

# Columbian sharp-tailed grouse brood success and chick survival in a wind-energy landscape

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## Abstract

Columbian sharp-tailed grouse (*Tympanuchus phasianellus columbianus*) have experienced range-wide population declines, primarily as a result of habitat loss or degradation, and currently occupy <10% of their historical range. Expansion of wind-energy development across the current, occupied Columbian sharp-tailed grouse range is a potential threat to the subspecies. To assess the potential effects of wind-energy development on vital rates of Columbian sharp-tailed grouse offspring, we monitored 68 broods of radio-marked females captured at 11 leks in restored grasslands within 14 km of a 215-turbine wind-energy development complex in eastern Idaho, USA from 2014–2015. We assessed the influence of wind turbine density, habitat characteristics, brood-rearing female age, hatch date, and weather on brood success and chick survival using an information-theoretic model selection approach. Wind turbine density did not influence early (14-day) brood success, but there was weak evidence for a negative effect of wind turbine density on late (42-day) brood success. There was strong evidence that increasing turbine density within the late brood-rearing home range negatively affected chick survival to 42 days after hatch. The probability of an individual chick surviving to 42 days decreased by 50% when there were  $\geq 10$  wind turbines within 2,100 m of the nest. Late brood success and chick survival increased with earlier hatch dates. There was weak evidence for positive effects of post-hatch precipitation on early brood success and chick survival and weak evidence that adult females had higher early brood success than yearlings. Habitat characteristics such as

vegetation composition in restored grasslands were poor predictors of offspring survival. Multiple variables, including wind-energy development, are important to Columbian sharp-tailed grouse brood success and chick survival. Wildlife managers should consider the potential for negative impacts of wind-energy development on Columbian sharp-tailed grouse recruitment when addressing wind-energy siting and mitigation.

#### KEYWORDS

brood success, chick survival, Columbian sharp-tailed grouse, Idaho, *Tympanuchus phasianellus columbianus*, wind energy

Wind-energy capacity in the United States increased over 3.5 times between 2010 and 2020, and in 2020, wind energy supplied 8.4% of the total electricity generated in the United States (U.S. Energy Information Administration 2021). Rapid growth in the wind-energy industry continues to concern wildlife managers because of potential impacts to wildlife populations. A substantial amount of research has occurred in the last 2 decades documenting effects of wind energy on birds, bats, and marine mammals (Schuster et al. 2015, Allison et al. 2019, Svedarsky et al. 2022). In the United States, prairie grouse species (*Tympanuchus* spp., *Centrocercus* spp.) are of particular concern because their habitats are frequently targeted for wind development, and most prairie grouse species are already experiencing long-term habitat and population declines (Storch 2007, Lipp and Gregory 2018).

The Columbian sharp-tailed grouse (*T. phasianellus columbianus*), 1 of 6 extant subspecies of sharp-tailed grouse found in North America (Johnsgard 1973), is endemic to shrub-steppe, grassland, mountain shrub, and riparian plant communities in western North America (Connelly et al. 1998). The subspecies currently occupies <10% of its historical range and has been petitioned twice for listing under the Endangered Species Act (U.S. Department of the Interior 2000, 2006). Declines in Columbian sharp-tailed grouse populations have been attributed to habitat loss resulting from conversion of native vegetation communities to cropland, overgrazing by livestock, shrub control, altered fire regimes, invasion of exotic plants, urban and rural development, and more recently, the loss of Conservation Reserve Program (CRP) land, which provides important breeding habitat throughout much of the subspecies' range (Hoffman and Thomas 2007). Energy development is also a potential threat to Columbian sharp-tailed grouse populations, but, until recently, energy development was rare within the occupied range, with the exception of coal mining (Hoffman et al. 2015). Recent expansion of wind-energy development within the core of occupied Columbian sharp-tailed grouse range in North America raises concerns over potential negative impacts to populations.

