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Research Paper

Thinning effects and underlying pathways for birds of conservation concern in New Mexico piñon-juniper woodlands

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ABSTRACT. Piñon-juniper woodlands are one of the largest ecosystems in the United States and harbor many piñon-juniper-associated bird species. It is a common practice to reduce tree cover and density of these woodlands for various objectives, including increasing livestock forage and reducing wildfire hazard. Understanding the different pathways of how piñon-juniper thinning affects bird species of conservation concern is important for both woodland management and avian conservation and thus warrants investigation. In this study, we aimed to understand the pathways of the effects of piñon-juniper woodland thinning on bird species groups of high, moderate, and low conservation concern, as well as seven priority bird species. During the month of May from 2021 to 2023, we collected count data with distance sampling and removal sampling information from 46 1 km × 1 km plots (23 treated ≤10 years previously and 23 controls). We then used these data to estimate abundance of bird species across the gradients of piñon-juniper thinning and eight environmental factors such as canopy cover. By using a path analysis based on N-mixture modeling, we were able to decompose the effects of piñon-juniper thinning on avian abundance that can be explained by the environmental factors considered or by other unmeasured factors. Our results revealed multiple pathways of the effects of piñon-juniper thinning on bird groups and species. Overall, piñon-juniper thinning had negative effects on the species group of high and moderate conservation concerns, mainly through reduced tree density and canopy cover. Piñon-juniper thinning also had negative effects on five priority species: Pinyon Jay (*Gymnorhinus cyanocephalus*), Woodhouse's Scrub-Jay (*Aphelocoma woodhouseii*), Juniper Titmouse (*Baeolophus ridgwayi*), Virginia's Warbler (*Leiothlypis virginiae*), Black-throated Gray Warbler (*Setophaga nigrescens*), and a positive effect on one priority species (Gray Vireo, *Vireo vicinior*), with this total effect being explained by environmental factors considered or unmeasured factors, depending on the species. Our results showed that the pathways of the effects of piñon-juniper thinning on avian biodiversity were complicated and multifaceted, and indicated that a reevaluation of thinning in piñon-juniper woodlands might be needed.

Effets de l'éclaircissement et voies sous-jacentes pour les oiseaux dont la conservation est préoccupante dans les forêts de pins pignons et de genévriers du Nouveau-Mexique

RÉSUMÉ. Les forêts de pins pignons et genévriers constituent l'un des plus grands écosystèmes des États-Unis et abritent de nombreuses espèces d'oiseaux associées aux forêts de pins pignons et genévriers. Le couvert arboré et la densité de ces forêts sont souvent réduits pour répondre à divers objectifs, notamment l'augmentation du fourrage destiné au bétail et la réduction des risques d'incendie de forêt. Il est important de comprendre les différentes voies par lesquelles l'éclaircissement des forêts de pins pignons et genévriers affecte les espèces d'oiseaux dont la conservation est préoccupante, tant pour la gestion des zones boisées que pour la conservation de l'avifaune, et cela justifie des recherches. Dans cette étude, nous avons cherché à comprendre les différents effets de l'éclaircissement des forêts de pins pignons et genévriers sur les groupes d'espèces d'oiseaux dont la conservation est très, modérément et peu préoccupante, ainsi que sur sept espèces d'oiseaux prioritaires. Au cours du mois de mai, de 2021 à 2023, nous avons recueilli des données de comptage avec des informations d'échantillonnage de distance et d'enlèvement sur 46 parcelles de 1 km × 1 km (23 traitées ≤ 10 ans auparavant et 23 témoins). Nous avons ensuite utilisé ces données pour estimer l'abondance des espèces d'oiseaux à travers les gradients d'éclaircissement des forêts de pins pignons et genévriers et huit facteurs environnementaux tels que la couverture de la canopée. En utilisant une analyse de cheminement basée sur la modélisation N-mixture, nous avons pu décomposer les effets de l'éclaircissement des pins pignons et genévriers sur l'abondance aviaire qui peuvent être expliqués par les facteurs environnementaux pris en compte ou par d'autres facteurs non mesurés. Nos résultats ont révélé des voies multiples pour les effets de l'éclaircissement des pins pignons et genévriers sur les groupes et les espèces d'oiseaux. Dans l'ensemble, l'éclaircissement des forêts de pins pignons et genévriers a eu des effets négatifs sur le groupe d'espèces dont les préoccupations en matière de conservation sont élevées et modérées, principalement en raison de la réduction de la densité des arbres et du couvert végétal. L'éclaircissement pins pignons et genévriers a également eu des effets négatifs sur cinq espèces prioritaires : le Geai des pinèdes (*Gymnorhinus cyanocephalus*), le Geai de Woodhouse (*Aphelocoma woodhouseii*), la Mésange des genévriers (*Baeolophus ridgwayi*), la Paruline de Virginia (*Leiothlypis virginiae*), la Paruline grise (*Setophaga nigrescens*), et un effet positif sur une espèce prioritaire, le Viréo gris (*Vireo vicinior*). Cet effet global s'explique par des facteurs environnementaux pris en compte ou des facteurs non mesurés, selon les espèces. Nos résultats ont montré que les effets de l'éclaircissement des forêts de pins pignons et genévriers sur la biodiversité aviaire étaient complexes et multifactoriels. Ils plaident en faveur d'une réévaluation de l'éclaircissement dans les forêts de pins pignons et genévriers.

