Habitat Use by Pinyon Jay and Gray Vireo at Farmington BLM Resource Area: Territory/Colony Scale Models

Final Report

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Abstract

In 2013, we began a multi-scale study of habitat use by Gray Vireo and Pinyon Jay at the BLM Farmington Resource Area (FRA). The goals of that four-year study were to:

1. create multi-scale habitat models for Gray Vireo and Pinyon Jay on BLM lands,
2. compare results to those of the four-year Department of Defense (DoD) study, and
3. provide management recommendations for piñon-juniper woodland habitats in the FRA.

We conducted the nest-scale habitat analysis for Pinyon Jays and Gray Vireos in 2013 and 2014 (Johnson et al. 2015). We began creating the landscape-scale habitat model in 2015 and completed it in 2017 (Johnson et al. 2017). For this project, we have completed the final phase of habitat modeling at the FRA, with the territory- and colony-scale models for Gray Vireo and Pinyon Jay, respectively. This report describes methods and presents the final predictive models: territory model for Gray Vireos and nesting colony model for Pinyon Jays.

We first surveyed for breeding territories (Gray Vireo) and nesting colonies (Pinyon Jay). We centered circular territory polygons of radius 149 m around the center point of 66 Gray Vireo territories and 264 random points in piñon-juniper habitat. We summarized mean values for a suite of covariates describing the landscape characteristics in the area of estimated territory centers and random available locations. We modeled Gray Vireo territory occurrence using generalized linear models with a binomial error distribution (also known as logistic regression). In addition to identifying covariates (and the nature of their influence) associated with territory occurrence, we generated surface predictions of the probability of territory occurrence across areas with mean canopy cover (within 149 m) above 0%.

We assumed that estimated Pinyon Jay colony boundaries encompassed areas of preferred nesting habitat, and we generated 100 samples of locations within these areas as representative of this habitat preference. We generated four times the sample of preferred nesting colony habitat in areas outside colony boundaries but within areas classified in the land cover data set as Sparse or Dense Piñon-Juniper Woodland. Additionally, as a conservative measure, we restricted this area of availability to areas with canopy cover (mean cover in 20 m pixels) over 10%, because all nests were in or within 5 m of areas with at least 10% canopy cover as estimated from the canopy data set. We used a modeling approach similar to that employed in modeling territory occurrence of Gray Vireos. We generated spatial predictions using the most supported model at the resolution of individual pixels.

The best model of Gray Vireo territory occurrence, after controlling for survey-related road effects, combined effects of topography and habitat. It had a goodness-of-fit *P*-value of 0.93 and an AUC of 0.96, indicating both a good fit and excellent discriminatory ability. The best model of Pinyon Jay colony occurrence included effects of topography, woodland, and distance to road. The AICc of the best model was 5.7 units lower than the next best model and had 94% of the total weight of the model set. This model had an AUC of 0.960, indicating an excellent discriminatory ability. The Hosmer-Lemeshow test (*P* = 0.27) indicated a good model fit.

Piñon-juniper habitat is widespread and abundant at the FRA (6389 km^2 of potential Gray Vireo habitat and 5,539 km^2 of potential Pinyon Jay habitat). However, only 255 km^2 (4%) of potential Gray Vireo habitat has >0.5 probability of being used as a territory. Likewise, only 384 km^2 (6.9%) is predicted Pinyon Jay colony habitat. Hence, it is not sufficient to conserve just any block of piñon-juniper habitat for these species. Importantly, specific characteristics of Gray Vireo territory and Pinyon Jay colony sites should be considered when managing their habitat.

Introduction

Piñon-juniper Habitats and Wildlife

Piñon-juniper (*Pinus edulis, P. monophylla, Juniperus* spp.) woodlands cover approximately 40 million hectares of the western US (Romme et al. 2009). Together, they are the dominant woodlands and most common vegetation type at the BLM Farmington, NM Resource Area (FRA), covering approximately 350,546 ha.

Several studies have attributed recent mortality, morbidity, and reduced productivity of piñon and juniper trees in the Southwest to climate change. Since 2001, dramatic, rapid, large-scale mortality of piñon trees has occurred in the southwestern US due to "global change-type drought" and associated insect and disease outbreaks (Allen-Reid et al. 2005, Breshears et al. 2005). A 2002–2004 drought in northern Arizona piñon-juniper woodlands reduced canopy cover by 55% (Clifford et al. 2011). Increased temperatures and drought have been associated with declines in piñon cone production (Redmond et al. 2012) and juniper, piñon, and oak mast production (Zlotin and Parmenter 2008). Under climate change, the range of piñon-juniper habitat is predicted to contract significantly across the Southwest and expand into northern New Mexico and Colorado (Cole et al. 2008, Thompson et al. 1998). A recent modeling effort predicts massive, widespread piñon and juniper mortality across the Southwest before 2100, which will have "profound impacts on carbon storage, climate forcing, and ecosystem services" (McDowell et al. 2015).

Numerous game animals and sensitive wildlife species depend directly on piñon and juniper trees for food and nest sites. Game species include turkey (*Meleagris gallopavo*), mule deer (*Odocoilus hemionus*), and elk (*Cervus elaphus*). Several federal Birds of Conservation Concern (BCC) (US Fish and Wildlife Service 2008)—Gray Vireo (*Vireo vicinior*), Pinyon Jay (*Gymnorhinus cyanocephalus*), and Black-chinned Sparrow (*Spizella atrogularis*)—breed in piñon-juniper habitats. The above bird species plus Juniper Titmouse (*Baeolophus ridgwayi*) are classified as New Mexico Department of Game and Fish (NMDGF) Species of Greatest Conservation Need (SGCN) (NMDGF 2015).

Piñon and juniper are masting species, producing large seed crops at irregular intervals (Zlotin and Parmenter 2008). Pinyon Jays have a close mutualism with piñon trees, serving as short- and long-distance seed dispersers for piñon pines, and piñon mast crops enhance Pinyon Jay reproductive success and survival (Ligon 1978, Marzluff and Balda 1992). The close mutualism between piñon pines and Pinyon Jays means that impacts to one species affect the other; hence, Pinyon Jays are an indicator species for health and productivity of piñon-juniper habitats.

A recent model of climate effects on birds and reptiles in the southwestern US projected a 25–31% decrease in the breeding range of the Pinyon Jay between 2012 and 2099. During the same time period, the Gray Vireo breeding range was projected to increase between 58% and 71% (van Riper et al. 2014). Another recent report on birds and climate change projects a 24% decrease in summer range and 37% decrease in winter range of the Pinyon Jay from 2000 to 2080 and an 832% increase in the summer range of the Gray Vireo during the same period (National Audubon Society 2015). These two bird species represent very different projected responses to climate change and can therefore serve as indicator species for the impacts of climate change on piñon-juniper wildlife habitats at the FRA. They can also be used to test the above predictions of climate impacts on wildlife.

The Project

In 2013, we began a multi-scale study of habitat use by Gray Vireo and Pinyon Jay at the FRA. The goals of that four-year study are to:

4. create multi-scale habitat models for Gray Vireo and Pinyon Jay on BLM lands,
5. compare results to those of the four-year Department of Defense (DoD) study, and
6. provide management recommendations for piñon-juniper woodland habitats in the FRA.

We conducted the nest-scale habitat analysis for Pinyon Jays and Gray Vireos in 2013 and 2014 (Johnson et al. 2015). We began creating the landscape-scale habitat model in 2015 and completed it in 2017 (Johnson et al. 2017). In 2017, we have completed the final phase of habitat modeling at the FRA, with the territory and colony scale models for Gray Vireo and Pinyon Jay, respectively. This report describes methods and presents the final predictive models: territory model for Gray Vireos and nesting colony model for Pinyon Jays.

Our study of habitat use by two at-risk species that differ in seasonal movements, social structure, and foraging habits, viewed at multiple scales and several sites across the state, provides a broad perspective on the management of piñon-juniper woodlands for piñon-juniper birds.

Methods

Study site

The study area includes the majority of land under BLM Farmington Field Office jurisdiction, excluding small, isolated parcels (Figure 1). The final study area is 907,120 ha in area and includes the majority of piñon-juniper habitat in the FRA.

Field work

Gray Vireo

Initial Gray Vireo field work was performed in 2013 by Animas Biological Studies, Durango, CO. We targeted four sites to survey for Gray Vireos: Aztec, Pump Canyon, Pump Mesa, and Crow Mesa (Figure 2). With prior knowledge of the presence of breeding Gray Vireos, we selected these sites to represent potential breeding habitat from the northern to the southern portions of the FRA. These sites represent only a portion of occupied Gray Vireo habitat in the FRA. In 2013, we visited Aztec on 4, 5, 17, and 19 June and 3 July. Crow Mesa we surveyed on 28 and 29 May and 12 and 13 June. We surveyed Pump Canyon on 23 May and 11 and 12 June. We visited Pump Mesa on 2, 9, 10, and 11 July. In addition, we conducted a single-day survey for Gray Vireos in the Mesa Mountains on 12 June 2013, in conjunction with another project on BLM lands.

Pump Canyon, Pump Mesa, and Crow Mesa have well-defined topographic boundaries; thus, we surveyed the majority, if not all, of the potential Gray Vireo habitat at these sites in 2013 and 2014. The Aztec area, however, is much more extensive and consists of canyons and rolling hills, absent of a single defining topographic feature, with a mosaic of piñon-juniper woodlands interspersed with sagebrush shrublands and rural areas. We focused our efforts on only a fraction of available Gray Vireo habitat in the Aztec site, attempting to maximize the area surveyed from the New Mexico–Colorado border south to the City of Aztec. Thus, Gray Vireos were not necessarily absent in areas adjacent to the territories we identified.

During initial visits to each site, if we did not detect spontaneous singing, we used playbacks of Gray Vireo vocalizations to determine presence/absence of territorial birds. We recorded locations of vireo detections using a GPS unit. We documented the number of birds detected, sex, and behavior (e.g., singing male, pair).

