Mountains). Land cover types associated with anthropogenic activities were relatively uncommon, with 1.4 % of the land area classified as planted/cultivated agricultural lands, and 0.8 % of the area classified as developed (Homer et al., 2015). Approximately 83,800 people lived in the PRB in 2010, with a human population density of 2.81 persons/km² (U.S. Census Bureau, 2017). The majority of the human population in the PRB (61.0%) was concentrated in only three cities: Gillette, Sheridan, and Buffalo (U.S. Census Bureau, 2017). Dominant human land uses within the study area included energy development (i.e., oil and natural gas extraction, coal mining), agriculture, and livestock ranching/grazing.

From 2003–2011, Wyoming was responsible for 20–30 % of the CBM production within the United States (U.S. Energy Information Administration, 2014),

with the PRB being one of the most productive CBM areas nationwide (U.S. Geological Survey, 2000). Much of the land surface and/or subsurface (i.e. mineral rights) within the PRB was managed by the U.S. Bureau of Land Management (BLM) through its Buffalo Field Office. The BLM required energy developers requesting permits for new CBM wells to survey for nesting raptors within 805 m (0.5 miles) of proposed development sites for the first five years following proposal submission (Powder River Basin Wildlife Taskforce, 2005). Through the duration of the study, well construction and other surface disturbances were restricted within 805 m of occupied raptor nests between 1 February and 31 July to avoid disturbance to breeding raptors. Most raptor nests in this study were either located on private land, or landlocked by private land and difficult for the public to access.

Field methods and data preparation

Surveys were conducted by private contractors in accordance with BLM-suggested protocols (Powder River Basin Wildlife Taskforce, 2005). Field personnel visually surveyed for new nests near proposed development sites each year from 2003 to 2011 (Andersen, 2007). Once nests were located, they were surveyed at least once between 15 April and 15 June during the year of discovery for signs of nesting activity within the nesting season (e.g., presence of adult, eggs or juveniles in nest, evidence of depredated nest contents, or evidence of abandoned eggs). Most unoccupied nests were visited twice each year to verify their activity status. Surveys were conducted by viewing the nest from the ground with optics, taking care not to disturb adults or juveniles in the nest (Steenhof and Newton, 2007). If a proposed well site had an active raptor nest very close by, such that biologists felt it could be influenced by daily activities associated with the well, the proposed well was often relocated (B. Ostheimer, personal communication). Only a portion (~70%) of nests documented in previous years were surveyed in any given subsequent year through 2011.

Not all planned CBM development took place; therefore, our sample included nests that had active CBM wells nearby and those that did not, thereby facilitating a comparison between nest-use rates at developed and undeveloped sites. The construction and decommission of CBM wells occurred throughout the duration of our study; therefore, nests changed development group assignments over the course of the study. To categorize nests into undeveloped and development groups annually, we obtained point locations of CBM wells (Wyoming Oil and Gas Conservation Commission, 2012). Each CBM well had a recorded date of construction; however, reliable information regarding the lifespan and removal of individual CBM wells was unavailable. We therefore assumed a 10-year lifespan for each CBM well in our study, as a conservative estimate of the production lifespan of individual CBM wells (International Energy Agency, 2012; De Bruin et al., 2013; Riazi and Gupta, 2016) and defined 'active wells' as those constructed within the last 10 years. After a CBM well is decommissioned,

very little human disturbance takes place at the well pad (B. Ostheimer, personal communication).

We calculated the distance from each nest to the nearest active CBM well annually using the *sp* (Pebesma and Bivand, 2005), *rgdal* (Bivand et al., 2016), and *rgeos* (Bivand and Rundel, 2016) packages in Program R (R Core Team, 2016). We considered nests ≤ 805 m from the nearest active CBM well to be nests at developed sites, and those > 805 m from the nearest active well to be nests at undeveloped sites. The 805-m threshold is reflective of the survey methods used to locate nests and thus maintained conformity between data collection and analytical methods. We assigned each nest site to one raptor species and excluded all nests from analysis that were used by more than one species during our study period.

Statistical analysis

We treated each nest as an independent sampling unit, after an examination of sample variograms (Pebesma, 2004) suggested a lack of spatial autocorrelation in nest-use across a range of nest proximities for the most abundant species, red-tailed hawk (*Buteo jamaicensis*). We constructed a nine-year nest-use history for each nest spanning 2003–2011, classifying each nest as occupied, unoccupied, or not surveyed for each year based on survey data. Nests in the dataset were not consistently surveyed multiple times within a year, which limited our ability to assess detection probability and utilize multi-season occupancy modeling, a common method used to estimate yearly occupancy rates corrected for imperfect detection (MacKenzie et al., 2006). Instead, we calculated an annual nest-use rate as the number of nests observed in use divided by the number of nests surveyed for each year. We conducted all analyses separately for each raptor species using Program R (R Core Team, 2016).

Overall trends in nest-use rates

We first summarized all nest data without regard to nearby CBM development. We calculated the yearly proportion of nests in use by species across the nine-year study to examine long-term trends and interspecific differences in nest-use rates. We generated 95% confidence intervals (CIs) for the yearly proportion of nests in use using a bootstrapping routine with 1,000 iterations, where nests in each group (e.g., all bald eagle, *Haliaeetus leucocephalus*, nests surveyed in 2003) were resampled with replacement (Manly, 1997; Carlisle and Albeke, 2016). No CIs appear in figures when there was no variation in nest use within the sample. We also summarized each species' nine annual nest-use rates into an overall mean nest-use rate using a weighted mean, where weights were proportional to the number of nests surveyed in that year. This had the effect of treating each observation of a nest as a datum, rather than the observed proportion in a year as such. For instance, in a two-year study with 40 of 100 sites used in year one and both of two sites used in year two, an unweighted average of the two proportions would