Key Words: *abundance modeling; avian conservation; avian diversity; Bayesian hierarchical model; path analysis; pinyon-juniper; woodland structure; woodland management*

INTRODUCTION

Piñon-juniper woodlands are the third-largest vegetation type in the U.S. (West 1988) and contain high bird diversity, high numbers of obligate or semi-obligate bird species, and many bird species of high conservation concern (Balda and Masters 1980, New Mexico Avian Conservation Partners 2016). When managing these woodlands, it is a common practice to reduce tree canopy cover and density to achieve various objectives, including creating more forage for livestock, reducing fire hazard, enhancing big game habitat, and improving habitat for grassland or sagebrush wildlife (Bombaci and Pejchar 2016). While tree reduction practices have been consistently conducted in piñon-juniper woodland ecosystems, the underlying pathways of their effects on avian species, especially those of conservation concern, have been little studied, limiting our ability to develop and evaluate conservation strategies. Therefore, understanding the effects of piñon-juniper thinning on bird species of conservation concern through different environmental factors is important for both woodland management and avian conservation (Evans 1988, Redmond et al. 2014).

New Mexico contains many piñon-juniper bird species of conservation concern and significant populations of these species (New Mexico Avian Conservation Partners 2016). For example, New Mexico has more of the range-wide Pinyon Jay (*Gymnorhinus cyanocephalus*), Woodhouse's Scrub-Jay (*Aphelocoma woodhouseii*), Juniper Titmouse (*Baeolophus ridgwayi*), and Virginia's Warbler (*Leiothlypis virginiae*) populations than any other state (Partners in Flight 2020). Therefore, evaluating bird responses to thinning in piñon-juniper woodlands in New Mexico is warranted.

For this study, we aimed to evaluate the underlying pathways of the effect of piñon-juniper woodland thinning on bird species groups of high, moderate, and low conservation concern, as well as seven priority bird species. We hypothesized that species of high concern (as a group) and moderate concern (as a group) would have negative relationships with thinning because most of these species have habitat needs that require piñon-juniper vegetation (Poole 2020). Of the seven priority species, we hypothesized that Pinyon Jay (Johnson and Balda 2020), Woodhouse's Scrub-Jay (Curry et al. 2020), Juniper Titmouse (Cicero et al. 2020), Virginia's Warbler (Olson and Martin 2020), Black-throated Gray Warbler (*Setophaga nigrescens*; Guzy and Lowther 2020), and Gray Vireo (*Vireo vicinior*; Barlow et al. 2020) would have negative relationships with thinning because existing literature shows they depend upon piñon-juniper woodlands for all or some aspects of their life history. We hypothesized that thinning would lower the abundance of these species by altering forest structures such as canopy cover, tree density, and tree height. We hypothesized that Black-chinned Sparrow (*Spizella atrogularis*) would have a positive relationship with thinning because the body of literature for this species shows shrubs, not piñon-juniper trees, are an important habitat component (Pandolfino et al. 2024).

We used data with distance sampling and removal sampling information to estimate abundance of bird species across the gradients of piñon-juniper thinning and several environmental factors. We used a path analysis (Clough 2012) based on N-mixture modeling to decompose the effects of piñon-juniper

thinning on avian abundance that can be explained by environmental factors such as tree density and canopy cover or other unmeasured factors. With this knowledge, we aimed to provide information that will be helpful for land managers.