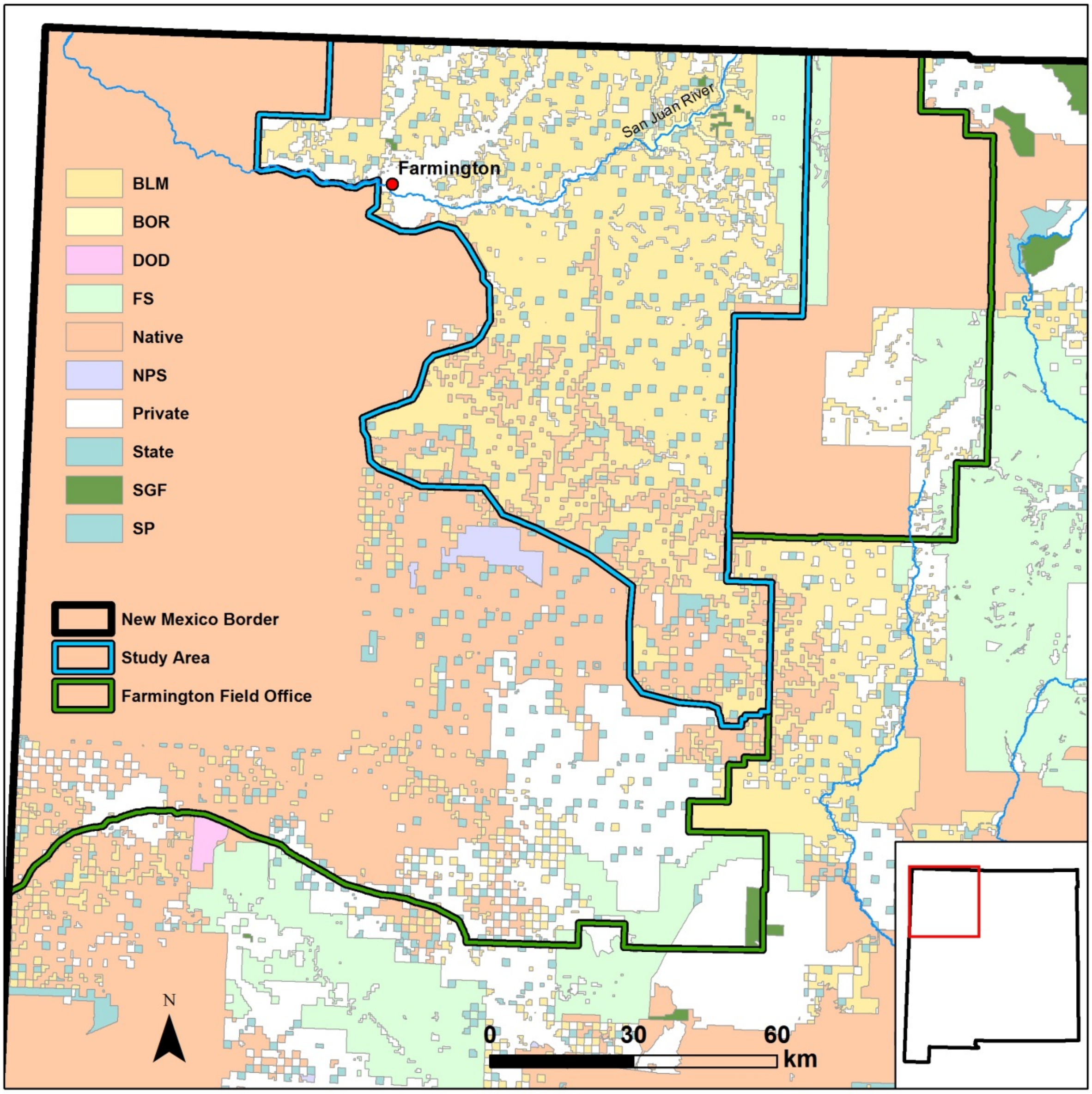

Figure 1. Study area within BLM Farmington Field Office jurisdiction.

During initial and follow-up visits to occupied territories, we observed vireos for nesting behavior and searched for nests. Where we located nests, we checked their contents, if possible, and recorded their locations using GPS.

In 2014, we revisited occupied Gray Vireo territories in the Aztec, Pump Canyon, Pump Mesa, and Crow Mesa study sites to locate additional active nests. We visited territories in the Aztec area on 22 and 23 May and 13 and 26 June. At Crow Mesa, we searched for nests from 27 to 29 May and on 10 and 18 June. We visited Pump Canyon territories on 15 May and 4, 11, 12, and 17 June; and Pump Mesa on 14 and 26 May; 12 and 17 June; and 1 July.

The data collected in 2013 and 2014 were used mainly to create Gray Vireo landscape- and nest-scale models (Johnson et al. 2014), but we also revisited these sites in 2016 to delineate territories for the territory-scale modeling. To collect territory-scale data, we visited previously occupied (2013–14) Gray Vireo territories at least four times spread across the portion of the 2016 breeding season when vireos are most vocal (May–mid-July) to document occupancy and to estimate territory boundaries. Field visits were conducted between approximately sunrise and noon, when vireos vocalize most. We visited territories in the Aztec area on 17 and 30 May and 13 and 28 June. At Pump Canyon, we visited territories on 13 May; 6, 21, and 22 June; and 13 July. At Pump Mesa, we visited territories on 11 May and 1, 14, 20, and 29 June. We visited territories on Crow Mesa on 19 and 31 May and 14 and 29 June. To develop a robust data set, we attempted to visit as many territories as possible within each of the four sites. However, we were unable to visit all of the territories identified in 2013 and 2014 with the allocated 2016 budget.

During initial visits to each territory in May 2016, we identified vocalizing adult male Gray Vireos, moved quickly to their locations, and marked those locations in the field using GPS units. We then followed these males, marking additional locations as they sang spontaneously, defended their territories from conspecifics, and performed courtship behaviors. While carefully observing these activities, we attempted to define and mark the approximate external boundaries of each territory to the extent possible. After field surveys in May, we overlaid Gray Vireo locations onto topographic maps using ArcGIS (Esri 2012) to initially count and approximate territories. Subsequent field visits to each territory followed the initial methods to collect additional locations and note nesting behavior.

Pinyon Jay

Pinyon Jay field work was performed by Natural Heritage New Mexico, UNM Biology Department. In April and May 2013, Natural Heritage New Mexico surveyed for nesting colonies of Pinyon Jays in the FRA. We first visited four potential sites where Pinyon Jays had been previously observed: Palluche Canyon, Cave Spring, Rawhide Canyon (all on 11 April, Figure 2), and Crow Mesa (12 April, Figure 2). Pinyon Jays had been observed only in the fall at Cave Spring, and Palluche Canyon was more difficult to access than Rawhide Canyon and Crow Mesa. We therefore began surveys at Crow Mesa and Rawhide Canyon, both sites where Pinyon Jays had been observed during the breeding season. We detected nesting activity at both Crow Mesa and Rawhide Canyon and thereafter focused our efforts for the rest of the breeding season at those two sites.

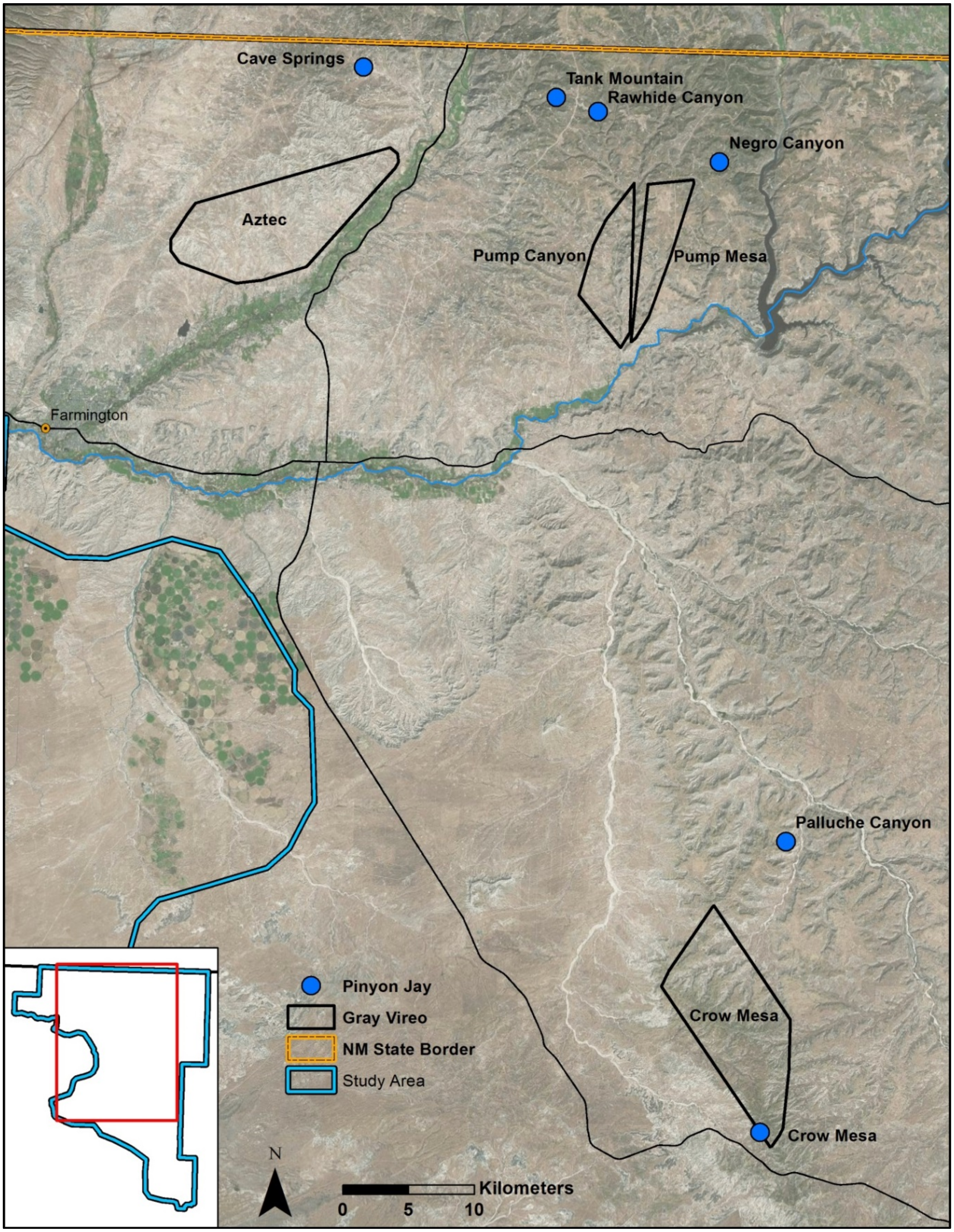

Figure 2. Gray Vireo territory and Pinyon Jay nesting colony study sites within the Farmington Resource Area.

During our reconnaissance visit to Crow Mesa on 12 April, Pinyon Jays were present, prompting us to look for nests. We made three additional visits to Crow Mesa (17 and 24 April, 2 May) to look for breeding activity and nests. We made two reconnaissance visits (11 and 25 April) to Rawhide Canyon to survey for Pinyon Jays. We returned twice (17 April, 3 May) to the colony site we had found in 2012 and five times (3, 7, 8, 14, and 15 May) to a new 2013 colony site to look for nests. The data collected in 2013 were used mainly to create Pinyon Jay nest-scale models (Johnson et al. 2014), but we used data from the delineated colony areas to model colony-scale habitat.

On 3-4 April 2016, after assessing potential habitat on the draft landscape-scale map, we searched for Pinyon Jays in suitable habitat west of Navajo Lake. We found two nests and one fledgling at a new colony, the Negro Canyon Colony, during this survey. We returned on 20 and 21 April and found 9 additional nests and delineated colony boundaries based on those nests.

Modeling

Gray Vireo

Territory estimation

We estimated the location and size of territories in several steps. Following field surveys, we suspected territory boundaries were poorly established in early (mid-May and prior) surveys. Mean centers of observations in early surveys were on average 101 m (*n* = 46, SD = 78, range = 4–411) from later (late May and after) observations.