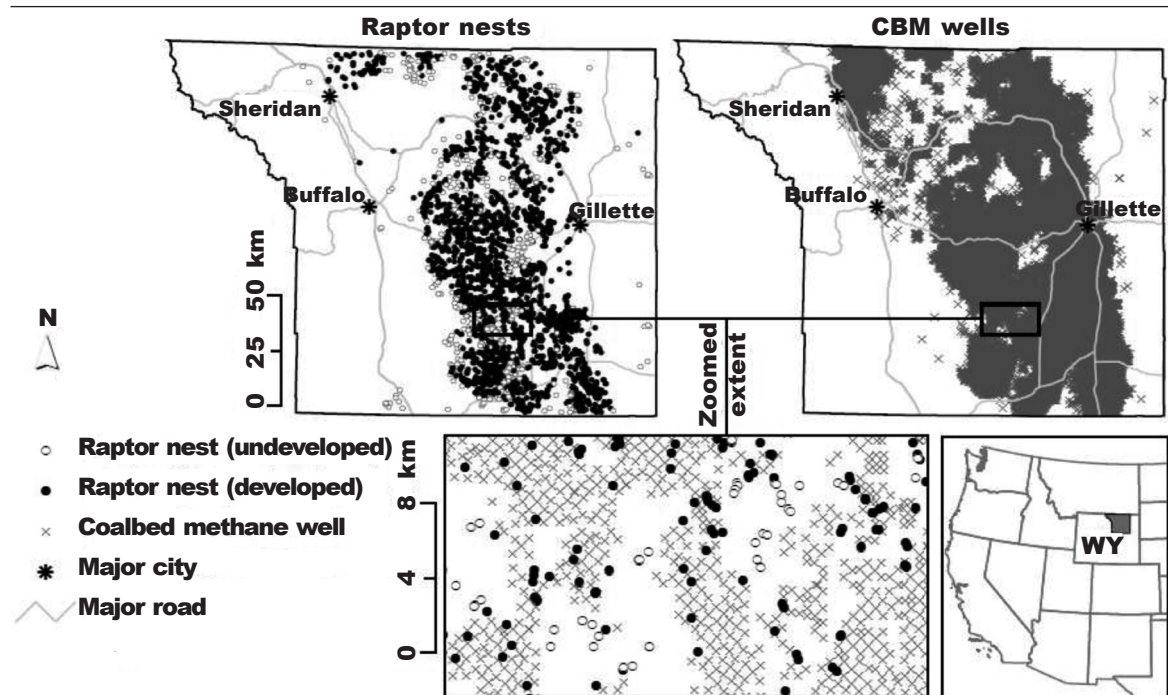


Fig. 1. Map of the Powder River Basin, Wyoming study area. Raptor nests of 12 species are shown ($n = 3,074$) as well as coalbed methane wells ($n = 28,786$). The inset map shows the proximity and distribution of nests at undeveloped sites (white circles) and developed sites (black circles) relative to wells (grey exes) within a zoomed extent. Where wells are highly dense, exes overlap each other and appear as grey polygons.

Fig. 1. Mapa de la zona de estudio en la cuenca del río Powder, en Wyoming. Se indican los nidos de 12 especies de rapaces ($n = 3.074$) y los pozos de metano en capas de carbón ($n = 28.786$). En el mapa ampliado se muestran la proximidad de los nidos a las zonas no extractivas (círculos blancos) y a las zonas extractivas (círculos negros) y su distribución en relación con los pozos (cruces grises). Donde los pozos están densamente distribuidos, las cruces se superponen entre sí y parecen polígonos grises.

yield an estimate of $(0.4 + 1.0)/2 = 0.7$. Weighting by the number surveyed each year effectively reflected that there were 102 observations, of which 42 (41.2%) were occupied.

Nest use relative to CBM development

We employed a control–impact statistical design to test for differences in nest use between nests at undeveloped and developed sites. For each species, we calculated this difference separately within each year, then summarized the annual differences into one overall nine–year measure. Because many nests did not include observations both before and after the construction of a nearby well, we lacked the temporal replication required to utilize a paired design (e.g., before–after–control–impact; Gotelli and Ellison, 2004). For each species, we compared the yearly proportion of nests in use between nests at developed and undeveloped sites across the nine–year study to examine whether nest–use rates were related to the

proximity of CBM development. To do so, we constructed a nine–year development–group history for each nest spanning the same period and assigning each nest to the developed or undeveloped group for each year based on CBM well locations and assumptions about well lifespan and an initial distance threshold of 805 m. Therefore, each nest was represented in our dataset as a nine–year nest–use history, a nine–year development–group history, and a species.

To summarize the CBM effect, we first calculated the difference in nest use between development groups (undeveloped–developed; therefore, positive values indicated higher nest use at undeveloped sites relative to developed sites) for each year, and then summarized those differences into one overall species–level measure using a weighted mean of the yearly differences. Because the number of nests within each development group varied from year to year, we weighted each year’s contribution to the overall mean difference, where weights were proportional to the inverse of the variance of the difference

between development group sample sizes. This was analogous to weighted least squares regression (Ramsey and Shafer, 2013), since sample variances are at least approximately inversely proportional to sample sizes. Thus for year i , the weight (w) was calculated using the following equation, where subscripts d and u stand for nests at developed and undeveloped sites, respectively:

$$\begin{aligned} w_i &= \frac{1}{V} \left(\frac{n_{id} n_{iu}}{n_{id} + n_{iu}} \right) / \sum_{i=1}^9 \frac{1}{V} \left(\frac{n_{id} n_{iu}}{n_{id} + n_{iu}} \right) \\ &= \frac{1}{V} \left(\frac{n_{id} n_{iu}}{n_{id} + n_{iu}} \right) / \frac{1}{V} \sum_{i=1}^9 \left(\frac{n_{id} n_{iu}}{n_{id} + n_{iu}} \right) \\ &= \left(\frac{n_{id} n_{iu}}{n_{id} + n_{iu}} \right) / \sum_{i=1}^9 \left(\frac{n_{id} n_{iu}}{n_{id} + n_{iu}} \right) \end{aligned}$$