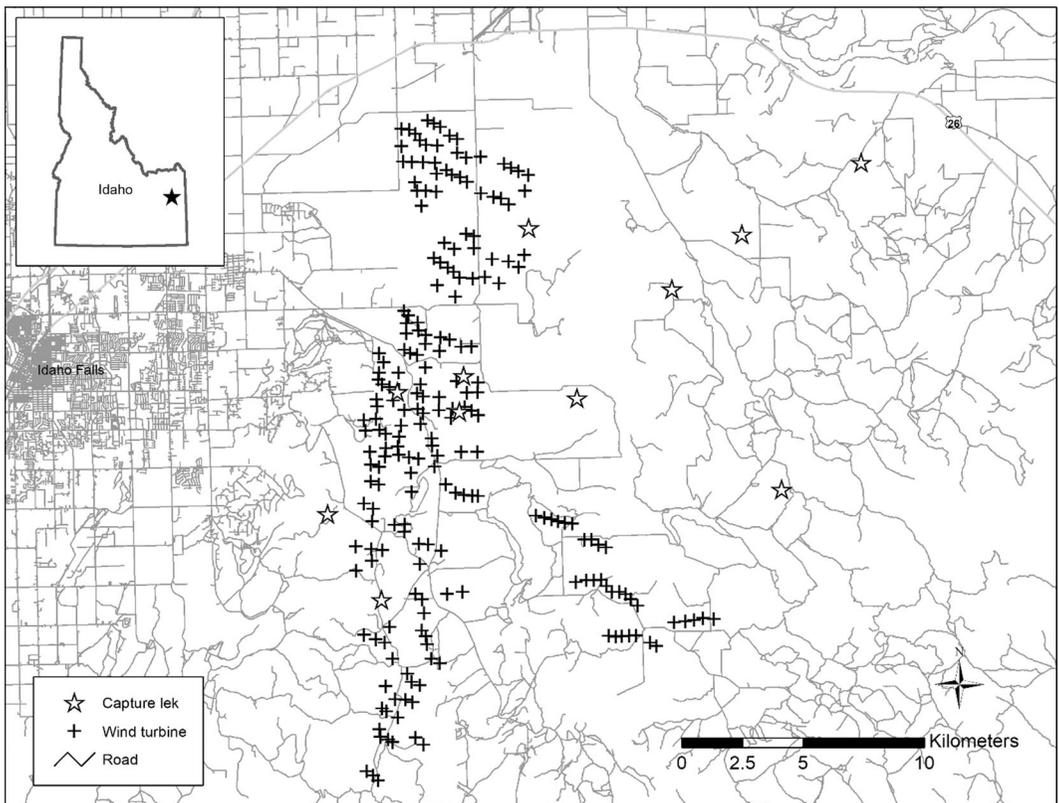
Several researchers have addressed the influence of wind-energy development on prairie grouse adult and nest survival (McNew et al. 2014, Winder et al. 2014, Harrison et al. 2017, Proett et al. 2019), but few have specifically addressed potential impacts on brood or chick demographics. Assessing brood and chick responses to wind energy is important because of the influence of recruitment on population growth rates in grouse species (Taylor et al. 2012, Dahlgren et al. 2016, Kane et al. 2017). In Nebraska, USA, Harrison (2015) reported no effects of a wind-energy facility on greater prairie-chicken (*T. cupido pinnatus*; prairie-chicken) brood survival in unfragmented grasslands. In a 2-year study in Wyoming, USA, greater sage-grouse (*Centrocercus urophasianus*; sage-grouse) brood survival was negatively influenced by distance to wind turbines; but over a 6-year concurrent study, there were no documented effects of the wind-energy facility on brood survival (LeBeau et al. 2014, 2017).

We investigated the effects of wind-energy development on Columbian sharp-tailed grouse brood success and chick survival in restored grasslands of eastern Idaho, USA. We hypothesized that brood success and chick survival

would be lower in habitats with greater wind turbine density because similar impacts were documented for sage-grouse in the vicinity of wind-energy development (LeBeau et al. 2014). We tested this hypothesis by modeling the effect of wind energy on brood success and chick survival after accounting for a suite of variables that could affect survival of broods and chicks, including hatch date (Matthews et al. 2011), age of brood-rearing female (Guttery et al. 2013), precipitation (Guttery et al. 2013), temperature (Goddard and Dawson 2009), habitat composition (Anderson et al. 2015), and roads.

## STUDY AREA

Our study was conducted in Bonneville County, Idaho, approximately 10 km east of Idaho Falls (Figure 1). Land ownership included Bureau of Land Management, Bureau of Reclamation, Idaho Department of Lands, Idaho Department of Fish and Game (IDFG), and private lands. There were 4 wind-energy facilities located within the 56,000-ha study area: Wolverine Creek, a 64-megawatt (MW) facility consisting of 43 1.5-MW turbines (completed in 2005); Goshen North, a 64-MW facility consisting of 83 1.5-MW turbines (completed in 2010); Horse Butte (Phase 1), a 60-MW facility consisting of 32 1.8-MW turbines (completed in 2012); and Meadow Creek, a 120-MW facility consisting of 57 2.1-MW turbines (completed in 2012). Additional wind-energy infrastructure included gravel access roads, maintenance buildings, electrical substations, and a small number of overhead transmission



**FIGURE 1** Study area with 11 occupied leks targeted for capture and monitoring of female Columbian sharp-tailed grouse from 2014–2015. The study area consisted of 215 operating wind turbines.

lines (most lines were buried). The wind-energy facilities within our study area were developed on leased portions of private land.