As the number of observations was typically small (mean = 8.0, SD = 2.6, range = 2–16), we estimated a single size for all territories by assuming a circle bounded most areas of seasonal activity among territorial males or mated pairs. We calculated the (global) radius and (per-territory) center location of territories in three steps. We first calculated 95% minimum convex polygons (MCP) around all observations within territories having at least five observations using the adeHabitat package (Calenge et al. 2015) in R (R Development Core Team 2014). Second, we employed ArcGIS (Esri 2012) to calculate the geometric center of each MCP. Third, we calculated the largest distance from MCP centers to the most distant MCP vertex. We employed the maximum distance (149 m, 7.0 ha) as the radius for circular territory estimates. This radius encompasses 414 of 425 observations of birds (97.4%) in late May or after. While territory sizes are not well-described for the Gray Vireo, this 7.0 ha estimated territory area is within the 2–10 ha range reported by Barlow et al. (1999) and similar to that reported by DeLong and Cox (2005), Johnson et al. (2014), and Wickersham and Wickersham (2016). Similarly, the 149 m radius is nearly identical to the spacing of individual territories in Wauer (1983) and Barlow (1978, both cited in Barlow et al. [1999]). We used this radius to summarize mean values for a suite of covariates (described below) describing the landscape characteristics in the area of estimated territory centers and random available locations. Random available locations were limited to areas with land cover in piñon-juniper classes (see Habitat and woodland characteristics, below) and occurring at least 149 m from estimated territory centers. Similarly, each of these random locations was spaced at least 149 apart. We used a set of 264 random locations (four times the number of territories) for comparison as this allowed us to capture broader ranges among landscape characteristics than a balanced 1:1 ratio of territories to random locations.

Covariates

We considered three covariate groups in modeling Gray Vireo territory occurrence (Table 1). These groups were landscape topography, habitat and woodland characteristics, and human disturbance.

Table 1. Covariates and descriptive statistics for Gray Vireo territory and random plots. Standard deviations (SD) for back-transformed covariates (following log-transformation) were calculated using the Taylor expansion.

	Territories		Random available areas	
Covariate	Mean (SD)	Range	Mean (SD)	Range
Topography				
Curvature	0.00 (0.13)	-0.47–0.45	0.01 (0.13)	-0.71–0.49
Heatload	0.84 (0.02)	0.81–0.90	0.83 (0.02)	0.73–0.93
Slope (°)[a]	6.2 (2.1)	2.9–17.1	6.9 (3.6)	1.4–29.9
Habitat				
Canopy cover (%)[a]	11.2 (4.0)	2.5–23.3	5.8 (4.4)	0.1–32.3
Scattered Piñon-Juniper Woodland land cover (%)	1.6 (2.1)	0.0–8.6	3.3 (6.6)	0.0–55.3
Sparse Piñon-Juniper Woodland land cover (%)	52.2 (23.3)	0.0–89.8	62.4 (28.1)	0–100
Dense Piñon-Juniper Woodland land cover (%)	26.5 (26.2)	0–91	10.9 (22)	0–96
Combined cover in shrub land cover (%)	6.1 (10.4)	0.0–40.4	7.4 (13.5)	0–65
Topographic convergence index	8.7 (0.5)	7.8–9.9	8.7 (0.7)	6.6–10.9
Disturbance				
Number of gas wells in territory (n)[a]	0.2 (0.5)	0–3	0.1 (0.3)	0–3
Distance to nearest gas well (m)[a]	207 (98)	65–580	276 (209)	60–4870
Disturbed gas well pad cover index (%)[a]	1.4 (2.9)	0.0–36.9	0.5 (1.4)	0.0–47.7
Distance to nearest gas well pad (m)[a]	178 (129)	37–1156	321 (327)	20–6234
Length of road within territory (m)[a]	41 (116)	0–1300	6 (17)	0–920
Impervious land cover index (%)[a]	8.2 (7.5)	0.0–28.4	1.1 (2.4)	0.0–38.7
Distance to nearest road (m)[a]	52 (36)	14–411	188 (213)	12–1868

a. Covariate was log-transformed (plus 1) prior to generating means and standard deviations. Values were then back-transformed to their original scale.

Topography. We derived several characteristics of local topography from the National Elevation Dataset at a ground resolution of 10 m. These characteristics were heat load (an index of solar exposure), curvature, and slope. Heat load was calculated using equations in McCune and Keon (2002) and was included due to a documented tendency for Gray Vireos to nest on slopes with westerly (Delong and Cox 2005) and southerly (Wickersham and Wickersham 2016) aspects elsewhere in New Mexico. Curvature and slope were calculated in ArcGIS (Esri 2012) and were included due to observations of nest sites in bowl-shaped areas at the foot of steeper slopes (Arbetan and Neville 2009, Wickersham unpublished data) or at the base of slopes within canyons (Britt and Lundblad 2009). These areas may provide additional protection from winds. Negative curvature values indicate a concave surface, while positive values indicate a convex surface.

Habitat. We expected characteristics of woodlands and other land cover classes to differentiate Gray Vireo territories from available areas. To quantify these woodland characteristics, we employed two data sources developed previously for the area (Johnson et al. 2017):
(1) categorical land cover data, and (2) an estimate of piñon or juniper canopy presence. We derived the percentage of each territory or random area in several land cover classes (or their

aggregates) suspected of being preferred (Dense Piñon-Juniper Woodland, Sparse Piñon-Juniper Woodland, Scattered Piñon-Juniper Woodland, Other Shrubland, Sagebrush Shrubland) or avoided (e.g., Agriculture, Barren/Sparsely Vegetated, Gambel Oak Woodland, Grassland, Human Disturbance) by Gray Vireos when establishing territories. We additionally examined contributions of cover across three piñon-juniper density classes (dense, sparse, and scattered) and the total area in non-piñon-juniper cover to differentiate Gray Vireo territories from available areas (land cover classes from Johnson et al. 2017). Using the canopy cover dataset, we calculated an estimated percent canopy cover at a 20-m resolution. Land cover data were aggregated to this resolution for consistency.

In addition to land and canopy cover, we calculated the topographic convergence index (TCI) from 10-m elevation data. Topographic convergence (or wetness) is a hydrological measure of upstream drainage area (i.e., higher values in canyon bottoms) and was included as we suspected it to be correlated with riparian and semi-riparian shrub cover in which Gray Vireos were observed foraging during field visits (L. Wickersham, unpublished data) and which was typically present in areas too small for detection during land cover classification.

Disturbance. Concern over the expansion of natural gas development in the Farmington area on Gray Vireo populations was raised by Stake and Garber (2009). We suspected human disturbance might deter territory establishment, yet we also recognized the tendency for Gray Vireos to nest in areas with adequate quantities of non-woodland cover. As natural gas wells are common in the study area, we suspected the presence of bare well pads and sound generated by active wells may deter territory establishment (Francis et al. 2011). To address these potential factors, we calculated disturbance covariates from two data sets. The first was a point shapefile indicating the location of natural gas wells obtained from New Mexico Oil Conservation Division (NMOCD 2017). The second was an index of well pad area (% area of territory) derived from the Human Disturbance class of the land cover data set (at a resolution of 20 m). This index was derived by isolating areas of disturbance by using ArcGIS (Esri 2012) (via the shrink and expand tools in the Spatial Analyst toolbox) to remove linear features (typically roads) from the Human Disturbance land cover class. This resulted in polygons that closely matched those in aerial photographs but which were not connected to linear road features.

As with the presence of well pads, we suspected the presence and characteristics of roads could negatively influence the distribution of territories. However, due to clustered sampling of territories near areas of road access, we first inspected differences between territory sampling areas and other areas with the expectation that sampled and non-sampled areas showed similar road characteristics. To do this, we compared the areas of territory sampling ($n = 4$, buffered by 2 km, area range = 2,812 – 7,117 ha) vs. circular non-sampled areas (4,904 ha; the mean of the four sampled areas). While differences were not significant (Wilcoxon rank-sum test: $W = 68$, $P = 0.20$), boxplots indicated higher road densities in these survey areas (mean = 25.1 m/ha) than non-sampled areas (mean = 19.5 m/ha).

To address this potential source of bias, we considered three related measures of road presence within territories and available, random area: (1) linear road length (from 2016 TIGER roads; U.S. Census Bureau), (2) distance from roads (from TIGER roads), and (3) impervious cover (>0% from the 2011 National Land Cover Dataset (NLCD; Homer et al. 2015)). Due to strong correlation ($|r| > 0.7$) among these variables, we used principal components analysis (via princomp in R) to generate three uncorrelated axes for use in models.

Modeling

We modeled Gray Vireo territory occurrence using generalized linear models with a binomial error distribution (also known as logistic regression). We employed several stages to this effect. As a preliminary, exploratory, stage, we employed linear (i.e. $y = \beta_0 + \beta_1 x$) vs. quadratic (i.e. $y = \beta_0 + \beta_1 x + \beta_2 x^2$) relationships between single covariates and the binary response (territory vs. random area) when we suspected the probability of territory occurrence was highest at intermediate levels of covariates (e.g., intermediate canopy cover). In the second stage, we built model sets for each covariate group (topography, habitat, and disturbance) by considering all additive combinations of each covariate. The road effect covariates (principal components 1 and 2) were included in all models to control for this potential road bias. In the final stage of modeling, we built a model set by employing the best (lowest-sample-adjusted Akaike information criterion [AICc]) additive combinations from each of the covariate groups and then combining them further. We assessed a standout model from this set as one having AICc < 4 units from the next-lowest AICc model. While models may sometimes be competitive with the lowest-AICc ("best") model in a data set (i.e., they have ΔAICc < 4), these models may contain uninformative parameters (i.e., having $P > 0.15$; Arnold 2010). In that event, we did not consider these models for model averaging (Burnham and Anderson 2002). We assessed the fit of models using the Hosmer-Lemeshow goodness-of-fit test (Hosmer et al. 2013) and the area under the receiver operating curve (AUC). The latter is a threshold-independent measure of agreement between observed responses (here territory vs. random area) and model-predicted probabilities (Fielding and Bell 1997). Goodness-of-fit test *P*-values greater than 0.05 indicate adequate model fit. AUC values of 0.7–0.8, 0.8–0.9, > 0.9 indicate acceptable, good, and excellent discriminatory ability of models. All covariates employed in models were correlated with absolute Pearson *r* values less than 0.5, reducing the possible biases associated with multicollinearity.

Prediction

In addition to identifying covariates (and the nature of their influence) associated with territory occurrence, we generated surface predictions of the probability of territory occurrence across areas with mean canopy cover (within 149 m) above 0%. These predictions were generated using the same surfaces from which we originally extracted values of covariates across 7.0 ha estimated territories and available, random areas. These surfaces are predicted such that values of each cell represent a probability that it was the center of Gray Vireo territory. These surfaces were developed using the raster package (Hijmans 2013) in R. As we included road-associated covariates to control for potential sampling biases, we did not expect these effects to be stationary across the study area. We addressed this by holding principal components from the three road covariates at their mean values (0 in all cases), which is similar to employing mean values of (raw) covariates (e.g., impervious cover [mean = 1.8%]).

Pinyon Jay

Colony areas

We first examined Pinyon Jay nests observed in colonies within the FRA between 2012 and 2016 and determined that locations of colonies detected in multiple years were overall stable. In turn, we combined all nests across years for Crow Mesa, Old Rawhide, New Rawhide, and Negro Canyon colonies for estimation of colony boundaries. As with determining territory centers in the Gray Vireo, Pinyon Jay colony boundaries were determined using a 95% minimum convex (bounding) polygon (MCP) using the adeHabitat package (Calenge et al. 2015) in R. This step tended to remove the nest most distant from other nests when making MCP calculations. The boundary of Old Rawhide, with only four nests, was made using an MCP from all nests.