We developed a randomization test to assess whether rates of nest use differed between development groups for each species. A randomization test is a non-parametric method for null hypothesis testing that was well suited to our study because the test can be adapted to accommodate non-standard test statistics, does not rely on parametric assumptions, and does not require random sampling of the population (Manly, 1997). The procedure of our randomization test mimicked the design and implementation of the study and employed a control-impact statistical design that treated each nest as a sampling unit, with each species analyzed separately. The null hypothesis was that development (i.e., being near a CBM well) had no effect on nest-use rates. We used 1,000 iterations of the following steps to simulate the repetition of the study where the null hypothesis was true, thus generating the null distribution against which to test our observed statistic (nine-year average difference in nest use between nests at undeveloped and developed sites). The principal mechanism for each iteration of the randomization test was reassigning each nest to a random development group, implying that if the null hypothesis were true, the assignment to development groups of each nest was meaningless. We first selected all nests that were surveyed in the first year of the study and randomized their development group assignments, maintaining the original, relative balance between the numbers of nests within each development group within that year. We then repeated that process for each year of the study. Because nests moved between development groups during the study period as CBM wells were built and decommissioned, we did not require nests in the randomization procedure to retain their development assignments across years. After randomizing development group assignments, we recalculated the statistic of interest (nine-year average difference in nest use between nests at undeveloped and developed sites) as previously described. All randomization tests were two-tailed and used $P < 0.05$ as the criterion to reject the null hypothesis.

Table 1. Sample size (n) of nests for each species of raptor documented nesting near planned areas of coalbed methane development in the Powder River Basin, Wyoming between 2003–2011: * species with fewer than 15 nests (excluded from analysis due to small sample size).

Tabla 1. Tamaño de la muestra (n) de nidos para cada especie de rapaz que se haya documentado nidificando cerca de yacimientos de metano en capas de carbón en la cuenca del río Powder, en Wyoming, entre los años 2003 y 2011: * especies con menos de 15 nidos (se excluyeron del análisis debido al reducido tamaño de la muestra).

Common name	Scientific name	n
Turkey vulture*	<i>Cathartes aura</i>	2
Bald eagle	<i>Haliaeetus leucocephalus</i>	28
Northern harrier	<i>Circus cyaneus</i>	28
Sharp-shinned hawk*	<i>Accipiter striatus</i>	1
Cooper's hawk	<i>Accipiter cooperii</i>	16
Swainson's hawk	<i>Buteo swainsoni</i>	90
Red-tailed hawk	<i>Buteo jamaicensis</i>	1,046
Ferruginous hawk	<i>Buteo regalis</i>	933
Golden eagle	<i>Aquila chrysaetos</i>	283
Barn owl*	<i>Tyto alba</i>	1
Great horned owl	<i>Bubo virginianus</i>	286
Burrowing owl	<i>Athene cunicularia</i>	139
Long-eared owl	<i>Asio otus</i>	87
Short-eared owl*	<i>Asio flammeus</i>	9
American kestrel	<i>Falco sparverius</i>	108
Merlin*	<i>Falco columbarius</i>	3
Peregrine falcon*	<i>Falco peregrinus</i>	4
Prairie falcon	<i>Falco mexicanus</i>	30

Alternative distance thresholds

The 805-m threshold dividing nests at developed from undeveloped sites was dictated largely by the BLM's protocols for nest searching, and most nest observations (73.5% when pooled across years and species) were from nests within 805 m of a CBM well (table 1s). The dataset did, however, include some nests farther from CBM development (likely because planned developments did not all take place), especially for abundant species. We therefore repeated the analysis using three additional distance thresholds to test whether our comparisons of nest use rates by development group were sensitive to the distance used to classify nests as either at a