The landscape in our study area was composed of foothills and gently sloping benches intersected by steep-sloped canyons, with elevations ranging from 1,500–2,200 m. The 2 most common soils are Ririe silt loam and Torriorthents-rock outcrop complex (U.S. Department of Agriculture 2016). Land cover was a matrix of active agriculture, CRP, and smaller patches of native brush and aspen (*Populus tremuloides*). The Tex Creek Wildlife Management Area (TCWMA), a 14,000-ha big-game winter range managed by IDFG is situated roughly in the center of the study area. The portion of TCWMA within the study area consists of historically farmed foothills and benches, many of which have been converted to perennial vegetation similar in composition and structure to CRP fields. The study area is a regional stronghold for Columbian sharp-tailed grouse, with 39 active leks documented in 2013 (A. Moser, IDFG, unpublished data). Common native vegetation across the study area included big sagebrush (*Artemisia tridentata*), antelope bitterbrush (*Purshia tridentata*), rabbitbrush (*Chrysothamnus* spp.), serviceberry (*Amelanchier* spp.), snowberry (*Symphoricarpos* spp.), aspen, and willow (*Salix* spp.). Vegetation commonly occurring in CRP fields and TCWMA fields included smooth brome (*Bromus inermis*), intermediate wheatgrass (*Thinopyrum intermedium*), crested wheatgrass (*Agropyron cristatum*), bluebunch wheatgrass (*Pseudoroegneria spicata*), big bluegrass (*Poa secunda*), basin wild rye (*Leymus cinereus*), cheatgrass (*B. tectorum*), alfalfa (*Medicago sativa*), yellow sweet clover (*Melilotus officinalis*), sanfoin (*Onobrychis viciifolia*), small burnet (*Saguisorba minor*), blue flax (*Linum lewisii*), and yarrow (*Achillea millefolium*). Common game species within the study area included mule deer (*Odocoileus hemionus*), elk (*Cervus canadensis*), moose (*Alces alces*), Columbian sharp-tailed grouse, ruffed grouse (*Bonasa umbellus*), and gray partridge (*Perdix perdix*). The regional climate is classified as continental with warm, dry summers (Jun–Aug) and cold, snowy winters (Nov–Mar). Mean annual precipitation is 30.8 cm and average daily temperatures range from 0.2°C to 14.8°C (Western Regional Climate Center 2016).

## METHODS

### Capture and monitoring

We captured female Columbian sharp-tailed grouse during March–May of 2014 and 2015 using walk-in traps with drift fences (Schroeder and Braun 1991). We captured birds at 11 leks, 7 of which were used for capture in both years of the study. The 11 capture leks ranged from 0.1–13.8 km from wind turbines. We selected leks based on size (i.e., count of  $\geq 10$  birds the previous year) and proximity to turbines to maximize capture efficiency and disperse our sample of radio-marked females evenly along a 14-km gradient from wind turbines. We aged captured females (adult vs. yearling) based on shape and wear of outer primary feathers (Ammann 1944) and weighed them to the nearest 5 g. We then banded them with uniquely numbered aluminum leg bands and fitted them with a 9-g necklace-style very high frequency radio-transmitter equipped with a mortality switch (model RI-2D, Holohil Systems, Carp, ON, Canada). We released radio-marked females at the capture site immediately after processing.

We monitored radio-marked females from the ground 2–3 times a week, following capture, using portable telemetry receivers and handheld Yagi antennas. We conducted fixed-wing aerial telemetry flights to locate radio-marked females that we were unable to locate using ground telemetry methods. To estimate pre-nesting and early incubation locations, we used a homing method described by White and Garrott (1990), circling females to within 30–50 m, without flushing, to minimize disturbance (Boisvert 2002, Gillette 2014). We recorded the estimated distance and bearing to each female and the observer's coordinates using handheld Garmin eTrex global positioning systems (GPS; Garmin International, Olathe, KS, USA).

When we found a radio-marked female in the same location on consecutive visits, we presumed she had initiated a nest. Using telemetry, we verified the nest location and flushed the female from the nest to obtain a clutch count. We then recorded the GPS coordinates of each nest and used telemetry to monitor nests 2–3 times a

week from a distance of >50 m. We monitored nests from GPS-marked reference points rather than visual markers, and only approached nests for the clutch count and to document nest fate when telemetry indicated the female had left the nest. At the final nest inspection, we recorded the number of hatched and unhatched eggs for all successful nests.

We monitored females that successfully hatched  $\geq 1$  chick by telemetry 2–3 days a week between 0700 and 1000, homing to within 30 m and taking care to not flush or disturb females or chicks. At 14 days after hatch, we approached the brood female to check for the presence of a brood (i.e.,  $\geq 1$  chick alive) by either observing or hearing chicks. Once we documented brood status, we immediately left the area to minimize disturbance to the brood. We continued to monitor brood females and record locations until 42 days after hatch. At 42 days after hatch, we verified brood status and chick abundance by conducting a chick count using 1–2 trained pointing or flushing dogs (Dahlgren et al. 2010b). Dahlgren et al. (2010b) documented a 96% probability of detecting 5–8-week-old sage-grouse chicks using trained dogs, compared to 72% using traditional walking counts. If we did not find  $\geq 1$  chick with the female during the 14-day brood check or 42-day flush count, we repeated protocols within 2–3 days to document chicks that were potentially undetected on the initial attempt. Because we did not mark chicks, we were unable to account for any effect brood-mixing might have had on our estimates (Dahlgren et al. 2010a).