We assumed that estimated colony boundaries encompassed areas of preferred nesting habitat and we generated 200 samples of locations within these areas as representative of this habitat preference. We used the log of the MCP area (in ha) of each colony to generate an area-weighted number of points across colonies. For comparison in generalized linear models, and to adequately sample areas outside of colonies, we generated four times the sample of preferred nesting colony habitat in areas outside colony boundaries yet within areas classified in the land cover data set as Sparse or Dense Piñon-Juniper Woodland. Additionally, as a conservative measure, we restricted this area of availability to areas with canopy cover (mean cover in 20 m pixels) over 10% (Johnson et al. 2017). All nests were detected in or within 5 m of areas with at least 10% canopy cover as estimated from the canopy data set.

Covariates

We considered the same three covariate groups in modeling colony occurrence of Pinyon Jays as used in modeling Gray Vireo territory occurrence. These covariates are shown in Table 2.

Table 2. Covariates and descriptive statistics for locations within Pinyon Jay colonies and random points within available habitat. See Covariates section below for methods used in calculation of covariates. Standard deviations (SD) for back-transformed covariates (following log-transformation) were calculated using the Taylor expansion.

	Colony locations		Random available locations	
Covariate	Mean (SD)	Range	Mean (SD)	Range
Topography				
Curvature	0.08 (1.51)	-6.13–6.02	-0.08 (2.15)	-10.69–12.91
Heatload	0.82 (0.04)	0.70–0.94	0.83 (0.04)	0.61–0.97
Slope (°)[a]	7.2 (4.7)	0.3–30.7	7.6 (5.5)	0.2–55.4
Habitat				
Canopy cover (%)[a]	17.5 (11.3)	0.5–48.7	7.8 (6.1)	0.5–56.0
Sparse Piñon-Juniper Woodland land cover (%)	29[b]	–	85[b]	–
Dense Piñon-Juniper Woodland land cover (%)	71[b]	–	15[b]	–
Patch size of continuous Piñon-Juniper Woodland class (ha)[a]	1767.9 (2050.0)	46.5–3535.2	240.5 (517.9)	0.1–5229.8
Distance to open water (m)[a]	439 (310)	80–1354	1020 (702)	63–4429
Disturbance				
Distance to nearest gas well (m)[a]	292 (108)	100–555	283 (212)	28–5014
Distance to nearest gas well pad (m)[a]	208 (116)	28–540	324 (341)	20–8911
Distance to nearest road (m)[a]	189 (196)	0–581	182 (206)	0–2225

a. Covariate was log-transformed (plus 1) prior to generating means and standard deviations. Values were then back-transformed to their original scale.

b. Number represents the percentage of all locations falling within a 20-m pixel of a given land cover category

Topography. We considered the effects of three covariates derived from elevation data (see Gray Vireo section above): heatload, curvature, and slope. As we expected each to potentially exhibit non-linear relationships with Pinyon Jay colony occurrence, we included quadratic terms in models (see modeling below). Additionally, we suspected relationships between preference of woodland areas and topographic covariates could be influenced by interactions with other coinciding conditions.

Habitat. We suspected woodland characteristics of areas in which Pinyon Jay colonies occurred to differ from available areas in the study area. We considered three covariates: (1) canopy cover, (2) classification as Sparse or Dense Piñon-Juniper Woodland, and (3) patch size of woodland (because Pinyon Jays nest colonially and therefore require larger patches of habitat than comparably-sized territorial species). We calculated patch size from continuous areas in the land cover data set classified as Sparse or Dense Piñon-Juniper Woodland having >0% canopy cover. Features employed in fragmenting woodlands in multiple patches were (1) disturbance (from the land cover data set) and (2) roads (with TIGER road features buffered by 6 m). We suspected canopy cover to potentially exhibit a non-linear relationship with Pinyon Jay colony occurrence; thus we included a quadratic term in models. In addition to woodland, we suspected the presence of water features could potentially attract nesting colony placement (Petersen et al. 2014). Surface water was indexed from water bodies (polygons) and both irrigation canals and main stems of area rivers from the 2010 National Hydrology Dataset. This dataset was augmented with point locations of guzzlers in the northern tier of the study area (John Hansen pers. comm.). We included a quadratic term for water distance as we suspected colonies may be more likely to be located near but not immediately adjacent to water sources (e.g., reservoirs).

Disturbance. We suspected the presence of human structures and activity could deter colony placement in the area. To address these potential factors, we included distance-to-feature surfaces for three disturbance feature types (TIGER roads, well pads index [see above], and well locations). As locations employed for sampling habitat within colonies were restricted to Piñon-Juniper Woodland land cover areas, some measures of disturbance employed in Gray Vireo territory modeling (e.g., percent impervious cover within a territory) were not available for modeling Pinyon Jay colony occurrence.

After initial inspection of colony locations and land cover we were concerned that the proximity of roads to three colony areas—which we suspected was purely coincidental—may bias estimates of other covariate effects if not addressed. We identified a quadratic relationship between colony occurrence and the distance to roads.

Modeling

We used a modeling approach similar to that employed in modeling territory occurrence of Gray Vireos. We modeled Pinyon Jay colony occurrence in two stages, first by determining the combination of covariates in the three groups (topography, woodland characteristics, and distance characteristics) most predictive (i.e., lowest-AICc) in logistic regression models in which the (dependent) response variable was colony (1) or non-colony (0) location. In the second stage, we built model sets for each covariate group by considering all additive combinations of each covariate. The quadratic road distance effect was included in all models to control for this potential road bias. Model assessment was identical to that employed for the Gray Vireo.

Prediction

We generated spatial predictions using the most supported model at the resolution of individual pixels. This involved using the linear combination of parameter estimates from this model and continuous raster layers arranged in a "stack" using the raster package (Hijmans 2013) in R. We used a 40 m resolution stack (values were mean-aggregated from their original 20 m resolution) due to computing time and because this appeared to provide adequate detail for local variation in topography, woodland, and human features. As colonies monitored by NHNM between 2007 and 2016 had a 95% minimum convex polygon area of 6.1 ha (n = 13 colony years with less than 50% overlap, unpublished data) and over 30 times the size of 40-m pixels, the spatial clustering of preferred areas was an important consideration in generating a prediction surface of areas likely to be used by nesting Pinyon Jay aggregated in colonies.

We addressed the differences in pixel vs. colony scales in several steps. Following prediction (at the pixel scale), we first examined predicted probability cutoff thresholds between 0 and 1 (using 0.05 unit increments) to identify a threshold with excellent prediction of colony areas and at least good prediction of non-colony areas. We found a cutoff of 0.20 met these criteria; 93% of colony locations were classified correctly (sensitivity), while 88% of non-colony locations were classified correctly (specificity). Next, using the radius (140 m) of a circle with an area equal to the median observed colony size (6.1 ha), we summed the number of all pixels with a predicted probability above the 0.20 threshold. Finally, using the geographic centers of five of six colony-year areas in the study area, we extracted the value from the previous step (i.e., model-predicted probability $\geq$ 0.20 within 140 m). We used a 25-pixel threshold, as centers of five of six colony-years had at least this value (range = 23–37) to assign locations as potentially suitable for Pinyon Jay colony placement.

Results

Gray Vireo

Sixty-six territories and 264 random, available areas were used for modeling. The best model of Gray Vireo territory occurrence, after controlling for survey-related road effects, combined effects of topography and habitat. While the AICc of this model (Table 3) was less than 4 units lower than the second best model (receiving 78% of weight in the model set), the next-best model (model 9) contained uninformative parameters (Arnold 2010). The best model had a goodness-of-fit P-value of 0.93 and an AUC of 0.96, indicating both a good fit and excellent discriminatory ability.

Road proximity

Two of the principal components describing variation in road attributes were identified as predictive in exploratory models. The first principal component was highly correlated with all three road attributes (percent impervious cover, road length, and distance to roads; r = 0.92, 0.85, and -0.93, respectively) and indicated areas surveyed for Gray Vireo territories had intermediate-to-high values (Figure 3a). The second principal component was most correlated with road length (r = 0.53) and less correlated with the other two attributes ($|r|$ < 0.3) and indicated surveyed areas had low values (Figure 3b).

Table 3. Final candidate model set predicting the probability of Gray Vireo territory occurrence relative to three covariate groups (topography, habitat, and disturbance). Indicated are number of model parameters (K), sample-adjusted Akaike information criteria (AICc), relative AICc (ΔAICc), model weight (w_i), model log-likelihood (LL), area under the receiver operating curve (AUC), a measure of classification accuracy, and Hosmer-Lemeshow goodness-of-fit test *P*-value (GOF). Models 2–9 all included the effects of roads.

Model	K	AICc	ΔAICc	w_i	LL	AUC	GOF
1 Null	1	332.3	161.3	0.00	-165.1	0.500	NA
2 Road effects only[a]	4	241.3	70.4	0.00	-116.6	0.847	0.19
3 Topography[b]	9	211.9	40.9	0.00	-96.6	0.914	0.07
4 Habitat[c]	14	190.0	19.1	0.00	-80.3	0.940	0.05
5 Disturbance[d]	6	240.1	69.1	0.00	-113.9	0.869	0.33
6 Topography + habitat	19	171.0	0.0	0.78	-65.3	0.962	0.33
7 Topography + disturbance	11	211.3	40.3	0.00	-94.2	0.920	0.01
8 Habitat + disturbance	16	192.2	21.3	0.00	-79.2	0.942	0.19
9 Topography + habitat + disturbance	21	173.5	2.5	0.22	-64.2	0.963	0.27

a. **Includes effects of principal component derived from road length, distance to roads, and impervious cover.**
b. **Includes additive effects of heatload, slope, and curvature.**
c. **Includes additive effects of percent canopy cover, residual percent cover in the Dense and Sparse Piñon-Juniper Woodland classes, and the interaction between canopy cover and Sparse Piñon-Juniper Woodland.**
d. **Includes estimated percent gas well pad cover.**

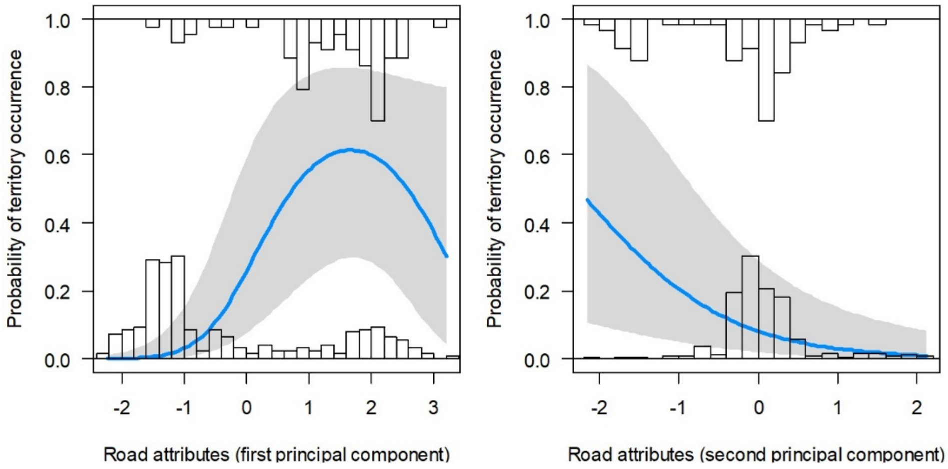

Figure 3. Plots of modeled differences in two principal components calculated from three road attributes (percent impervious cover, road length, and distance to roads) in areas sampled (Gray Vireo territories) vs. unsampled areas (random, available areas). Also indicated are histograms displaying the relative frequency distribution of principal components in territories (upper histogram) and random, available areas (lower histogram). Gray error bands indicate 95% confidence intervals.