METHODS

Study area and survey sites

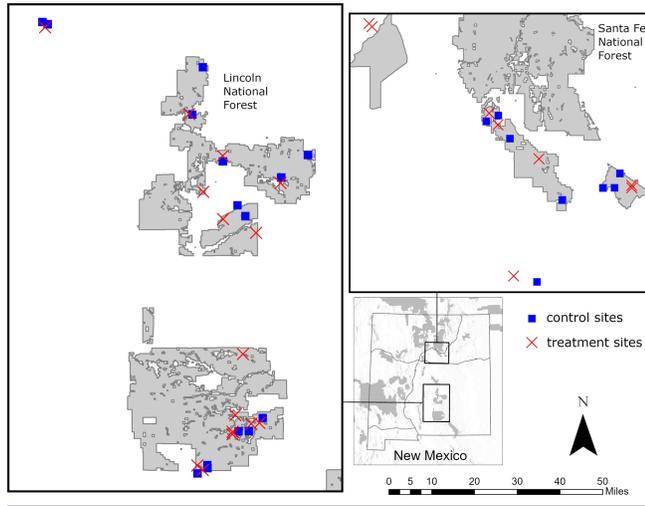
The study area covered piñon-juniper woodlands in north-central, central and south-central New Mexico (Fig. 1). Vegetation subtypes occurring within the study area were piñon-juniper savanna, persistent piñon-juniper woodland, and an ecotone between persistent piñon-juniper woodland and ponderosa pine forest (Romme et al. 2009). Dominant tree species were two-needle pinyon (*Pinus edulis*), one-seed juniper (*Juniperus monosperma*), Rocky Mountain juniper (*Juniperus scopulorum*), and alligator juniper (*Juniperus deppeana*). We randomly selected a total of 46 survey sites in any subtype or ecotone of piñon-juniper woodland, including 23 treatment sites that overlapped with areas where piñon-juniper woodland thinning occurred within 10 years prior to this study, and 23 control sites where no thinning has occurred or where woodlands have recovered from past disturbances (Fig. 1, Appendix 1: Table S1). Piñon-juniper thinning treatments employed a variety of methods, including mechanical thinning and prescribed fire, and had a variety of prescriptions, including evenly-spaced thinning and mosaic thinning, in which unthinned clumps of trees, in varying sizes, were retained. Survey sites were located on land managed by the Lincoln National Forest, Los Alamos National Lab, New Mexico State Land Office, and the Santa Fe National Forest.

These sites were surveyed using the same protocol as the Integrated Monitoring in Bird Conservation Regions (IMBCR) Program (Pavlacky et al. 2017), and thus include distance and removal sampling information to allow unbiased inference of population abundance. These sites were surveyed during mid- to late-May in 2021, 2022, and 2023, with 30 (65.2%) sites being surveyed in all three years, 12 (26.1%) sites being surveyed in two years, and only 4 (8.7%) sites being surveyed in one year. A site is a 1km × 1km grid that contains maximumly 16 evenly spaced point count locations that are 250m apart as spatial replicates to further facilitate estimation of observation errors. At each point, trained researchers recorded the number, distance, and timing of any bird species they observed within 6 minutes. At each point, four quadrants were established in four cardinal directions, respectively (i.e., Quadrant 1: 0–90 degrees, Quadrant 2: 90–180 degrees, Quadrant 3: 180–270 degrees, Quadrant 4: 270–360 degrees). In each quadrant, for the nearest individual piñon or juniper tree species, distance to tree was measured using a rangefinder, tree diameter at root crown was measured using a diameter measuring tape, and tree height was measured visually. If there was not a piñon or juniper tree within 50 meters, a zero was recorded. The percentages of grass, herbaceous, and shrub cover were also recorded within a 50-meter radius at each point, using visual estimation, per the IMBCR protocol.

Species of conservation concern

To evaluate responses of the bird community, we considered 40 species that breed in piñon-juniper woodlands (Appendix 1: Table S1), according to Birds of the World species accounts (Poole

Fig. 1. The location of the study area in New Mexico and the locations of the treatment and control survey sites in the study area.



2020), and had at least 10 counts. We used the New Mexico Avian Conservation Partners (NMACP) conservation lists to assign species to 3 groups with high (4 species on the Level 1 list), moderate (11 species on the Level 2 list), and low conservation concern (25 species not on either list). The NMACP is the state chapter of Partners in Flight (PIF), and the NMACP species lists were developed using a slightly modified PIF scoring evaluation (New Mexico Avian Conservation Partners 2016). Population trend, population size, range size, threats, and the importance of New Mexico for each bird species were considered when assigning birds to the above-mentioned lists. We represent the results for the entire community as well as each species group.