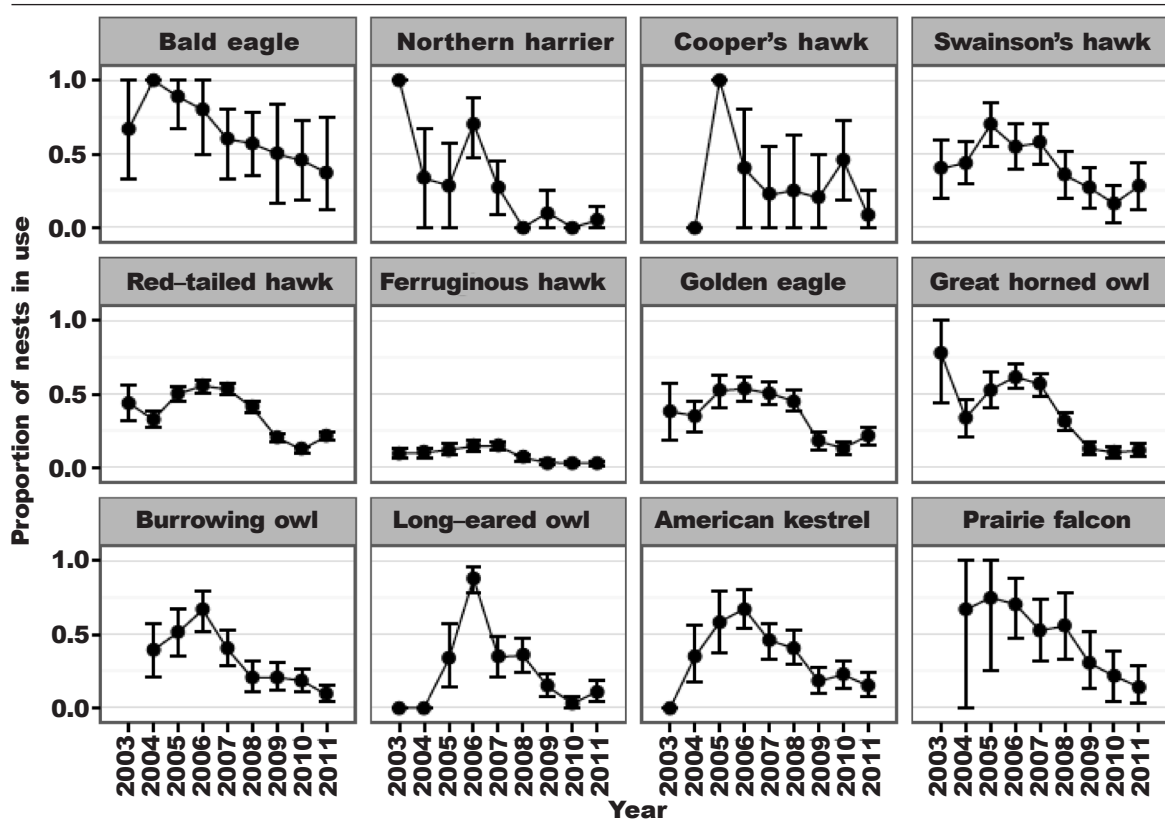


Fig. 2. The annual proportion (± 95% CI) of raptor nests in use from 2003–2011 in the Powder River Basin, Wyoming, USA.

Fig. 2. Proporción anual (± 95% IC) de nidos de rapaces en uso entre 2003 y 2011 en la cuenca del río Powder, en Wyoming, EE.UU.

developed or undeveloped site. These additional distance criteria were approximately half, twice, and three times as large as the original distance criteria (400 m, 1,610 m and 2,415 m, respectively). Because most nests monitored were near CBM development, not all species had nests far enough from CBM wells to have nests in the 'undeveloped' category when the larger distance criteria were applied. Therefore, we restricted this portion of the analysis to the four species for which there were nests in both development groups at even the 2,415 m distance criteria (i.e. red-tailed hawk; ferruginous hawk, *Buteo regalis*; golden eagle, *Aquila chrysaetos*; and great horned owl, *Bubo virginianus*).

Results

We analyzed 12,977 observations from 3,074 raptor nests of 12 species conducted across nine years (table 1). The four most prevalent species (red-tailed hawk, ferruginous hawk, golden eagle, and great horned owl) accounted for the vast majority (82.9 %, $n = 2,548$) of nests. When pooled across years and the

four most abundant species, 54.4 % of observations were from nests within 400 m of a CBM well, 88.8% within 1,610 m, and 94.4% within 2,415 m. Based on our assumption of well lifespan, there were ~14,000 active wells in the PRB when the study began in 2003. Wells were constructed at a fairly constant rate between 2003 and 2009, when the number of active wells peaked at ~26,000. Well counts then declined to ~21,000 active wells in 2011 (fig. 1s).

Annual trends in nest-use rates

The mean proportion of nests in use varied from year to year. Trends in nest use were non-linear and cyclical in appearance, especially for those species with larger sample sizes (fig. 2). Trends were fairly consistent across species; for most, the peak of nest use was in 2005 or 2006, and the lowest between 2009 and 2011 (fig. 2). The average proportion of nests in use varied across species, as did the magnitude of changes in use from year to year (fig. 2). Bald eagles had the highest overall average use (63.6 %), whereas ferruginous hawks had the lowest (8.2 %). All other species averages ranged from 19.5–42.6 % (table 2s).

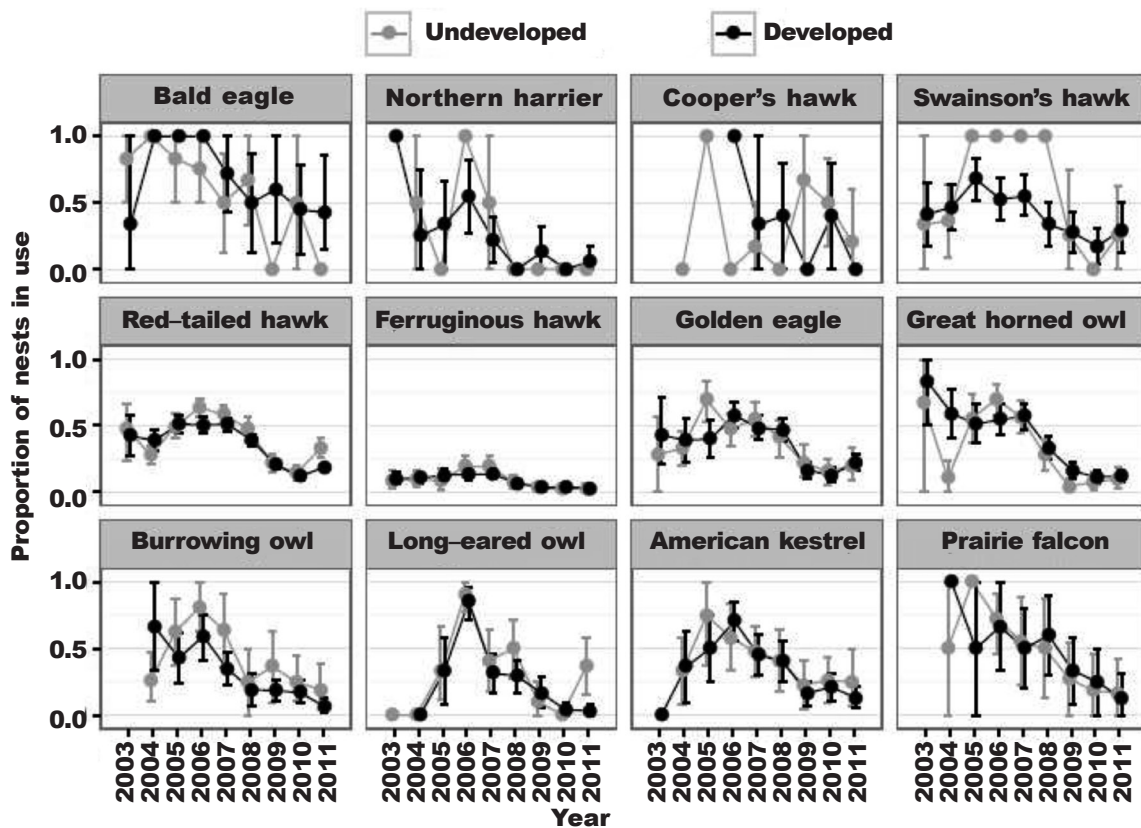


Fig. 3. The annual proportion (\pm 95% CI) of raptor nests in use, by development group, from 2003–2011 in the Powder River Basin, Wyoming, USA. Nests at developed sites were those \leq 805 m from the nearest active coalbed methane well, and nests at undeveloped sites were those $>$ 805 m from the nearest active coalbed methane well.