Topographic covariates

Three topographic covariates were identified for inclusion in final models. These were heatload, linear and quadratic slope, and linear and quadratic curvature (Figure 4). Relationships in the best model indicated a higher probability of territory occurrence at higher heatload values (**Error! Reference source not found.**, Figure 4a), both low and higher curvature values (Figure 4b), and intermediate but low (approximately 5°) slope values (Figure 4c).

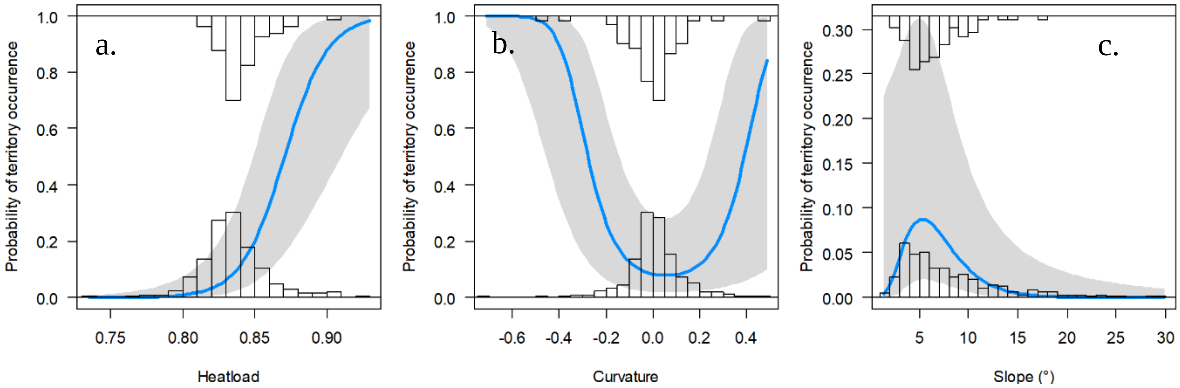

Figure 4. Plots indicating changes in the probability of territory occurrence relative to three topographic covariates. Relationships indicated an increasing probability of occurrence at higher heatload values (a), both lower (concave) and higher (convex) surfaces (b), and low slope values (approximately 5°, c). Also indicated are histograms displaying the relative frequency distribution of covariate values in territories (upper histogram) and random, available areas (lower histogram). Gray error bands indicate 95% confidence intervals. Curvature is multiplied by 100 to improve display.

Habitat covariates

Prior to modeling, we identified linear or quadratic relationships between canopy cover and cover in piñon-juniper land cover classes (Figure 5). To avoid issues associated with multicollinearity, we removed the correlation with canopy cover from these land cover covariates for use in models by taking residuals from ordinary least squares models of percent cover in each class predicted by (linear) canopy cover. A quadratic canopy cover term was used in generating residuals from the Sparse Piñon-Juniper Woodland class. Among all habitat covariates considered, three covariates were identified for inclusion in final models. These were linear and quadratic canopy cover, linear and quadratic (residual) cover in the Sparse Piñon-Juniper Woodland class (meaning cover in the sparse class, removing the effect of canopy cover), and linear and quadratic (residual) cover in the Dense Piñon-Juniper Woodland class (meaning cover in the dense class, removing the effect of canopy cover). Additionally, the interaction between canopy cover and Sparse Piñon-Juniper Woodland class cover was included in models (Figure 5).

Table 4. Parameter estimates from the best model of Gray Vireo territory occurrence in the Farmington BLM Resource Area. Covariates were scaled to a mean of zero and a standard deviation of 1. Hence, effect sizes are relative. Parameter estimate, standard error (SE), z-value (*z*), and *P*-value are indicated. Squared terms are indicated with a superscript '2'.

Covariate	Estimate	SE	*Z*	*P*
Intercept	-2.652	1.047	-2.533	0.011
RoadPC2[a]	-0.668	0.226	-2.960	0.003
RoadPC1[b]	2.867	0.571	5.021	0.001
RoadPC1^2	-1.345	0.452	-2.973	0.003
Heatload	1.498	0.396	3.782	0.000
Curvature	-0.290	0.269	-1.078	0.281
Curvature^2	0.355	0.114	3.115	0.002
Slope[c]	-0.706	0.414	-1.704	0.088
Slope^2	-0.822	0.358	-2.296	0.022
Cancover[c,d]	9.859	2.626	3.754	0.001
Cancover^2[c]	-7.916	2.399	-3.300	0.001
SparsePJ[e]	-3.351	1.075	-3.118	0.002
SparsePJ^2[e]	-0.828	0.378	-2.191	0.028
RdensePJ[f]	1.387	0.744	1.864	0.062
RdensePJ^2[f]	0.475	0.246	1.934	0.053
Cancover:RsparsePJ	8.204	2.707	3.030	0.002
Cancover:RsparsePJ^2	1.400	0.685	2.044	0.041
Cancover^2:RsparsePJ	-4.239	1.967	-2.155	0.031
Cancover^2:RsparsePJ^2	-1.267	0.823	-1.540	0.124

a. **First principal component of variation among linear road length, distance from roads, and impervious cover**
b. **Second principal component of variation road and impervious cover covariates**
c. **This covariate was log-transformed prior to scaling.**
d. **Mean canopy cover of piñon-juniper woodland**
e. **Mean cover in the Sparse Piñon-Juniper Woodland land cover class. This covariate was converted to a residual which was uncorrelated with canopy cover (Cancover).**
f. **Mean cover in the Dense Piñon-Juniper Woodland land cover class. This covariate was converted to a residual which was uncorrelated with canopy cover (Cancover).**

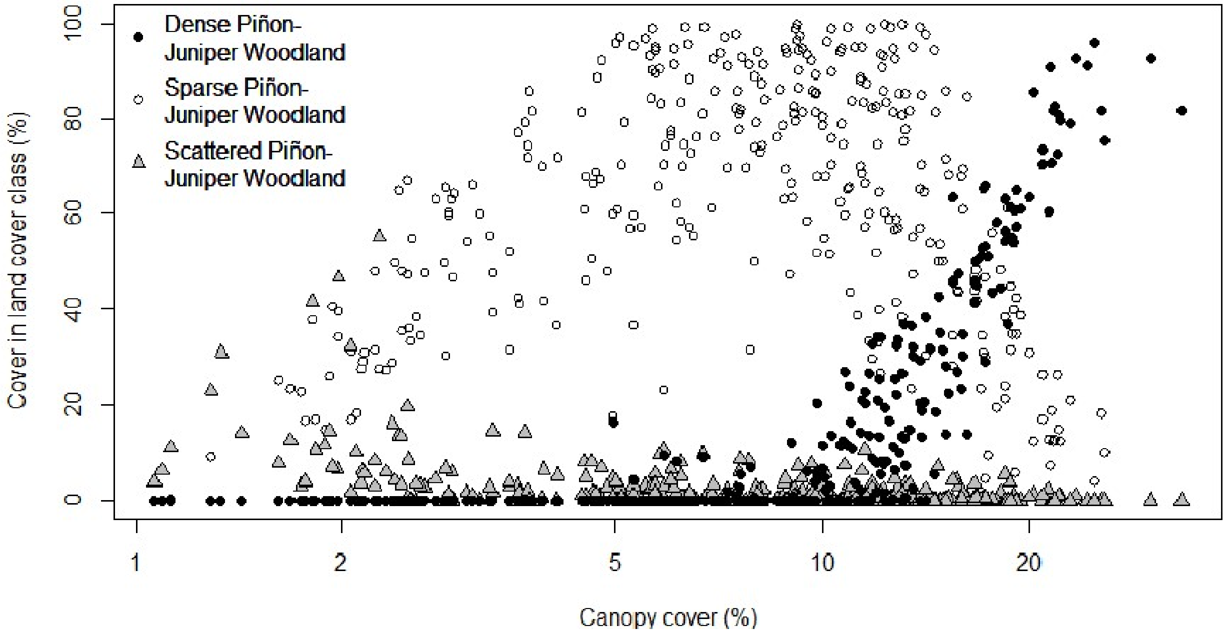

Figure 5. Relationships between estimates of canopy cover (%) and percent cover among Gray Vireo territories and random, available areas in the three Piñon-Juniper Woodland land cover classes.

Relationships in the best model indicated a higher probability of territory occurrence at intermediate canopy cover (Figure 6a) and intermediate (residual) land cover in the Sparse Piñon-Juniper Woodland class (Figure 6b). That is, territories were more likely to occur where canopy cover was intermediate and land cover in the Sparse Pinyon-Juniper Woodland class was also intermediate, controlling for the relationship with overall canopy cover. Both relationships varied by levels of the other covariate, with clearest shifts in the peak of territory occurrence probability relative to canopy cover (Figure 6a). A notable positive effect of cover in the Dense Piñon-Juniper Woodland class on the probability of territory occurrence was evident (below). However, 95% confidence intervals of this effect bounded zero.

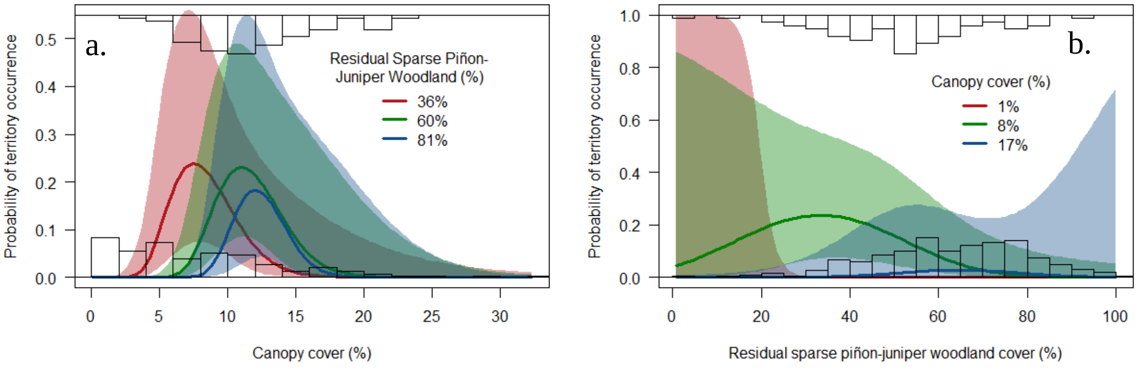

Figure 6. Relationships between the probability of Gray Vireo territory occurrence and canopy cover (a) and the (residual) cover in the Sparse Piñon-Juniper woodland class (b). Relationships are indicated for three levels (10th percentile, median, and 90th percentile) of the other covariate. Also indicated are histograms displaying the relative frequency distribution of covariate values in territories (upper histogram) and random, available areas (lower histogram). Error bands indicate 95% confidence intervals. A value of 60% was added to residual sparse Piñon-Juniper woodland cover values for easier interpretability.