We also present the results for seven high priority species of conservation concern: Pinyon Jay, Woodhouse's Scrub-Jay, Juniper Titmouse, Virginia's Warbler, Black-throated Gray Warbler, Black-chinned Sparrow, and Gray Vireo. Pinyon Jay, Woodhouse's Scrub-Jay, and Juniper Titmouse occur throughout piñon-juniper woodlands in New Mexico; the Virginia's Warbler occurs in New Mexico in piñon-juniper woodlands and ponderosa pine forests with substantial amounts of shrubby Gambel oak; The Black-throated Gray Warbler has a larger range than the other priority species and uses a variety of ecosystems for breeding throughout North America, and in New Mexico, it is a bird of higher elevation piñon-juniper woodlands; the Black-chinned Sparrow is found in lower elevation piñon-juniper woodlands in the southern half of New Mexico; the Gray Vireo is found throughout New Mexico in lower elevation piñon-juniper woodlands (Partners in Flight 2020). The largest populations of Pinyon Jay (29%), Woodhouse's Scrub-Jay (20%), Juniper Titmouse (41%), and Virginia's Warbler (36%) of any states are found in New Mexico (Partners in Flight 2020). For Black-throated Gray Warbler, Black-chinned Sparrow, and Gray Vireo, 7%, 4%, and 17% of its global population is found within the state's borders, respectively (Partners in Flight 2020).

These seven species are all listed as species of concern by NMACP. They were identified through a poll that asked NMACP members which species they were most interested in regarding the effects of thinning in piñon-juniper woodlands. All seven species are also United States Fish and Wildlife Service (USFWS) Bird of Conservation Concern (U.S. Fish and Wildlife Service 2021); all but Woodhouse's Scrub-Jay are Species of Greatest Conservation Need (SGCN) in New Mexico (New Mexico Department of Game and Fish 2016); Pinyon Jay, Virginia's Warbler, Black-chinned Sparrow, and Gray Vireo are PIF watch list species (Partners in Flight 2020); Pinyon Jay and Black-chinned Sparrow are Road to Recovery (R2R) Tipping Point Species; and Pinyon Jay is also an International Union for the Conservation of Nature Red List species (BirdLife International 2020).

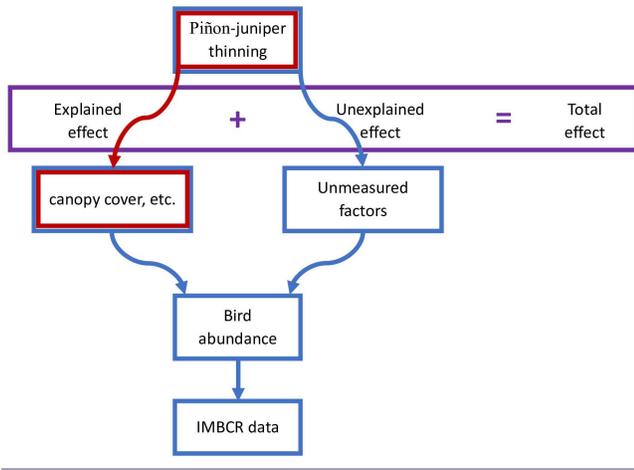
Covariates

We considered the proportion of treatment and eight vegetation metrics as covariates in our analysis. We first calculated the proportion of each grid that overlapped with the area under piñon-juniper thinning practice. This variable ranges from 41.2% to 96.8% for treatment sites, and takes the value of 0% for control sites. This variable is the main covariate that explains the effect of treatment on bird abundance. In addition to proportion of treatment, we considered eight vegetation attributes as additional covariates including mean tree height, mean tree diameter at root crown, tree density, percent canopy cover, the proportion of piñon in the piñon-juniper woodland, percent grass cover, percent herbaceous cover, and percent shrub cover. Mean tree height, diameter at root crown, tree density and the proportion of piñon were calculated from measurements obtained in the four quadrants. Tree density was calculated as $\text{trees/ha} = 1/d^2 \times 10,000$, where d is mean distance from center point to maximumly four trees measured in the four quadrants (Johnson et al. 2017). Canopy cover was calculated from the rangeland analysis platform (RAP) tree canopy layer. The proportion of piñon in the piñon-juniper woodland was calculated as the number of piñon trees divided by the total number of piñon and juniper trees. We conducted a variance inflation factor (VIF) test on all the 9 covariates considered, and a VIF value less than 6 was considered a lack of evidence for multicollinearity (Appendix 1: Table S2).