## Covariates

We developed a suite of variables that we predicted could explain variation in survival of Columbian sharp-tailed grouse broods and chicks in the study area (Table 1). To evaluate the effect of habitat characteristics while accounting for habitat changes (primarily CRP field conversions) between years, we developed year-specific, land cover type layers of the study area within a geographic information system (GIS; ArcGIS 10.3, Esri, Redlands, CA, USA). We used 2013 and 2015 National Agriculture Imagery Program (NAIP) imagery to manually digitize land cover types within 5 km of capture leks. We expanded the GIS map, where necessary, to incorporate nest and brood locations that extended farther than 5 km from capture leks. When land cover identification from NAIP imagery was uncertain, we used field observations to verify land cover types. To evaluate the effects of anthropogenic features, we included roads and wind turbines in our GIS map. We incorporated roads using United States government open source road data layers (U.S. Census Bureau 2015) and manually digitized roads from NAIP imagery where road layers were incomplete. We incorporated wind turbine locations from the 2014 United States Geological Survey onshore wind turbine location data layer (Diffendorfer et al. 2015).

We further categorized restored grasslands (primarily CRP and TCWMA fields) with on-the-ground visual assessments of dominant grass type and forb canopy cover, using 2 trained observers for consistency. We chose to conduct simple, field-based classifications rather than use seeding records because seeding records may not have accurately represented the vegetation composition of fields at the time of our study (particularly in the case of older CRP plantings that included rhizomatous grasses). For each unique patch within restored grasslands, we classified the dominant grass type into one of the following categories: bunchgrass, rhizomatous grass (i.e., smooth brome or intermediate wheatgrass), and crested wheatgrass. These grass categories allowed us to examine the effects of grass structure on brood success and chick survival and were representative of grass types commonly found in CRP in Idaho. Next, we visually estimated and categorized forb canopy cover within each patch into 1 of 5 bins: <2%, 2–10%, 11–20%, 21–30%, and >30% canopy cover. We manually digitized each unique patch within the restored grassland type using hand-drawn polygons from field maps for reference. We attributed each polygon with the mean value of the assigned forb cover bin (e.g., 11–20% bin = 15%).

Previous researchers of prairie grouse ecology documented the influence of weather variables on brood and chick survival (Goddard and Dawson 2009, Guttery et al. 2013). Therefore, we evaluated the effect of precipitation in the 10 days prior to nest hatch, with the hypothesis that precipitation in this interval would positively affect

**TABLE 1** Variables considered in models describing Columbian sharp-tailed grouse brood success and chick survival in eastern Idaho, USA, 2014–2015.

Variable	Description
Year	Study year (categorical = 2014 or 2015)
Hatch day	Ordinal hatch date
Female age	Age of brood-rearing female (categorical = immature or adult)
Prev precip	Average daily precipitation (mm) 10 days prior to hatch
Post precip	Average daily precipitation (mm) 2 days prior to 7 days after hatch
Post average temp	Average daily temp (°C) 2 days prior to 7 days after hatch
Post average low temp	Average daily low temp (°C) 2 days prior to 7 days after hatch
Post min. low temp	Min. daily low temp (°C) 2 days prior to 7 days after hatch
Bunch X	Area (ha) of restored grassland dominated by bunchgrass within X distance (m) of hatched nest
Rhizo X	Area (ha) of restored grassland dominated by smooth brome or intermediate wheatgrass within X distance (m) of hatched nest
Crest X	Area (ha) of restored grassland dominated by crested wheatgrass within X distance (m) of hatched nest
Forb >30 X	Area (ha) of restored grassland with >30% forb canopy cover within X distance (m) of hatched nest
Forb <2 X	Area (ha) of restored grassland with <2% forb canopy cover within X distance (m) of hatched nest
Ag X	Area (ha) of agriculture within X distance (m) of hatched nest
Roads X	Area (ha) of roads within X distance (m) of hatched nest
Turb X	Number of turbines within X distance (m) of hatched nest

success and survival by increasing food availability and abundance for chicks (Flanders-Wanner et al. 2004, Goddard and Dawson 2009). We also considered the effects of precipitation and temperature from 2 days prior to 7 days following hatch because wet and cold weather during the first week of life, when chicks are unable to thermoregulate, might negatively affect chick survival (Mendenhall and Milne 1985, Goddard and Dawson 2009). Because we did not monitor nests every day, we included the 2 days prior to the estimated hatch date to account for uncertainty in hatch date. We evaluated 3 different daily temperature (°C) metrics—average daily temperature, average daily low temperature, and minimum daily low temperature—and only carried the best performing of the correlated temperature metrics forward in our iterative model building and evaluation process. We obtained daily precipitation and temperature data from the Bureau of Reclamation Ririe Dam weather station that lies within the study area (Bureau of Reclamation 2016). Finally, we evaluated 2 additional variables that influence offspring survival in grouse: within-season hatch date and brood-rearing female age (Gutteny et al. 2013, Dahlgren et al. 2016).

## Model development and analyses

We used 3 measures of offspring survival in our analyses: early brood success, late brood success, and chick survival. We defined early brood success as  $\geq 1$  chick surviving through 14 days after hatch and late brood success

as  $\geq 1$  chick surviving to 42 days after hatch. To assess chick survival to 42 days after hatch, we first examined egg shell remains during our nest fate assessments to determine the number of chicks that hatched per successful nest. At 42 days, we used the flush counts with trained dogs to determine the number of surviving chicks for each female that nested successfully (i.e.,  $\geq 1$  hatched egg). We then subtracted the number of surviving chicks from the number of hatched eggs to determine the number of chicks per successful nest that did not survive to 42 days.