Fig. 3. Proporción anual (\pm 95% IC) de nidos de rapaces en uso, por grupo de extracción, entre 2003 y 2011 en la cuenca del río Powder, en Wyoming, EE.UU. Los nidos en zonas extractivas se encontraban a \leq 805 m del pozo activo de metano en capas de carbón más cercano, mientras que los nidos en zonas no extractivas se encontraban a $>$ 805 m del pozo activo de metano en capas de carbón más cercano.

Nest use relative to CBM development

Trends in nest use were similar between nests at undeveloped and developed sites for most species (fig. 3). Nests at undeveloped sites had higher use than nests at developed sites for red-tailed hawks (effect size = 5.1%, $P < 0.01$), burrowing owls (*Athene cunicularia*, 11.5%, $P = 0.02$), and long-eared owls (*Asio otus*, 9.5%, $P = 0.02$; fig. 4). Of the remaining nine species, differences in nest use between development groups were equivocal at the $\alpha = 0.05$ level (fig. 4). We likely had minimal statistical power to detect any effect of CBM development on nest use for rarer species, however, which had smaller sample sizes.

Alternative distance thresholds

Differences in nest-use rates between nests at undeveloped and developed sites did not vary across

the four different distance-to-development thresholds for ferruginous hawk, golden eagle, and great horned owl (fig. 5). For red-tailed hawks, the direction of the difference was the same across threshold distances (i.e., higher use at undeveloped sites relative to developed sites), and the effect size generally increased with the distance threshold. For all species, there was substantial overlap among the 95% CIs for the effect sizes across scales (fig. 5).

Discussion

One growing form of human-induced habitat change with largely unknown consequences to breeding birds is extraction for energy resources (Northrup and Wittemyer, 2013; Donazar et al., 2016). Raptor species may be particularly vulnerable to energy development due to their often large area requirements (Watson

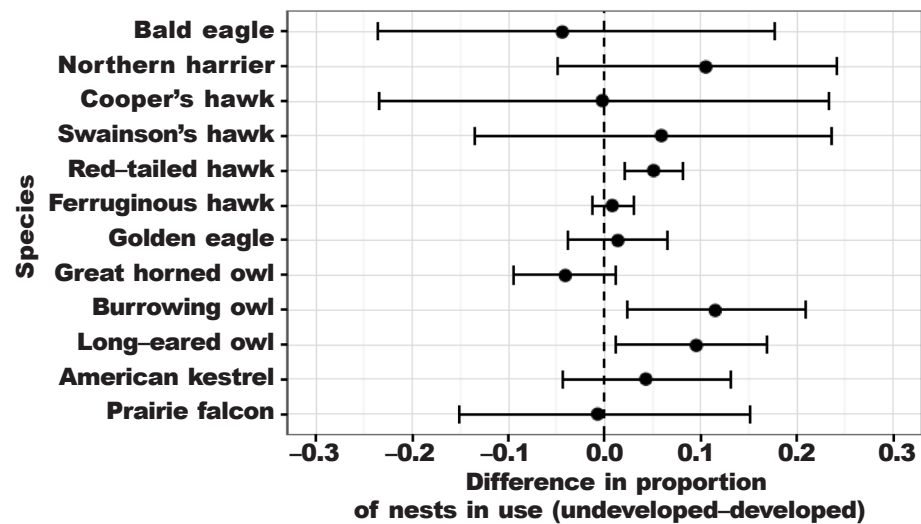


Fig. 4. The nine-year average difference (\pm 95% CI) in the annual proportion of raptor nests in use from 2003–2011 in the Powder River Basin, Wyoming, USA. The difference was calculated as undeveloped – developed, so positive values indicate higher use at undeveloped sites relative to developed sites. Nests at developed sites were those \leq 805 m from the nearest active coalbed methane well, and nests at undeveloped sites were those $>$ 805 m from the nearest active coalbed methane well.

Fig. 4. Diferencia media de los nueve años (\pm 95% IC) en la proporción anual de nidos de rapaces en uso entre 2003 y 2011 en la cuenca del río Powder, en Wyoming, EE.UU. La diferencia se calculó como zonas no extractivas – zonas extractivas, de tal forma que los valores positivos indican un mayor uso en las primeras en comparación con las últimas. Los nidos en zonas extractivas se encontraban a \leq 805 m del pozo activo de metano en capas de carbón más cercano, mientras que los nidos en zonas no extractivas se encontraban a $>$ 805 m del pozo activo de metano en capas de carbón más cercano.