Modeling approach

We developed a path analysis (Clough 2012) based on a multi-species N-mixture model (Royle 2004, Yamaura et al. 2016) (Fig. 2). A path analysis is capable of decomposing the total effect of a covariate on the response variable into explained effect and unexplained effect. More specifically, an N-mixture model that uses thinning treatment and other environmental variables as covariates is capable of revealing the unexplained effect (i.e., the effect that cannot be explained by the environmental variables considered) of thinning since the effects of these environmental variables are already accounted for in the model. This regression also reveals the effects of the environmental variables considered. An additional analysis is needed to reveal the effects of thinning on these environmental variables, and thus the explained effect (i.e., the effect that can be explained by the environmental variables considered) of thinning can be calculated (details to follow). Eventually, the total effect of thinning can be calculated by adding up the explained and unexplained effects.

Fig. 2. Diagram of path analysis showing how the explained, unexplained, and total effects of piñon-juniper thinning on bird abundance are estimated from IMBCR data. The blue part represents the N-mixture component of the path analysis which reveals the unexplained effect of thinning as well as the effects of other covariates (e.g., canopy cover) on bird abundance; the red part represents the additional component of the path analysis to reveal the effects of thinning on other covariates, and thus the explained effect of thinning on bird abundance; and the purple part represents the calculation of the total effect by adding up explained and unexplained effects.



The N-mixture model contains a process sub-model that describes true abundance as a function of covariates including piñon-juniper treatment and other vegetation attributes mentioned above. The model then contains an observation sub-model that links count data with true abundance while accounting for imperfect detection. Species were treated as a random effect in the model. More specifically, we have

$$\left. \begin{aligned} N_{i,j} &\sim \text{Poisson}(\lambda_{i,j}) \\ \log(\lambda_{i,j}) &= \beta_{0,j} + \beta_{1,j}X_{i,1} + \dots + \beta_{k,j}X_{i,k} \\ \beta_{k,j} &\sim \text{Normal}(\mu_k, \zeta_k) \end{aligned} \right\} \quad (1)$$

in which $N_{i,j}$ is the true abundance of species j at site i , $\lambda_{i,j}$ is the expectation of $N_{i,j}$ and $\log \lambda_{i,j}$ is a function of environmental covariates including $X_{i,1}$ as the piñon-juniper thinning treatment and $X_{i,2}$ to $X_{i,k}$ as other covariates as mentioned previously. For tree height, tree diameter at root crown, tree density, and canopy cover, a quadratic term was included and constrained to negative to achieve ecologically plausible relationships for these covariates. We then assumed that species-specific intercept and slope parameters follow Normal distributions such that $\beta_{0,j|k} \sim \text{Normal}(\mu_{0,k}, \sigma_{group}^2)$, in which $\mu_{0,k}$ is the mean of $\beta_{0,i}$ for any species j that belongs to group k , and σ_{group} is the within-group standard deviation. We further assumed to have $\mu_{0,k} \sim \text{Normal}(\mu_{0,grand}, \sigma_{grand}^2)$, in which $\mu_{0,grand}$ is the grand mean of $\beta_{0,i}$ for any species, and σ_{grand} is the between-group standard deviation. With such a hierarchical structure, our model allows the evaluation of an effect at the community, group, and species levels.

We then have

$$\left. \begin{aligned} y_{i,j,p,d,s} &\sim \text{Multinomial}(N_{i,j}, \pi_{i,j,p,d,s}) \\ \pi_{i,j,p,d,s} &= \frac{2 \times \sigma_j^2 \times \left[\exp\left(\frac{-D_{d,L}^2}{2 \times \sigma_j^2}\right) - \exp\left(\frac{-D_{d,U}^2}{2 \times \sigma_j^2}\right) \right]}{r^2} \times \left[(1 - \theta_j)^{s-1} \times \theta_j \right] \end{aligned} \right\} \quad (2)$$

$$\left. \begin{aligned} \log(\sigma_j) &\sim \text{Normal}(\mu_\sigma, \zeta_\sigma) \\ \text{logit}(\theta_j) &\sim \text{Normal}(\mu_\theta, \zeta_\theta) \end{aligned} \right\}$$

in which $y_{i,j,p,d,s}$ is count data at site i for species j at point p in distance bin b and time interval s , $\pi_{i,j,p,d,s}$ is detection probability which is further decomposed into a distance component with parameter σ_j , lower boundary of distance bin b , $D_{d,L}$, and upper boundary $D_{d,U}$, and a time component with parameter θ_j . Species-specific parameters $\log(\sigma_j)$ and $\text{logit}(\theta_j)$ were further assumed to follow Normal distributions. The fact that the data were collected at multiple points as spatial replicates at each site and contained distance and removal sampling information allows the separation of detection processes from true abundance at the site level.