Because selection of nesting habitat might be based on its quality as brood-rearing habitat (Gibson et al. 2016), we assessed the influence of vegetation composition, anthropogenic features, and agriculture on Columbian sharp-tailed grouse offspring survival at 2 biologically relevant spatial scales around nests. The scales we selected were approximations of early (14-day) and late (42-day) brood-rearing home ranges. Ninety percent of broods in this study used locations within 950 m and 2,100 m of the nest during the first 14 and 42 days after hatch, respectively. Therefore, we assessed the effect of variables hypothesized to influence early brood success within 284-ha circular buffers around nests (radius = 950 m) and variables hypothesized to influence late brood success and chick survival within both 284-ha and 1,385-ha circular buffers around nests (radius = 2,100 m).

We modeled early and late brood success using logistic regression in R (version 3.1.1, R Core Team 2014) and chick survival with mixed-effects logistic regression using the R package lme4 (Bates et al. 2014) and ggeffects (Ludecke 2018) for visualization of marginal fixed effects. We included a brood identifier as a random intercept effect in all chick survival models to account for potential non-independence of individual chicks from the same brood. To avoid multicollinearity, we did not include correlated variables ( $|r| \geq 0.65$ ) in any single model. We employed a multi-step, information-theoretic approach (Burnham and Anderson 2002) to build and evaluate candidate models describing early and late brood success and chick survival. First, we compared a model for variation between study years to an intercept-only model. If the year model performed  $\geq 2.0$  corrected Akaike's Information Criterion ( $AIC_c$ ) units better than the intercept-only model, we included year as a fixed-effect in all ensuing models. Next, we compared univariate models for each variable, or additive models of each variable combined with year (when year was carried forward), to intercept-only or year-only models. We considered variables to have support when their inclusion resulted in a model performing  $\geq 2.0$   $AIC_c$  units better than a model without them. We then constructed additive models of all combinations of uncorrelated, supported variables from the prior step, using  $AIC_c$  from univariate models to select between correlated variables. We also considered a model containing an interaction between average daily precipitation from 2 days prior to 7 days following hatch and the best supported (i.e., lowest  $AIC_c$  in previous modeling step) variable describing temperature from 2 days prior to 7 days following hatch, to evaluate whether specific combinations of temperature and precipitation in the week following hatch affected survival. We compared all additive and supported univariate models and selected the model with the lowest  $AIC_c$  score as the best base model for each analysis. As a final step to assess the effect of wind-energy development, we used  $AIC_c$  to evaluate whether adding wind-energy variables (i.e., number of wind turbines within each distance buffer) to each base model improved model fit (Dinsmore et al. 2002, Webb et al. 2012).

## RESULTS

We monitored 68 Columbian sharp-tailed grouse broods during 2014–2015 (2014 = 31, 2015 = 37). We removed 2 broods from analyses that moved to inaccessible private lands and subsequently could no longer be monitored. Because the fate of unmarked broods and chicks could not be determined following the death of a radio-marked female, we also removed broods and chicks from analyses when the brood females died. We removed 9 broods from 14- and 42-day brood survival analyses because the brood females were killed in the first 14 days after hatch and an additional 3 broods from 42-day brood survival analysis because of brood female mortalities or radio-collar failures between 14 and 42 days after hatch. We acknowledge some uncertainty in our survival calculations and analyses, resulting from the removal of these broods. In 2014, 84% of broods survived to day 14 ( $n = 25$ ) and 60% of broods survived to day 42 ( $n = 25$ ). In 2015, 59% of broods survived to day 14 ( $n = 32$ ) and 45% of broods survived

to day 42 ( $n = 29$ ). We included 529 chicks from 54 nests in our chick survival analysis, 91 (17%) of which survived to 42 days old.

Temperature metrics were correlated with hatch date, pre- and post-hatch precipitation metrics were correlated, and all road and turbine variables were correlated at both scales; therefore, we did not combine them in any additive models. The top model describing 14-day brood success included a year effect, a positive effect of female age (i.e., higher brood success for adult females), and a positive effect of post-hatch precipitation (Table 2).

**TABLE 2** Comparison of models from the final step (i.e., evaluation of wind-energy variables added to best base model) of our multi-step modeling approach for evaluating logistic regression models describing 14- and 42-day brood success and 42-day chick survival of Columbian sharp-tailed grouse in eastern Idaho, USA, 2014–2015. The best base model developed from the initial steps of model construction and selection process is indicated with an asterisk.