et al., 2014; Crandall et al., 2015), relatively slow life histories (Bennett and Owens, 2002), and demonstrated sensitivity to human disturbance and habitat alteration (White and Thurow, 1985; Kostrzewa, 1996; Krüger, 2002; Martínez–Abraín et al., 2010; Brown et al., 2014; Coates et al., 2014). We leveraged a large dataset to evaluate temporal patterns of nest–site use by 12 species of raptors in relation to the proximity of CBM development in Wyoming, USA. The mean rate of nest use varied annually in an apparently non-linear manner for all 12 species. Three species (i.e. red-tailed hawk, burrowing owl, and long-eared owl) were significantly more likely to use nests away from CBM wells. The red-tailed hawk result was somewhat surprising given that this species is considered to be one of the more disturbance-tolerant raptor species (Berry et al., 1998; Hobbs et al., 2006; Coates et al., 2014; Duerr et al., 2015). Similarly, burrowing owls tend not to significantly alter behaviors in relation to human disturbance or land use type (Plumpton and Lutz, 1993; Chipman et al., 2008). Different types of, or distances to, human disturbance, however, may elicit varying responses by wildlife, and to our knowledge, no other published study has examined the responses of red-tailed hawks or burrowing owls to coalbed–methane development. Long-eared owls

are known to be sensitive to development-related habitat loss and to human disturbance at nest and roost sites (Marks et al., 1994). Additionally, long-eared owls tend to prefer nesting areas containing fewer paved roads (Martínez and Zuberogitia, 2004). Our work further confirms the sensitivity of long-eared owls to human activity and extends those activity types to include CBM development. Collectively, our results suggest unique responses of raptor species to energy development (also see Smith et al., 2010), and taken in the context of previous work, that behavioral responses within species can vary across different environmental contexts.

The suite of species examined in our study displayed wide diversity in their traits, including morphological (e.g., body size), behavioral (e.g., foraging strategies and activity periods), and natural history (e.g., home range size, specific nesting requirements). Differing species-specific responses of raptors nesting in relation to nearby CBM development were therefore not surprising (also see Martínez–Abraín et al., 2010). One potential reason for the weak relationship between nest–site use and CBM development for many species is that suitable nest sites can be limiting (Newton, 1998) and the construction of the large nests often built by raptors

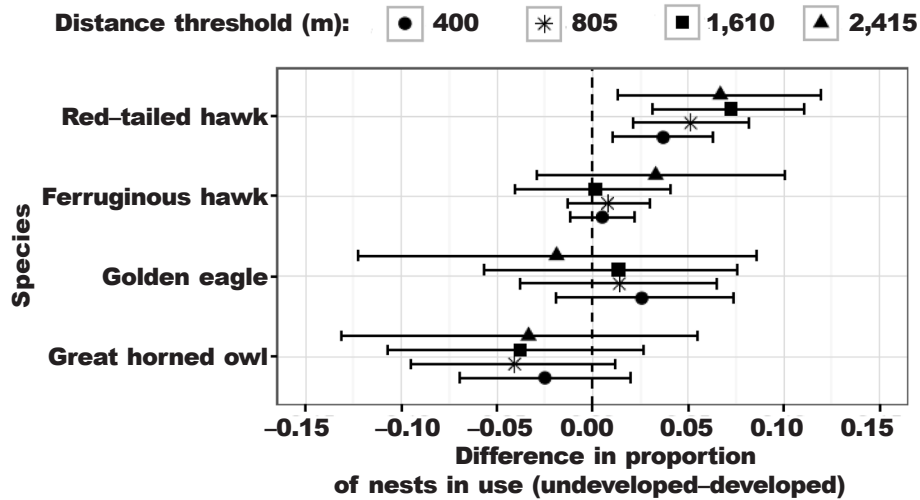


Fig. 5. The nine-year average difference (\pm 95% CI) in the annual proportion of raptor nests in use from 2003–2011 in the Powder River Basin, Wyoming, USA across multiple scales of analysis (i.e., the minimum distance a nest at an undeveloped site could be from an active coalbed methane well). The difference was calculated as undeveloped – developed, so positive values indicate higher use at undeveloped sites relative to developed sites. Nests at developed sites were those \leq the specified distance from the nearest active coalbed methane well, and nests at undeveloped sites were those $>$ the specified distance from the nearest active coalbed methane well.

Fig. 5. Diferencia media de los nueve años (\pm 95% IC) en la proporción anual de nidos de rapaces en uso entre 2003 y 2011 en la cuenca del río Powder, en Wyoming, EE.UU. en múltiples escalas de análisis (esto es, la distancia mínima de un pozo activo de metano en capas de carbón). La diferencia se calculó como zonas no extractivas – zonas extractivas, de tal forma que los valores positivos indican un mayor uso en las primeras en comparación con las últimas. Los nidos en zonas extractivas se encontraban a \leq la distancia especificada del pozo activo de metano en capas de carbón más cercano, mientras que los nidos en zonas no extractivas se encontraban a $>$ la distancia especificada del pozo activo de metano en capas de carbón más cercano.

is a significant energetic investment (Moller and Nielsen, 2015). Birds would therefore have to weigh the potential costs of remaining faithful to nest sites in disturbed areas versus the costs of locating or building a new nest structure. If the actual fitness costs of nest-site use in developed areas are low, parent birds would likely remain site-faithful to those territories and nests, but assessing fitness measures (i.e. survival and reproductive success) was outside the scope of this study. A critical next step for future work is to evaluate actual habitat preferences and fitness outcomes in relation to energy development infrastructure (Hethcoat and Chalfoun, 2015b). Otherwise, one cannot discern whether nest-site use of birds in areas of energy development is an adaptive response versus an ecological trap (Robertson and Hutto, 2006). One of the major impetuses for this study was to determine whether the 805-m buffers implemented by the BLM were biologically meaningful in terms of raptor responses and sufficient for protective measures. Our analysis of distance thresholds entailed approximately halving, doubling,

and tripling the 805-m radius, which did not result in significant differences in the direction or size of the observed effect for any of the four species examined. These results suggest that the 805-m radius may be sufficient for limiting avoidance of areas with nearby CBM development by raptors for nesting, but more targeted study of actual nesting productivity in relation to CBM should be conducted for confirmation.