To understand the effects of piñon-juniper thinning on bird abundance through other environmental factors such as tree density and canopy cover, we also estimated the relationships between these covariates and the proportion of treatment (Fig. 2). With this information, we calculated the explained effect of piñon-juniper thinning on bird abundance through all the environmental factors considered as $\exp(\sum_{k=2}^K \beta_{k,j} X_{i,k} | \text{treatment} = 1) - \exp(\sum_{k=2}^K \beta_{k,j} X_{i,k} | \text{treatment} = 0)$, in which $\beta_{k,j}$ for $k = 2, \dots, K$ is the effects of the covariates other than the proportion of treatment on the abundance of species j at the log scale, $X_{i,k} | \text{treatment} = 1$ is the predicted value of covariate k (e.g., tree density) if a site is 100% covered by treatment, and $X_{i,k} | \text{treatment} = 0$ is the predicted covariate value if a site is not covered by treatment at all. Eventually, we added up the explained and unexplained effects as the total effect of piñon-juniper thinning on bird abundance (Fig. 2).

Model implementation and post-model analysis

We conducted Markov chain Monte Carlo (MCMC) computing in Nimble (de Valpine et al. 2017) through the R programming language (R Development Core Team 2019). We used vague priors: i.e., Normal (0, 1) for any mean, intercept and slope parameter; Gamma (0.01, 0.01) for any standard deviation parameter; Uniform (0, 1) for any probability parameter) throughout the study. To generate posterior samples, we used 3 chains and 500,000 iterations including 300,000 burn-in, thinned by 100, resulting in 6000 posterior samples for each parameter. The convergence of the MCMC computing was checked using the diagnostic plot of the posterior samples and Brooks-Gelman-Rubin Diagnostics, where $Rhat \leq 1.02$ was considered indicative of convergence (Brooks and Gelman 1998)

We calculated tail probability (p -tail) to measure the uncertainty of the effect of any covariate on bird abundance. The tail probability was defined as the proportion of posterior samples that are below 0 for a positive effect or above 0 for a negative effect. We reported the p -tail statistics, with a smaller p -tail value representing a higher certainty of the effect, and vice versa (Zhao et al. 2023).

RESULTS

Effect of piñon-juniper thinning on environmental factors

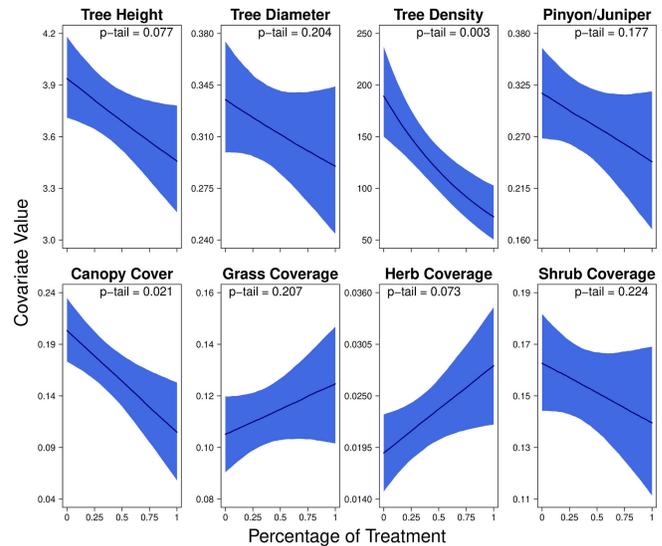
Piñon-juniper thinning had negative effects on tree density (p -tail = 0.003) and canopy cover (p -tail = 0.021), while its effects on other environmental covariates considered were less certain (p -tail = 0.073~0.224, Fig. 3). These results indicated that the effect of piñon-juniper thinning on bird abundance was more likely to be explained through reduced tree density and canopy cover than through the other environmental covariates considered.