Model <sup>a</sup>	$K^b$	AIC <sub>c</sub> <sup>c</sup>	$\Delta AIC_c$	$w^d$
14-day brood success				
Year <sup>e</sup> + female age + post precip*	4	67.0	0.0	0.56
Year + female age + post precip + turb 950	5	68.8	1.9	0.22
Year	2	69.4	2.5	0.16
Year + turb 950	3	71.5	4.6	0.06
42-day brood success				
Hatch day + turb 2100	3	74.2	0.0	0.34
Hatch day*	2	74.8	0.6	0.25
Hatch day + turb 950	3	75.1	1.0	0.21
Intercept only	1	76.9	2.7	0.09
Turb 2100	2	77.5	3.3	0.06
Turb 950	2	78.2	4.1	0.04
42-day chick survival <sup>f</sup>				
Hatch day + post precip + turb 2100	5	414.4	0.0	0.77
Hatch day + post precip + roads 2100*	5	417.2	2.8	0.19
Hatch day + post precip + turb 950	5	420.2	5.8	0.04
Turb 2100	3	436.4	22.0	<0.01
Intercept only	2	441.2	26.9	<0.01
Turb 950	3	442.1	27.7	<0.01

<sup>a</sup>Variables include cumulative precipitation (mm) 2 days prior to 7 days after hatch (post precip), number of turbines within 950 m of a hatched nest (turb 950), number of turbines within 2,100 m of a hatched nest (turb 2100), and area (ha) of roads within 2,100 m of a hatched nest (roads 2100). Roads 2100 was correlated with turbine variables at both spatial scales. Therefore, instead of adding turbine variables to the best base model in the final modeling step for 42-day chick survival, we replaced roads 2100 with turbine variables and compared models.

<sup>b</sup>Number of estimated parameters for the model.

<sup>c</sup>Akaike's Information Criterion corrected for small sample size.

<sup>d</sup>Akaike weights.

<sup>e</sup>Year outperformed an intercept-only model in the initial step of the model construction and selection process for 14-day brood success, and therefore was included in all subsequent models.

<sup>f</sup>Each chick survival model also included a brood identifier as a random effect.

The parameter estimate for the year effect suggested that broods were approximately 83% less likely to succeed to 14 days in 2015 than in 2014. There was uncertainty in the precipitation and female age effects in the top model; 95% confidence intervals on both parameter estimates included zero (Table 3). The univariate wind turbine model performed worse than an intercept-only model. The additive model combining year, female age, post-hatch precipitation, and the number of wind turbines within 950 m of the nest had a  $\Delta AIC_c < 2.0$  but was outperformed by the simpler model, suggesting the wind turbine variable was an uninformative parameter in the additive model (Arnold 2010).

The top model describing 42-day brood success included negative effects of hatch day and the number of wind turbines within 2,100 m of the nest. There was some model uncertainty, with the top model receiving 34% of the Akaike weight and 2 other models with  $\Delta AIC_c < 2.0$ , although 2 of the 3 competitive models included wind-energy variables. The top model suggested that broods were approximately 6% less likely to succeed to 42 days with each 1-day increase in ordinal hatch day. There was uncertainty in the effect of the wind turbine variable in the top model; the 95% confidence interval included zero. Univariate wind turbine models for both spatial scales performed worse than an intercept-only model.

The top model of 42-day chick survival combined negative effects of hatch day and the number of wind turbines within 2,100 m of the nest with a positive effect of post-hatch precipitation. The top model outperformed all competing models, with no other model with  $\Delta AIC_c < 2.0$ . When ordinal hatch day ( $\bar{x} = 22$ ) and average daily post-hatch precipitation ( $\bar{x} = 0.19$  mm) were held at their means, the top model suggested that the probability of an individual chick surviving to 42 days decreased by approximately 50% when there were  $\geq 10$  turbines within 2,100 m of the nest (Figure 2). The top model also suggested that chicks were approximately 7% less likely to survive to 42 days with each 1-day increase in ordinal hatch day. The 95% confidence interval on the wind turbine and hatch day variables excluded zero, but there was uncertainty in the effect of precipitation. The univariate model

**TABLE 3** Coefficient estimate ( $\beta$ ), standard error, and 95% confidence interval for variables from the best models describing Columbian sharp-tailed grouse 14- and 42-day brood success and 42-day chick survival in eastern Idaho, USA, 2014–2015.