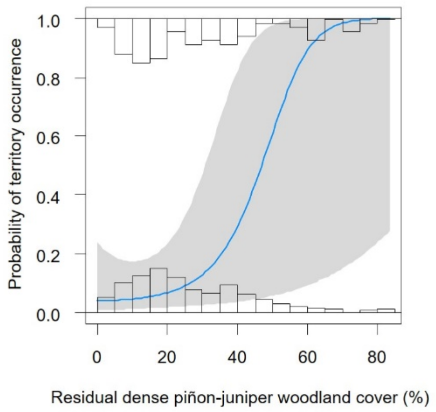

Figure 7. Relationship between the (residual) cover in the Dense Piñon-Juniper Woodland class and the probability of Gray Vireo territory occurrence. A value of 27% was added to residual dense Piñon-Juniper Woodland cover values for easier interpretability. Also indicated are histograms displaying the relative frequency distribution of values in territories (upper histogram) and random, available areas (lower histogram). Error bands indicate 95% confidence intervals.

Disturbance covariates

Linear and quadratic terms of estimated percent cover by gas well pads emerged in first-stage models (Table 3, model 5), and the global model (model 9) including this covariate received 22% of the total Akaike weight (w_i) of the final candidate set. However, parameter estimates associated with this covariate had P-values > 0.15. This indicated that, relative to model 6, these additional terms were uninformative (Arnold 2010).

Gray Vireo territory prediction surfaces

The model-predicted surface classifying areas as likely to be centers of Gray Vireo territories indicated that out of 6,389 km^2 of areas meeting the criteria of available habitat (i.e., having >0% Piñon-Juniper Woodland within 149 m), 255 km^2 (4.0%) had at least a 0.5 probability of being the center of a territory (Figure 8).

Slightly more than half of the territory prediction for Gray Vireo is in Sparse Piñon-Juniper Woodland, and almost 30% is in Dense Piñon-Juniper Woodland (Table 5). The model predicts that Gray Vireos will establish territories in these two habitats disproportionately compared to their availability in the study area (50.5% vs. 37% of study area available in Sparse Piñon-Juniper Woodland; 29.4% vs. 4.9% available in Dense Piñon-Juniper Woodland.

Human Disturbance is 5.6% of the model, Sagebrush Shrubland makes up about 5%, and Grassland is about 4%. These three habitats comprise smaller proportions of the territory model than expected, given their availability (Table 5). The other habitat types make up less than 2% of the model (Table 5).

Table 5. Habitat types in the Gray Vireo and Pinyon Jay models, and availability within the study area.

	Gray Vireo		Pinyon Jay		Study Area	
	Model (ha)	Model (%)	Model (ha)	Model (%)	total ha available	% study area
Sparse Piñon-Juniper Woodland	50,254	50.5	45,003	57.1	278,168	30.7
Dense Piñon-Juniper Woodland	29,185	29.4	20,313	25.8	44,036	4.9
Scattered Piñon-Juniper Woodland	1,898	1.9	1,409	1.8	28,343	3.1
Ponderosa Pine Woodland	1,398	1.4	669	0.8	5,936	0.7
Gambel Oak Woodland	107	0.1	60	0.1	464	0.1
Montane Chaparral	92	0.1	89	0.1	322	0.04
Sagebrush Shrubland	5,088	5.1	3,939	5.0	109,723	12.1
Other Shrubland	810	0.8	261	0.3	18,841	2.1
Grassland	3,590	3.6	3,365	4.3	258,586	28.5
Riparian Woodland and Shrubland	538	0.5	170	0.2	8,450	0.9
Wetland	18	0.02	12	0.02	326	0.04
Open Water	342	0.3	36	0.05	5,262	0.6
Barren/Sparsely Vegetated	496	0.5	335	0.4	79,535	8.8
Agriculture	86	0.1	12	0.02	9,040	1.0
Human Disturbance	5,532	5.6	3,179	4.0	60,115	6.6
Total	99,434		78,851		907,146	

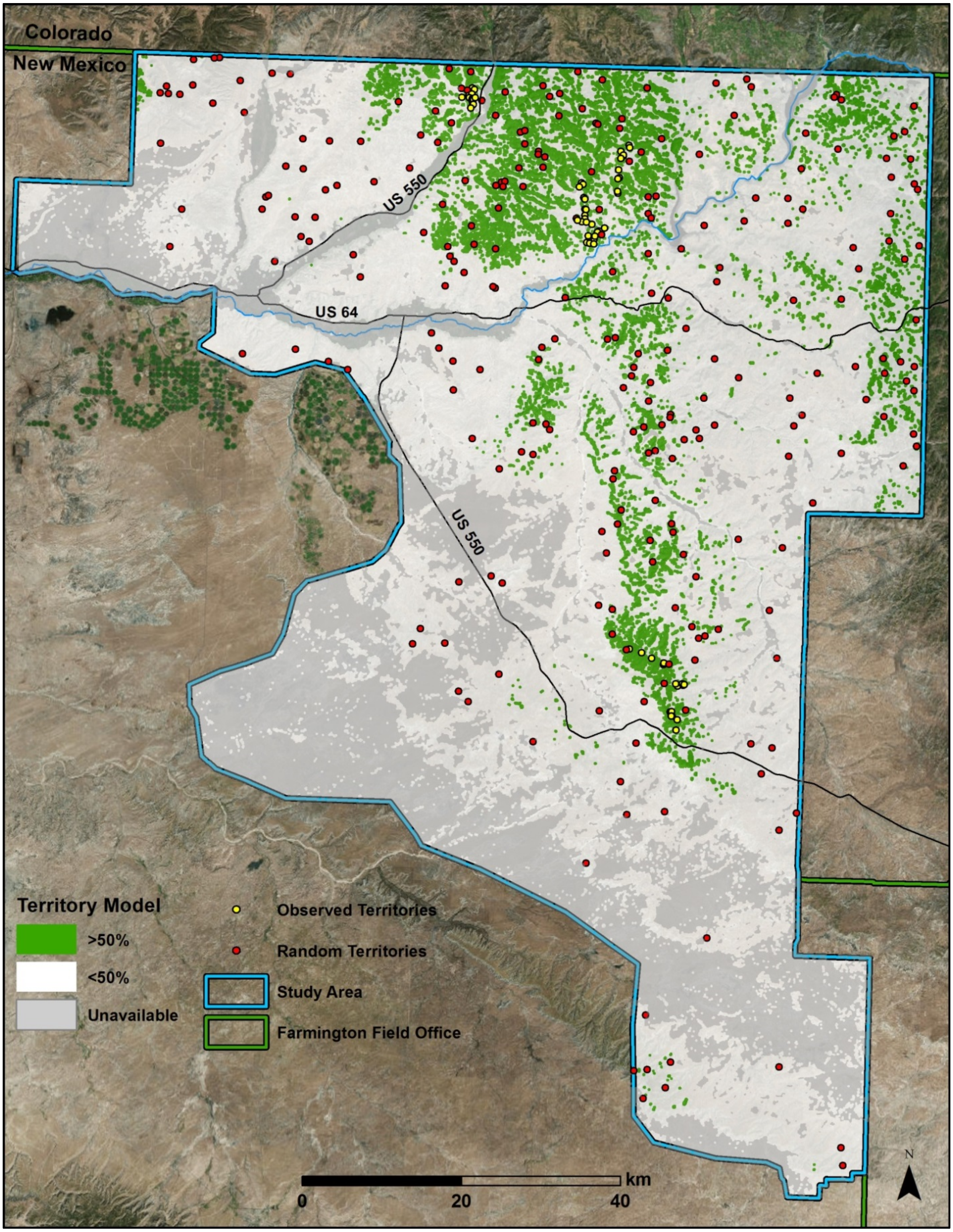

Figure 8. Predicted probability from best model of Gray Vireo territory distribution assuming mean road and other disturbance conditions. Cells have a 40 m resolution. Areas in green are those with a predicted probability above 0.5. Individual 40-m cells classified as Gray Vireo territory centers were buffered by 149 m for this figure to better illustrate the area considered.

Pinyon Jay

One-hundred random locations within Pinyon Jay colonies and 400 random, available locations outside colonies were employed in models. The AICc of best model was 5.7 units lower than the next best model and had 94% of the total weight of the model set (Table 6). This model had an AUC of 0.960, indicating an excellent discriminatory ability. The Hosmer-Lemeshow test ($P = 0.27$) indicated a good model fit.

Table 6. Final candidate model set predicting the probability of Pinyon Jay colony occurrence relative to three covariate groups (topography, woodland characteristics, and distance metrics). Indicated are number of model parameters (K), sample-adjusted Akaike information criteria (AICc), relative AICc (ΔAICc), model weight (wi), model log-likelihood (LL), area under the receiver operating curve (AUC), a measure of classification accuracy, and Hosmer-Lemeshow goodness-of-fit test P-value (GOF). Models 2–9 all included the effect of roads.

	Model	K	AICc	ΔAICc	w_i	LL	AUC	GOF
1	Null	1	502.4	283.9	0.00	-250.2	NA	NA
2	Road effect only[a]	3	452.5	234.0	0.00	-223.2	0.695	0.19
3	Topography[b]	6	441.3	222.9	0.00	-214.6	0.757	0.07
4	Woodland[c]	7	233.7	15.2	0.00	-109.7	0.948	0.03
5	Distance[d]	4	441.1	222.6	0.00	-216.5	0.758	0.03
6	Topography + woodland	10	224.2	5.7	0.05	-101.9	0.956	0.44
7	Topography + distance	7	433.4	214.9	0.00	-209.6	0.770	0.40
8	Woodland + distance	8	227.4	8.9	0.01	-105.5	0.955	0.14
9	Topography + woodland + distance	11	218.5	0.0	0.94	-98.0	0.960	0.27

a. **Includes the quadratic effect of distance to road.**
b. **Includes the interacting effects of heatload and slope.**
c. **Includes additive effects of Piñon-Juniper patch size, the density class (Sparse vs. Dense) Piñon-Juniper woodland classes, and the additive quadratic effect of distance to water.**
d. **Includes the distance to gas wells.**

Road proximity

As noted, we controlled for the close proximity of roads to colonies by including a linear and quadratic effect of road distance in each model considered. Estimates from the best model indicated within-colony locations were most likely to be approximately 50–100 m from a road (Figure 9).

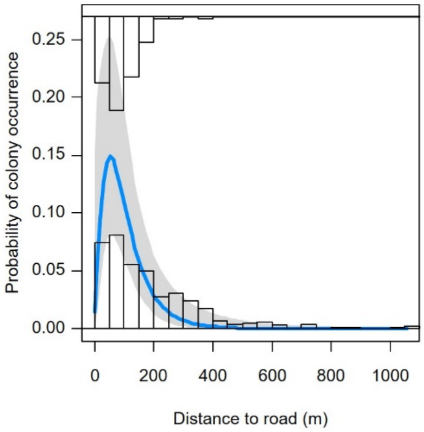

Figure 9. Relationship between the distance to road and the probability of Pinyon Jay colony occurrence. Models indicated the importance of controlling for the coinciding occurrence of roads and colonies in models. Also indicated are histograms displaying the relative frequency distribution of road distance values in colony sampling locations (upper histogram) and random, available areas (lower histogram). Error bands indicate 95% confidence intervals.

Topographic covariates

The interaction between topographic heatload and slope indicated within-colony locations were most likely to occur on more gradual slopes with low heatload values (Table 7). We illustrate this relationship relative to both covariates in Figure 10. Note that when heatload was high (0.88), slope had no effect (the blue line). Similarly, in 10a, heat load had no effect when slope was steep. In other words, these two covariates had a multiplicative effect when combined (i.e., when both were low), but one did not mitigate the other when one or the other condition was "poor" (i.e., high heatload or high [steep] slopes).