Effect of piñon-juniper thinning on bird abundance

We found that piñon-juniper thinning had negative effects on the bird community, the species groups of high and moderate concerns, as well as five (i.e., Pinyon Jay, Woodhouse's Scrub-Jay, Juniper Titmouse, Virginia's Warbler, Black-throated Gray Warbler) out of the seven priority species, with the explained and unexplained portions of the total effect varying among bird groups and species (Fig. 4). More specifically, the negative total effect of piñon-juniper thinning on the community (p -tail = 0.115; Fig. 4) was a consequence of the negative explained effect (p -tail = 0.023) mainly through canopy cover (p -tail = 0.022; Fig. 5) eclipsed by the positive unexplained effect (p -tail = 0.050). The negative total effect of thinning on the species group of high concern (p -tail = 0.001) was a combination of the negative explained effect (p -tail = 0.008) through both tree density (p -tail = 0.005) and canopy cover (p -tail = 0.022) and the negative unexplained effect (p -tail = 0.051; Figs. 4 and 5). The negative total effect of thinning on the species group of moderate concern (p -tail = 0.085) was a consequence of the opposite effects of thinning through tree density (positive, p -tail = 0.041) and canopy cover (negative, p -tail = 0.025) leading to a negative but relatively uncertain explained effect (p -tail = 0.138) as well as a negative but also uncertain unexplained effect (p -tail = 0.221; Figs. 4 and 5). For species of low conservation concern, there was no total effect (p -tail = 0.442) from thinning on their abundance, which was a consequence of a negative explained effect (p -tail = 0.020) mainly through canopy cover (p -tail = 0.022) balanced by a positive unexplained effect (p -tail = 0.000; Figs. 4 and 5).

For the priority species, there was a negative total effect (p -tail = 0.001) from thinning on Pinyon Jay abundance, mainly unexplained (p -tail = 0.000; Figs. 4 and 5). Woodhouse's Scrub-Jay also had a negative total effect (p -tail = 0.006) from thinning on abundance as a combination of a negative explained effect (p -tail = 0.027) through both tree density (p -tail = 0.018) and canopy cover (p -tail = 0.043) and a negative unexplained effect (p -tail = 0.084; Figs. 4 and 5). Juniper Titmouse had a negative total effect (p -tail = 0.035) on their abundance from thinning that was mostly due to the negative explained effect (p -tail = 0.009) through both tree density (p -tail = 0.004) and canopy cover (p -tail = 0.033; Figs. 4 and 5). Virginia's Warbler showed a negative total effect (p -tail = 0.190) on their abundance from thinning that was mainly due to the negative explained effect (p -tail = 0.065) through canopy cover (p -tail = 0.022; Figs. 4 and 5). Black-throated Gray Warbler had a negative total effect (p -tail = 0.012) on their abundance from thinning, and it was mostly due to the negative explained effect (p -tail = 0.012) through canopy cover (p -tail = 0.022; Figs. 4 and 5).

Fig. 3. The effects of piñon-juniper thinning on other environmental covariates (line: median, band: 80% Credible Interval). The unit is meter for tree height and tree diameter at root crown, and number of trees per hectare for tree density. A smaller p -tail statistic indicates a higher certainty of the effect, and vice versa.



5). Black-chinned Sparrow showed a uncertain total effect (p -tail = 0.389) on their abundance from thinning due to the fact that both explained (p -tail = 0.301) and unexplained effects (p -tail = 0.262) were uncertain for this species (Figs. 4 and 5). The Gray Vireo was the only priority species that showed a positive total effect (p -tail = 0.176) from thinning on abundance, but mostly unexplained (p -tail = 0.035; Figs. 4 and 5).