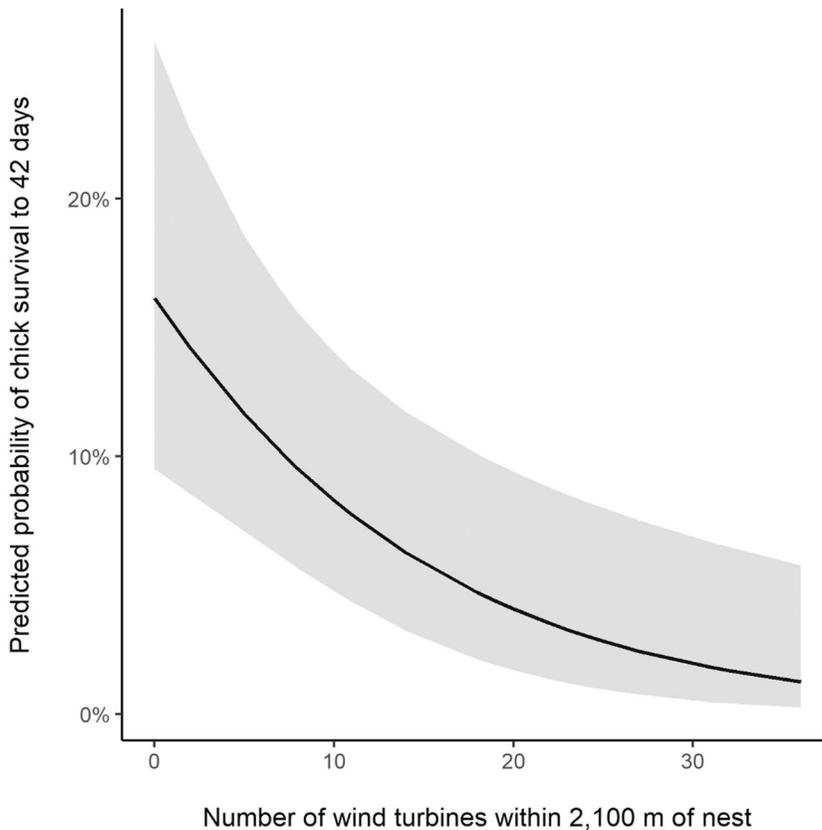
Variable	$\beta$	SE	95% CI	
			Lower	Upper
14-day brood success				
Year <sup>a</sup>	-1.767	0.711	-3.161	-0.374
Female age <sup>b</sup>	-1.107	0.703	-2.485	0.271
Post precip <sup>c</sup>	2.587	1.512	-0.376	5.550
42-day brood success				
Hatch day	-0.057	0.025	-0.107	-0.007
Turb 2100 <sup>d</sup>	-0.046	0.028	-0.101	0.010
42-day chick survival				
Hatch day	-0.073	0.021	-0.114	-0.032
Post precip	1.485	0.796	-0.075	3.045
Turb 2100	-0.076	0.025	-0.125	-0.027

<sup>a</sup>Categorical variable where parameter represents the effect of 2015 compared to 2014.

<sup>b</sup>Categorical variable where parameter represents the effect of the brood female being a yearling compared to the brood female being an adult.

<sup>c</sup>Cumulative precipitation (mm) 2 days prior to 7 days after hatch.

<sup>d</sup>Number of turbines within 2,100 m of a hatched nest.



**FIGURE 2** Marginal fixed effect (with shaded 95% CI) of the number of wind turbines within 2.1 km of the nest from our best mixed-effect model describing the probability of Columbian sharp-tailed grouse chick survival to 42 days of age, Idaho, 2014–2015.

for wind turbines within 2,100 m of the nest outperformed an intercept-only model, but the univariate model for wind turbines within 950 m of the nest did not.

## DISCUSSION

Eastern Idaho grasslands are a stronghold for Columbian sharp-tailed grouse, supporting 60–65% of the remaining breeding population in the United States (Hoffman and Thomas 2007). Wildlife professionals need information to address the management of this subspecies in current and proposed wind-developed landscapes within the region. Individual chick survival to 42 days old was negatively influenced by wind energy, and specifically, by the number of wind turbines within the late brood-rearing home range. Additionally, there was weak evidence that the number of wind turbines within the late brood-rearing home range negatively affected 42-day brood success. These results support our predictions based on similar findings for sage-grouse broods (LeBeau et al. 2014, Kirol et al. 2020) but are contrary to findings of Harrison (2015) and LeBeau et al. (2017) who reported no effect of wind turbines on brood survival of prairie-chickens and sage-grouse, respectively.

Wind-energy infrastructure or associated habitat fragmentation could result in increased predation on grouse offspring (LeBeau et al. 2014). Although we were unable to document causes of mortality for chicks that died in our

study, Manzer and Hannon (2008) reported mammals to be the primary predators of radio-marked sharp-tailed grouse chicks in the first 30 days after hatch. Decreased offspring survival in our study could have resulted from increased mammalian predation if turbine access roads or resulting habitat fragmentation facilitated mammalian predator movements and hunting efficiency (Dickie et al. 2017). Prairie-chickens in Oklahoma avoided roads and altered their movement speed in response to roads, possibly viewing these areas as high-risk sites (Londe et al. 2022). While we did not estimate Columbian sharp-tailed grouse space use, changes in movement patterns in response to anthropogenic development may result in habitat avoidance or loss or lead to trade-offs with other behaviors, which can cause reduce fitness and survival (Hernandez and Laundre 2005).

Anthropogenic noise associated with wind turbines may indirectly affect grouse offspring survival. While previous research has documented the responses of lekking prairie grouse to turbine noise (Smith et al. 2016, Whalen et al. 2018), anthropogenic noise may also affect grouse behavior during other stages of the breeding season. Female sharp-tailed grouse use gathering and contact calls to communicate with chicks during the brood-rearing period (Connelly et al. 2020). Grouse chicks use distress calls during dangerous encounters (Connelly et al. 2020). Chick survival in our study could have been negatively affected if wind turbine noise interfered with vocal communication between brood females and chicks or affected their ability to detect predator cues (Jung et al. 2020).