Table 7. Parameter estimates from the best model of Pinyon Jay colony occurrence in the BLM Farmington Resource Area. Covariates were scaled to a mean of zero and a standard deviation of 1. Hence, effect sizes are relative. Parameter estimate, standard error (SE), z-value (*z*), and *P*-values are indicated. Squared terms are indicated with a superscript '2'. Covariate descriptions can be found in Table 2.

Covariate	Estimate	SE	*Z*	*P*
Intercept	-2.762	0.361	-7.659	0.000
RoadDist^{a,b}	-1.420	0.336	-4.222	0.000
RoadDist^{2a,b}	-0.830	0.262	-3.169	0.002
Heatload	-0.880	0.470	-1.873	0.061
Slope^{a}	-0.720	0.212	-3.395	0.001
Patchsize^{a,c}	1.987	0.319	6.237	0.000
PJcat^{d}	2.182	0.393	5.553	0.000
WaterDist^{a,e}	-2.292	0.402	-5.703	0.000
WaterDist^{2a,e}	-0.748	0.215	-3.472	0.001
GasDist^{a,f}	0.649	0.235	2.766	0.006
Heatload:slope	0.716	0.344	2.082	0.037

a. **This covariate was log-transformed prior to scaling.**
b. **Distance to nearest road**
c. **Size of patch defined by continuous areas classified as Spare or Dense Piñon-Juniper Woodland**
d. **A dummy variable indicating whether locations fell in Dense Piñon-Juniper Woodland (vs. Sparse Piñon-Juniper Woodland [intercept])**
e. **Distance to nearest area of open water.**
f. **Distance to nearest gas well.**

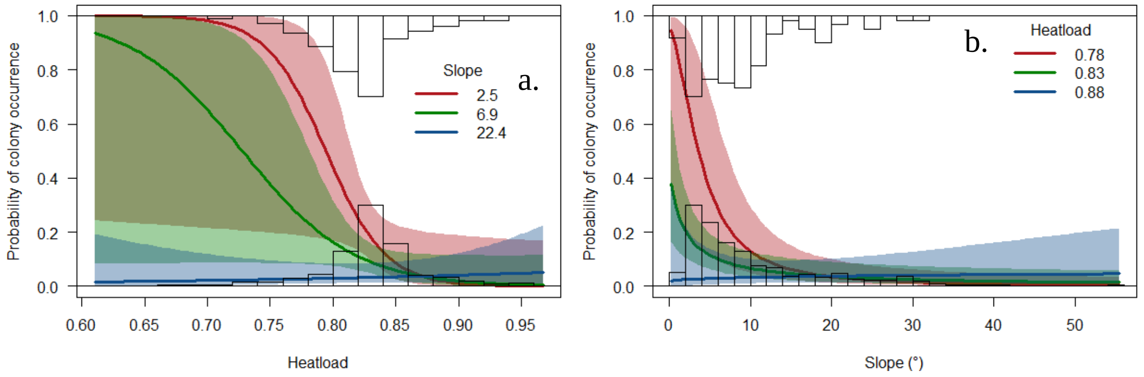

Figure 10. Relationships between the probability of Pinyon Jay colony occurrence and heatload (a) and slope (b). Relationships are indicated for three levels (10th percentile, median, and 90th percentile) of the other covariate. Also indicated are histograms displaying the relative frequency distribution of covariate values in colony sampling locations (upper histogram) and random, available areas (lower histogram). Error bands indicate 95% confidence intervals. Interactions indicated highest probabilities of colony occurrence in lower-heatload areas (typically with more northeastern-facing slopes) having gentler slopes.

Habitat covariates

Parameter estimates from the best model indicated within-colony locations were most likely to occur in larger patches of piñon-juniper woodland (Figure 11a) and where woodland was classified as Dense Piñon-Juniper Woodland in the land cover map (Figure 11b). Within-colony areas were most likely to occur at approximately 300–400 m from surface water (Figure 11c).

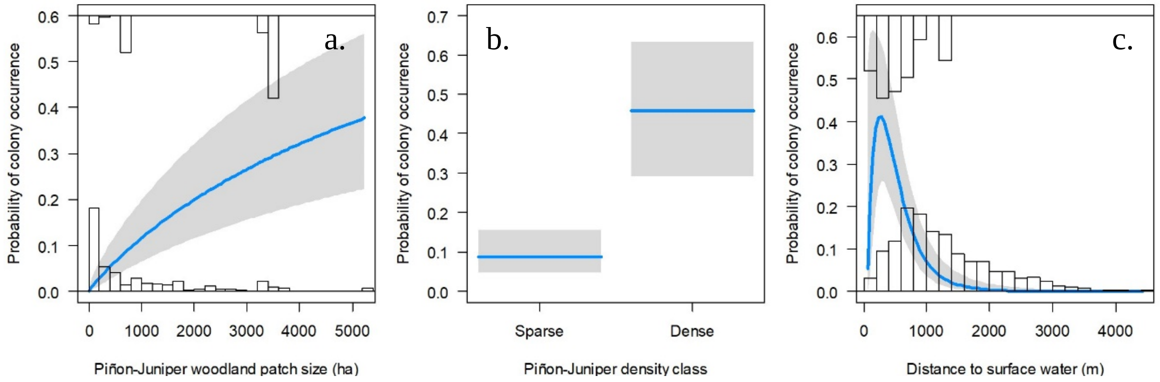

Figure 11. Relationship between probability of Pinyon Jay colony occurrence and Piñon-Juniper woodland patch size (a), Piñon-Juniper woodland density category (b), and distance to surface water (c). Also indicated are histograms displaying the relative frequency distribution of continuous covariates in colony (upper histogram) and non-colony (lower histogram) sampling locations (upper histogram) and random, available areas (lower histogram). Error bands indicate 95% confidence intervals.

Disturbance covariates

Only one disturbance covariate (distance to nearest gas well) was selected in the first stage of modeling and also appeared in the best stage-two model. This model indicated a higher probability of colony occurrence at large distances from gas well point locations (Figure 12), though 95% confidence intervals were wide at large distances.

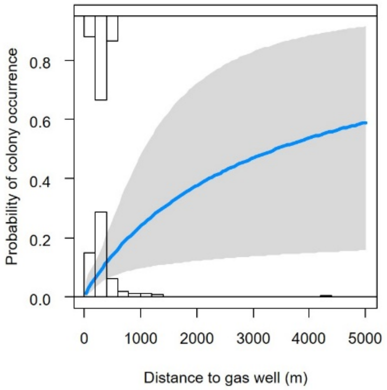

Figure 12. Relationship between probability of Pinyon Jay colony occurrence and distance to gas wells. Also indicated are histograms displaying the relative frequency distribution of distance to gas wells in colony (upper histogram) and non-colony (lower histogram) sampling locations (upper histogram) and random, available areas (lower histogram). Error bands indicate 95% confidence intervals. Plots indicate colonies were more likely to be located away from gas wells.

Pinyon Jay colony prediction surfaces

The model-predicted surface classifying areas as likely to be within areas of colonial Pinyon Jay nesting indicated that out of 5,539 km^2 of areas meeting the criteria of available habitat (i.e., classified as Sparse or Dense Piñon-Juniper Woodland, having an estimated piñon-juniper canopy cover >0 %, and outside areas identified as disturbed), 384 km^2 (6.9%) met the criteria of potentially supporting a surrounding Pinyon Jay colony (Figure 13).

The Pinyon Jay colony model includes 57.1% Sparse Piñon-Juniper Woodland, compared to only 35.7% of the study area. Similarly, the Pinyon Jay colony model contains about five times the percentage of Dense Piñon-Juniper Woodland as the study area (25.8% vs. 4.9%) (Table 5). The model contains 5% Sagebrush Shrubland, 4.3% Grassland, and 4% Human Disturbance. The other habitat types comprise less than 2% each of the model (Table 5).

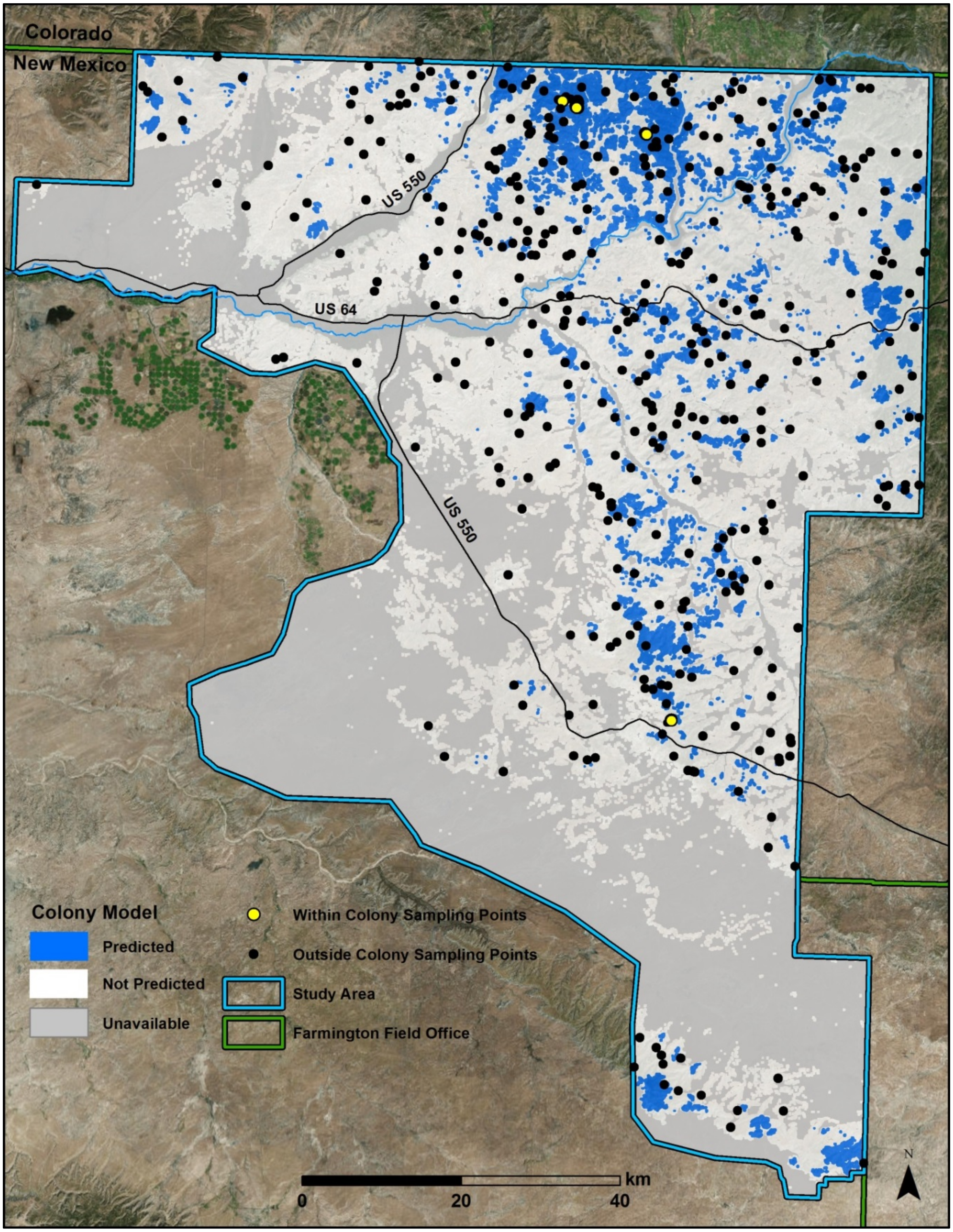

Figure 13. Locations most likely to be centers of Pinyon Jay colony nesting assuming mean road distances. Cells have a 40 m resolution. Areas in blue are cells meeting two conditions: (1) a predicted probability of at least 0.2 predicted by the best model and (2) at least 25 cells within 140 m. The 140 m distance was an approximation of colony size (6.1 ha). The first condition was a balance between the sensitivity and specificity of model predictions while the latter condition ensured locations of potential suitable colony habitat were adequately aggregated in an area large enough to accommodate the median observed colony size. Individual 40-m cells classified as potential colony centers were buffered by 140 m for this figure to better illustrate the area considered. See Pinyon Jay: Prediction for additional details.