If the temporal patterns in nest-site use in our study reflected actual population trends (Sergio and Newton, 2003; Kennedy et al., 2014), there were likely key factors affecting local raptor populations independent of potential energy-development effects. Raptor occupancy, site fidelity, and population trends are known to be associated with local prey availability (Smith et al., 1981; MacLaren, et al. 1988; Woffinden and Murphy, 1989; Kostrzewa, 1996; Kochert and Steenhof, 2002; Sergio et al., 2006; Millsap et al., 2015) which varies temporally and spatially (Fedy and Doherty, 2011; Simes et al., 2015). Raptor prey deficits can be exacerbated by exogenous factors such as

drought (Ranta et al., 1999); and 2004 was a relatively dry year (U.S. Geological Survey, 2017), which may have precipitated subsequent predator responses with a one to two-year time lag (e.g., Lehtikoinen et al., 2011). Future work designed to assess the influence of energy development on raptor populations should therefore account for other key population drivers such as food availability and weather (Steenhof et al., 1997). Some rodent species, especially generalists such as deer mice (*Peromyscus maniculatus*), can increase in abundance around energy development (Hethcoat and Chalfoun, 2015b), which may actually benefit some raptor species. Finally, the lowest rates of nest-site use were generally observed during the last several years of the study (2009–2011, fig. 2). Therefore, continued monitoring of raptor populations in this region would likely be of particular interest to conservation practitioners and may shed light on the population cycling suggested by our results and which has been documented for some raptor prey in Wyoming (Fedy and Doherty, 2011).

We acknowledge some important caveats and limitations of our study. Some raptor species, such as golden eagles and ferruginous hawks, maintain several potential nest sites within their territory among which they can rotate in different years (Kochert and Steenhof, 2002; Smith et al., 2010; Millsap et al., 2015). Surveyors in our study monitored nest sites and not entire nesting territories, which means that our nest-use rates were likely consistently lower than actual territory-use rates for species with multiple nests per territory. Additionally, two of the three species (red-tailed hawk and burrowing owl) for which we observed a negative association between nest-use rates and CBM development were those with some of the highest sample sizes of nests. Sample size may therefore have played a role in our ability to detect effects for the rarer species.

Density dependence can have strong effects on bird populations, and fluctuations in abundance or nest-site use over time and space can be indicative of density-dependent regulation (Newton, 1998). The breeding-season abundance and distribution of raptors in particular can be limited by a lack of suitable nest sites, especially in open habitats with few natural structures (e.g., cliffs and trees; Steenhof et al., 1993; Newton, 1998). Indeed, raptors have colonized previously unsuitable areas after artificial structures suitable for nesting (such as those associated with energy development and transmission lines) were installed (Steenhof et al., 1993; Newton, 1998). The colonization of newly suitable areas can therefore be a manifestation of density dependence, as individuals escape intra- or inter-specific competition for resources (Newton, 1998). We observed fluctuations in nest-use rates through time, but we lacked information regarding key factors such as available nest substrates, prey densities, and densities of co-existing raptors, with which to assess potential density-dependent responses (Newton, 1998).

In summary, we documented non-linear annual patterns of nest-site use for 12 species of raptors in the Powder River Basin, Wyoming, USA, an arid basin

heavily influenced by coalbed-methane development. Three species displayed potential avoidance of nesting within 805 m of CBM development, though the mechanisms for these patterns remain unclear. Future work that clarifies actual nesting habitat preferences and outcomes in relation to energy development, while simultaneously accounting for local prey availability, densities of competitors, and weather, would be highly beneficial. Disentangling the specific attributes of energy extraction (e.g., habitat change, noise, movement, artificial light) that elicit wildlife responses would also be a particularly fruitful line of inquiry.

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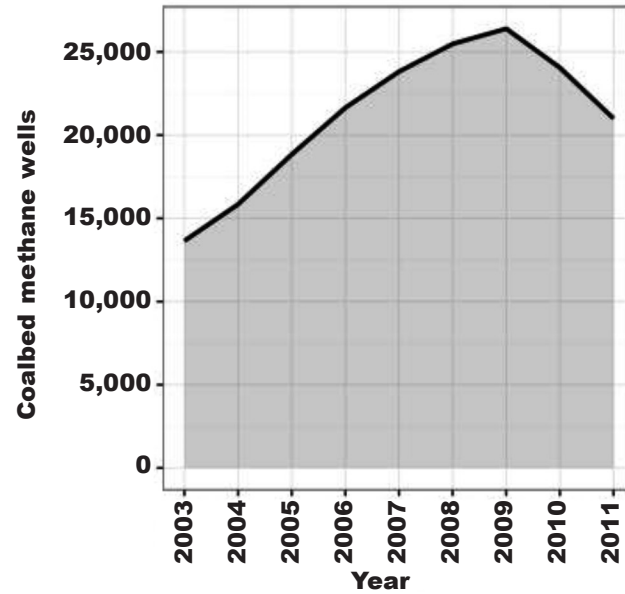
Supplementary material

Fig. 1s. The number of active coalbed methane wells from 2003–2011 in the Powder River Basin, Wyoming. These data assume a 10–year lifespan for each well.

Fig. 1s. Número de pozos activos de metano en capas de carbón entre 2003 y 2011 en la cuenca del río Powder, en Wyoming. Estos datos suponen una vida útil de 10 años para cada pozo.

Table 1s. Sample sizes for each species–year–development group combination. Developed nests were those ≤ 805 m from the nearest active coalbed methane well, and undeveloped nests were those > 805 m from the nearest active coalbed methane well: Y, year; Ud, undeveloped; D, developed; T, total.

Tabla 1s. Tamaños de muestra para cada combinación del grupo especie–año–actividad extractiva. Los nidos en zonas extractivas se encontraban a ≤ 805 m del pozo activo de metano en capas de carbón más cercano, mientras que los nidos en zonas no extractivas se encontraban a > 805 m del pozo activo de metano en capas de carbón más cercano. (Para las abreviaturas, véase arriba).