Lower offspring survival around wind turbines could be expected if habitat quality in the vicinity of turbines was inherently lower. High-quality brood habitats allow chicks to move easily through vegetation, provide protection from predators and adverse weather, and provide adequate food resources (Bergerud and Gratson 1988). Columbian sharp-tailed grouse broods select habitats with higher grass and forb cover than random sites (Apa 1998, Boisvert 2002, Collins 2004) and may experience decreased fitness in less diverse vegetative cover types (Boisvert 2002, Gillette 2014). We assessed the influence of vegetation characteristics typically found in Columbian sharp-tailed grouse habitats in our study area for 2 reasons: to account for potential differences in habitat quality between locations with and without turbines and to determine vegetation characteristics important to offspring fitness in the context of CRP and other restored grasslands. We found no important relationships between any of our measures of offspring fitness and the vegetation characteristics assessed in our models.

Forb cover and associated insects likely benefit grouse chicks by providing the nutritional requirements necessary soon after hatch (Kirsch 1974, Svedarsky et al. 2022). We modeled forb cover as a functional group and did not collect data at the plant species level. We may have failed to detect an influence of forb cover on offspring survival if particular forb species provided better habitat for either Columbian sharp-tailed grouse chicks or the insects they forage on. The grass functional groups we hypothesized to influence chick movement, concealment, or thermal cover were also not influential to our measures of offspring survival. Because we only documented chick presence at 14 and 42 days old, and did not have marked chicks, we were unable to document specific daily chick movements and habitat selection. It is possible that chick survival was related to vegetation characteristics at finer scales than we were able to quantify with our 2 scale buffers around nest sites.

We found weak evidence for positive effects of post-hatch precipitation on early brood success and 42-day chick survival. Pre-hatch weather conditions can positively influence grouse chick survival by improving food and cover resources (Erikstad 1985), but cool, wet post-hatch conditions may negatively influence chick survival during the first week of life when chicks are unable to thermoregulate (Flanders-Wanner et al. 2004). Goddard and Dawson (2009) documented increased sharp-tailed grouse chick survival in northern British Columbia, Canada, with wet pre-hatch weather and decreased chick survival with wet post-hatch weather. Eastern Idaho experiences hot, dry summers with most spring–summer precipitation occurring prior to hatch. In years where precipitation is not paired with extreme cold temperatures, post-hatch precipitation in eastern Idaho may stimulate forb and insect production necessary for Columbian sharp-tailed grouse hatchling survival without negatively affecting thermoregulation.

Top models of offspring survival in our study also included hatch date and brood-rearing female age. Late brood success and 42-day chick survival were associated with earlier nest hatch dates. Decreased offspring survival later

in the season has been documented in prairie grouse (Fields et al. 2006, Matthews et al. 2011) and may be attributable to declining female condition as the season progresses (Thogmartin and Johnson 1999), heat stress and water loss (Fields et al. 2006), or decreased food availability (Matthews et al. 2011). Columbian sharp-tailed grouse chicks in eastern Idaho may benefit from early hatch dates because of the detrimental effects of decreased moisture and increased temperature as the breeding season progresses. There was weak evidence that adult females in our study were more successful in rearing broods to 14 days of age than yearlings. While better reproductive performance in adults may be expected in longer-lived upland bird species, this is not always observed (Dahlgren et al. 2010a, Guttery et al. 2013).

We estimated chick survival to 42 days after hatch, a measure of individual offspring survival that has not been included in previous studies examining impacts of wind-energy development on prairie grouse. We chose to estimate chick survival because relationships between covariates and recruitment could be masked with a low-resolution measure of offspring survival (e.g., brood success equals  $\geq 1$  chick alive), particularly for species with larger clutch and brood sizes. Because we estimated chick survival with dog flush counts of unmarked chicks, we acknowledge that brood-mixing could have resulted in biased survival estimates. Brood-mixing has been documented in upland bird species (Dahlgren et al. 2010a, Orange et al. 2016), but we are unaware of evidence of brood-mixing in Columbian sharp-tailed grouse. We found relatively strong evidence that chick survival was negatively influenced by the number of wind turbines within 2,100 m of the nest, an effect that was only weakly detected when using the more traditional brood-success metric.

## MANAGEMENT IMPLICATIONS

Increasing wind turbine density at the brood-rearing home range scale (i.e., within 2,100 m of the nest) negatively affects chick survival. The current Western Association of Fish and Wildlife Agencies guidelines for the management of Columbian sharp-tailed grouse populations and their habitats recommend no surface occupancy of energy developments within 2 km of occupied leks, to protect nesting and brood-rearing habitats. Our results confirm the importance of considering brood-rearing habitats during wind-energy siting and mitigation. We recommend that future research in energy-developed habitats consider relationships between Columbian sharp-tailed grouse chick predators and habitat fragmentation to better identify mechanisms affecting chick survival.

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## CONFLICTS OF INTEREST

The authors declare no conflicts of interest.

## ETHICS STATEMENT

Our animal capture and handling protocols were approved by the Utah State University Animal Care and Use Committee (protocol 2286).

## DATA AVAILABILITY STATEMENT

Data available on request from the authors.

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