Discussion

Modeling considerations

It was important to sample the range of environmental conditions in the FRA via a dispersed selection of negative-response locations (i.e., random areas within available habitat). Atypical for our approach for modeling distributions, however, was the aggregation of positive-response observations (territories for the Gray Vireo, randomly selected pixels within colonies for the Pinyon Jay) in space. In the Gray Vireo, this aggregation occurred within the Aztec study areas due to sampling approach. That is, we did not survey all possible habitat within the boundaries of that study area that lacked a single defining topographic feature (see Methods). In the Pinyon Jay, the clustering of positive samples was simply due to the colonial nesting pattern of the species. This aggregation can, however, create biases in estimation. Previous concerns about pseudoreplication (Hurlbert 1984) have more recently and more appropriately been framed as violations of the assumption of independence of errors (i.e., model residuals). These violations may arise in space (i.e., spatial autocorrelation) or time (i.e., serial autocorrelation) and there are a number of approaches to reduce this autocorrelation (e.g., Dormann et al. 2007). In this study, we found spatial autocorrelation (from model residuals, measured via Moran's *I* correlograms) was adequately small only when considering residuals from negative and positive observations separately. This, unfortunately, introduced an unknown degree of bias to parameter estimates and, in turn, predictions. Future efforts may reduce this possibility for bias by employing a more dispersed sample of territories in the Gray Vireo and, if possible, a larger number of colonies for the Pinyon Jay. The latter, unfortunately, is difficult due to low densities of Pinyon Jay colonies across landscapes.

The Gray Vireo territory predictive model and Pinyon Jay predictive colony model are meant to indicate general areas where each species could establish territories or colonies. However, the land cover percentages in each model (Table 5) are not meant to be taken as specific management prescriptions. Largely as a consequence of the modeling procedures, very small areas of each of the land cover classes appear in both models, but the specific proportions should not be taken as management recommendations. For example, the Gray Vireo model does not mean that Gray Vireos require territories with 0.3% Open Water or 5.6% Human Disturbance.

Likewise, the proportions of the dominant land cover classes (Sparse and Dense Piñon-Juniper Woodland) in each model are influenced by the buffering around territory or colony pixels and the influence of other covariates such as topography in the modeling process. They can serve as general guidelines for which land cover types and canopy densities are important to these birds but should not be taken as specific numerical prescriptions for habitat management.

Gray Vireo

Gray Vireo territories were associated with all three road covariates: percent impervious cover, road length, and distance to roads. The association with the two principal components indicated road proximity is most likely a result of the necessity of focusing surveys in road-accessible areas within a vast landscape. The road effect covariates (principal components 1 and 2) were included in all models to control for this potential road bias. Although the effect of roads may be due to sampling bias, it does suggest that Gray Vireos do not strongly avoid placing territories near roads. Importantly, our study areas are all highly dissected by roads (mainly associated with natural gas infrastructure); thus, few areas exist within the landscape in which Gray Vireos could establish territories that were not in close proximity to roads.

Gray Vireo territories were located where heat load values were higher, relative to random sites. Higher heat loads likely occur where slope is low and canopy is open (see below), although these covariates were not highly correlated. Curvature values on territories tended to be both high and low, but not intermediate, indicating either convex or concave, and not flat, topography. Slope was low on territories, relative to random sites. In a related study on DoD lands in New Mexico, we found some similar results. At Camel Tracks Training Area (CTTA) and White Sands Missile Range (WSMR), Gray Vireo territories occurred in areas with lower solar radiation and either intermediate (CTTA) or lower (WSMR) slopes compared with non-territories (Johnson et al. 2014). Though we did not measure heatload in that study, likely areas with lower solar radiation also have lower heatloads.

Canopy cover tended to be intermediate on Gray Vireo territories, relative to available habitat. On territories, land cover in the Sparse Piñon-Juniper Woodland class was intermediate and high in the Dense Piñon-Juniper Woodland class (although the effect of this covariate was weak). This indicates that Gray Vireos nest in moderately open piñon-juniper habitats, especially compared to Pinyon Jays (see below) and other woodland-associated bird species.

Pinyon Jay

Estimates from the best model indicated within-colony locations were most likely to be approximately 50–100 m from a road. It is possible that Pinyon Jays prefer to nest 50–100 m from a road, but we cannot easily imagine why that might be the case. Alternatively, this result may have been a chance association resulting from the small number of colonies studied. We therefore controlled for proximity of roads to colonies by including a linear and quadratic effect of road distance in each model considered.

Pinyon Jay colonies had lower heatload than random sites, indicating they were more likely to occur on NE-facing slopes. This result agrees with our impression based on field surveys that colonies tend to face NE. Similarly, a colony-scale predictive model at Kirtland Air Force Base indicated that colonies are located on N-facing aspects (Johnson et al. 2016). This result is in contrast to a colony-scale model for White Sands Missile Range, which predicted colonies on S-facing aspects (Johnson et al. 2016).

In the FRA, colonies also tended to be on gentler slopes ($<15^o$) than random sites within piñon-juniper habitat. Colony-scale predictive models at Kirtland Air Force Base and White Sands Missile Range indicated that colonies occurred on higher slopes than those at the FRA: 23^o and 11.6^o, respectively (Johnson et al. 2016). This difference in modeling results among study sites is likely due to characteristics of the study areas.

Colonies occurred in larger patches of piñon-juniper woodland than are available on the landscape, and they were more likely to occur in Dense than Sparse or Scattered Piñon-Juniper Woodland land cover types (as defined by Johnson et al. 2017). It should be noted that the cutoff between Dense and Sparse Piñon-Juniper Woodland map units was originally defined based on where Pinyon Jays and Gray Vireos tended to nest; hence, this association is not surprising. Nonetheless, it is clear that Pinyon Jays nest in areas of higher canopy cover than do Gray

Vireos, and these areas have higher canopy cover than randomly-selected sites within piñon-juniper woodland.

Previous colony-scale models included 18.7 % of available Piñon Woodland, Piñon-Juniper Woodland, and Juniper Woodland and Savanna habitat types at Kirtland Air Force Base and 41% of Piñon Woodland at White Sands Missile Range (Johnson et al. 2016). All three models suggest that suitable colony habitat for Pinyon Jays is much less abundant than appears at first glance, but the current model indicates that suitable habit is especially limited at the FRA, compared to piñon-juniper habitat in general.

This study confirmed that Pinyon Jay colonies are typically within easy flying distance of water, as first noted by Petersen et al. (2014). In the current analysis, surface water included anything in the National Hydrology Dataset (NHD) that was classified with a polygon, plus linear water features (e.g., ditches and rivers) suspected of having water for at least part of each year. However, this approach, and using a simple distance measure to the nearest water feature, may not reflect conditions in a given year. For example, a small impoundment present in the NHD and near a Pinyon Jay colony may not have had available surface water for the years in which the colony was active.

Colonies also tended to be farther from gas wells than random sites. Although Figure 12 might suggest that the highest probability of finding a Pinyon Jay colony occurs at around 5 km from a gas well, this figure is meant to illustrate a linear relationship. All actual colonies were located fewer than 1.0 km from a gas well, and random locations were closer, but not much closer, to gas wells than colonies. These relationships are influenced by the very high density of gas wells in the study area.

Management for both species

Piñon-juniper habitat is widespread and abundant at the FRA (6389 km^2 of potential Gray Vireo habitat and 5,539 km^2 of potential Pinyon Jay habitat). A possibly surprising result of this study is that only 255 km^2 (4%) of potential Gray Vireo habitat has >0.5 probability of being used as a territory. Likewise, only 384 km^2 (6.9%) is predicted Pinyon Jay colony habitat (classified as Sparse or Dense Piñon-Juniper Woodland, having an estimated piñon-juniper canopy cover >0 %, and outside areas identified as disturbed). Hence, it is not sufficient to conserve just any block of piñon-juniper habitat for these species. Importantly, specific characteristics of Gray Vireo territory and Pinyon Jay colony sites should be considered when managing habitat.

Note also that because of the unavoidable spatial autocorrelation encountered in this study (discussed above) and the small sample size of Pinyon Jay colonies, these results should be considered preliminary. More study is necessary at the FRA and other areas before we have high confidence in specific habitat recommendations. Until such studies are available, the general habitat management recommendations provided here are a significant improvement over other currently available information.

Gray Vireo

Based on the results of this modeling study, we recommend that areas in the FRA meeting the following criteria be managed as Gray Vireo territory habitat. Areas of piñon-juniper woodland with intermediate canopy cover (5–15% aerial canopy cover) are suitable nesting habitat for

Gray Vireos. Territories are typically covered in 20-80% Sparse Piñon-Juniper Woodland, with lesser components of Dense Piñon-Juniper Woodland, and they may include Sagebrush Shrubland (Johnson et al. 2017). Territories are found in areas with concave or convex topography and low (5%) slope. While disturbance factors (i.e., roads and gas well pads) do not seem to influence habitat occupancy in the FRA, more study is needed in landscapes with little or no disturbance for comparison. Gray Vireos may exhibit an avoidance response or establish territories at higher densities in relatively undisturbed habitats. Based on considerable variation we have observed in Gray Vireo nesting habitat (Johnson et al. 2014), these recommendations may or may not be generally applicable for Gray Vireos nesting in other areas.

Pinyon Jay

Based on the results of this modeling study, we recommend that areas in the FRA meeting the following criteria be managed as Pinyon Jay nesting colony habitat. Pinyon Jay colonies tend to be located on more gradual slopes than randomly-available sites, and these colony sites have lower heat load than random sites, indicating a preference for NE-facing slopes.

Colonies are located within very large patches of piñon-juniper woodland (≥3500 ha). They establish colonies more often in Dense, as compared to Sparse, Piñon-Juniper Woodland (as delineated by Johnson et al. 2017), with the ratio of Dense to Sparse Piñon-Juniper Woodland about 4:1. Pinyon Jay colonies are typically within easy flying distance to surface water, at distances ranging from 100–1000 m, but at the FRA, they are most commonly found approximately 500 m from surface water.

Pinyon Jay colonies are farther from gas wells than random sites; the recommended distance from a suitable Pinyon Jay colony site to a gas well is >500 m. These recommendations may be generally applicable to other study areas, but specifics will depend on the type and characteristics of habitat used by the jays. For example, Pinyon Jays may select dense piñon-juniper habitat for nesting relative to surrounding non-colony habitat, but the exact density and canopy cover may vary by site.

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