Common name	Y	Ud	D	T	Common name	Y	Ud	D	T
Bald eagle	2003	6	3	9	Red-tailed hawk	2003	21	45	66
Bald eagle	2004	5	1	6	Red-tailed hawk	2004	173	147	320
Bald eagle	2005	6	3	9	Red-tailed hawk	2005	128	186	314
Bald eagle	2006	8	2	10	Red-tailed hawk	2006	182	295	477
Bald eagle	2007	8	7	15	Red-tailed hawk	2007	194	402	596
Bald eagle	2008	6	8	14	Red-tailed hawk	2008	126	470	596
Bald eagle	2009	1	5	6	Red-tailed hawk	2009	135	527	662
Bald eagle	2010	2	9	11	Red-tailed hawk	2010	154	594	748
Bald eagle	2011	1	7	8	Red-tailed hawk	2011	137	645	782
Northern harrier	2003	0	1	1	Ferruginous hawk	2003	68	204	272
Northern harrier	2004	2	4	6	Ferruginous hawk	2004	86	270	356
Northern harrier	2005	1	6	7	Ferruginous hawk	2005	46	267	313
Northern harrier	2006	6	11	17	Ferruginous hawk	2006	73	305	378
Northern harrier	2007	4	18	22	Ferruginous hawk	2007	115	403	518
Northern harrier	2008	2	16	18	Ferruginous hawk	2008	92	317	409
Northern harrier	2009	4	16	20	Ferruginous hawk	2009	119	391	510
Northern harrier	2010	5	16	21	Ferruginous hawk	2010	107	370	477
Northern harrier	2011	3	18	21	Ferruginous hawk	2011	101	420	521
Cooper's hawk	2003	0	0	0	Golden eagle	2003	7	14	21
Cooper's hawk	2004	2	0	2	Golden eagle	2004	46	36	82
Cooper's hawk	2005	2	0	2	Golden eagle	2005	36	50	86
Cooper's hawk	2006	3	2	5	Golden eagle	2006	57	90	147
Cooper's hawk	2007	6	3	9	Golden eagle	2007	62	110	172
Cooper's hawk	2008	3	5	8	Golden eagle	2008	46	124	170
Cooper's hawk	2009	3	7	10	Golden eagle	2009	45	140	185
Cooper's hawk	2010	6	5	11	Golden eagle	2010	52	158	210
Cooper's hawk	2011	5	7	12	Golden eagle	2011	45	162	207
Swainson's hawk	2003	3	17	20	Great horned owl	2003	3	6	9
Swainson's hawk	2004	11	30	41	Great horned owl	2004	29	27	56
Swainson's hawk	2005	2	31	33	Great horned owl	2005	27	41	68
Swainson's hawk	2006	2	38	40	Great horned owl	2006	60	68	128
Swainson's hawk	2007	3	44	47	Great horned owl	2007	60	93	153
Swainson's hawk	2008	1	30	31	Great horned owl	2008	61	116	177
Swainson's hawk	2009	4	33	37	Great horned owl	2009	49	165	214
Swainson's hawk	2010	2	29	31	Great horned owl	2010	53	171	224
Swainson's hawk	2011	8	24	32	Great horned owl	2011	42	190	232

Table 1s. (Cont.)

Common name	Y	Ud	D	T	Common name	Y	Ud	D	T
Burrowing owl	2003	0	0	0	American kestrel	2003	0	4	4
Burrowing owl	2004	19	9	28	American kestrel	2004	12	11	23
Burrowing owl	2005	16	21	37	American kestrel	2005	8	16	24
Burrowing owl	2006	16	32	48	American kestrel	2006	12	34	46
Burrowing owl	2007	11	49	60	American kestrel	2007	21	40	61
Burrowing owl	2008	12	42	54	American kestrel	2008	17	47	64
Burrowing owl	2009	11	71	82	American kestrel	2009	22	55	77
Burrowing owl	2010	20	77	97	American kestrel	2010	23	57	80
Burrowing owl	2011	21	78	99	American kestrel	2011	16	70	86
Long-eared owl	2003	1	0	1	Prairie falcon	2003	0	0	0
Long-eared owl	2004	21	2	23	Prairie falcon	2004	2	1	3
Long-eared owl	2005	9	12	21	Prairie falcon	2005	2	2	4
Long-eared owl	2006	22	28	50	Prairie falcon	2006	11	6	17
Long-eared owl	2007	17	35	52	Prairie falcon	2007	9	10	19
Long-eared owl	2008	18	41	59	Prairie falcon	2008	8	10	18
Long-eared owl	2009	20	49	69	Prairie falcon	2009	11	12	23
Long-eared owl	2010	14	54	68	Prairie falcon	2010	11	12	23
Long-eared owl	2011	19	62	81	Prairie falcon	2011	12	16	28

Table 2s. The weighted mean proportion of nests in use for 12 raptor species nesting in the Powder River Basin, Wyoming between 2003–2011.

Tabla 2s. Proporción media ponderada de nidos en uso para 12 especies de rapaces que anidan en la cuenca del río Powder, en Wyoming, entre 2003 y 2011.

Common name	Scientific name	Nests in use
Bald eagle	<i>Haliaeetus leucocephalus</i>	63.6%
Northern harrier	<i>Circus cyaneus</i>	19.5%
Cooper's hawk	<i>Accipiter cooperii</i>	27.1%
Swainson's hawk	<i>Buteo swainsoni</i>	42.6%
Red-tailed hawk	<i>Buteo jamaicensis</i>	33.2%
Ferruginous hawk	<i>Buteo regalis</i>	8.2%
Golden eagle	<i>Aquila chrysaetos</i>	33.7%
Great horned owl	<i>Bubo virginianus</i>	28.6%
Burrowing owl	<i>Athene cunicularia</i>	27.9%
Long-eared owl	<i>Asio otus</i>	26.2%
American kestrel	<i>Falco sparverius</i>	32.7%
Prairie falcon	<i>Falco mexicanus</i>	39.3%