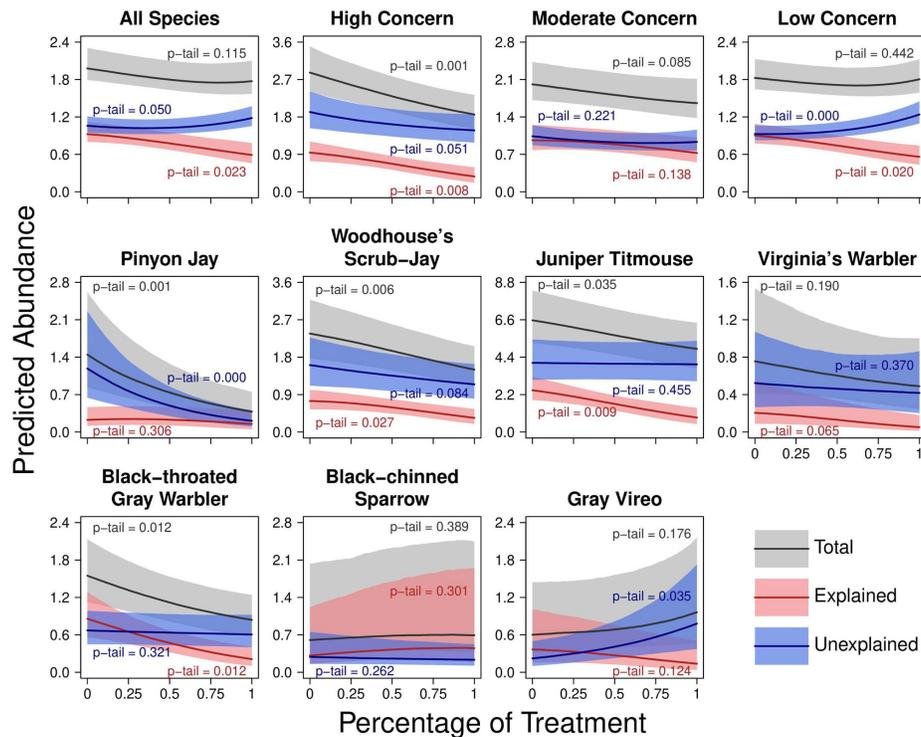
Effect of environmental factors on bird abundance

The community, as well as species groups of moderate and low concerns, had negative relationships with tree density, while the species group of high concern had a quadratic relationship. For priority species, Pinyon Jay and Black-chinned Sparrow had negative relationships with tree density, while Woodhouse's Scrub-Jay, Juniper Titmouse, Virginia's Warbler, Black-throated Gray Warbler, and Gray Vireo had quadratic relationships (Fig. 6).

The community as well as species groups of high and low concerns had quadratic relationships with canopy cover, while the species group of moderate concern had a positive relationship. For priority species, Pinyon Jay, Woodhouse's Scrub-Jay, Juniper Titmouse, and Gray Vireo had quadratic relationships with canopy cover, while Virginia's Warbler and Black-throated Gray Warbler had positive relationships (Fig. 7).

The community and species groups of moderate and low concerns had negative relationships with tree height, while the species group of high concern had a quadratic relationship. Among priority species, all species had quadratic relationships with tree height, except for Black-throated Gray Warbler which had a negative

Fig. 4. Response curves showing the total, explained and unexplained effects (line: median, band: 80% Credible Interval) of piñon-juniper thinning on the abundance of all 40 bird species, each of the 3 species groups, and each of the 7 priority species. P-tail statistics for total, explained and unexplained effects are shown in the same color of the corresponding effect.



relationship. Tree diameter at root crown positively influenced the community, species groups of high and moderate concerns, as well as Woodhouse's Scrub-Jay, Juniper Titmouse, Virginia's Warbler, and Gray Vireo. The species group of low concern and Pinyon Jay, Black-throated Gray Warbler and Black-chinned Sparrow had quadratic relationships with tree diameter at root crown. The proportion of piñon trees positively influenced the community, all three species groups as well as all priority species except for Pinyon Jay and Gray Vireo which had negative relationships with this variable (Appendix 1: Fig. S2).

Grass coverage negatively influenced the community, the species group of low concern, Virginia's Warbler, Black-chinned Sparrow and Gray Vireo, and positively influenced the species group of high concern, Woodhouse's Scrub-Jay, Juniper Titmouse and Black-throated Gray Warbler. Herb coverage positively influenced the species group of high concern, Pinyon Jay, Woodhouse's Scrub-Jay, Juniper Titmouse and Gray Vireo, and negatively influenced the species group of moderate concern, Black-throated Gray Warbler and Black-chinned Sparrow. Shrub coverage positively influenced the community, species groups of moderate and low concerns, Pinyon Jay, Woodhouse's Scrub-Jay, Virginia's Warbler, Black-throated Gray Warbler and Black-chinned Sparrow, and negatively influenced the species group of high concern and Juniper Titmouse (Appendix 1: Fig. S2).

Detection parameters

The posterior median was 55.2 (80% Credible Interval 51.0, 60.0) for the mean distance sampling parameter with a median standard deviation at the log scale of 0.362 (80% CI 0.303, 0.441) across

species. The posterior median was 0.397 (80% CI 0.260, 0.487) for the mean removal sampling parameter with a median standard deviation at the logit scale of 1.004 (80% CI 0.547, 1.628).

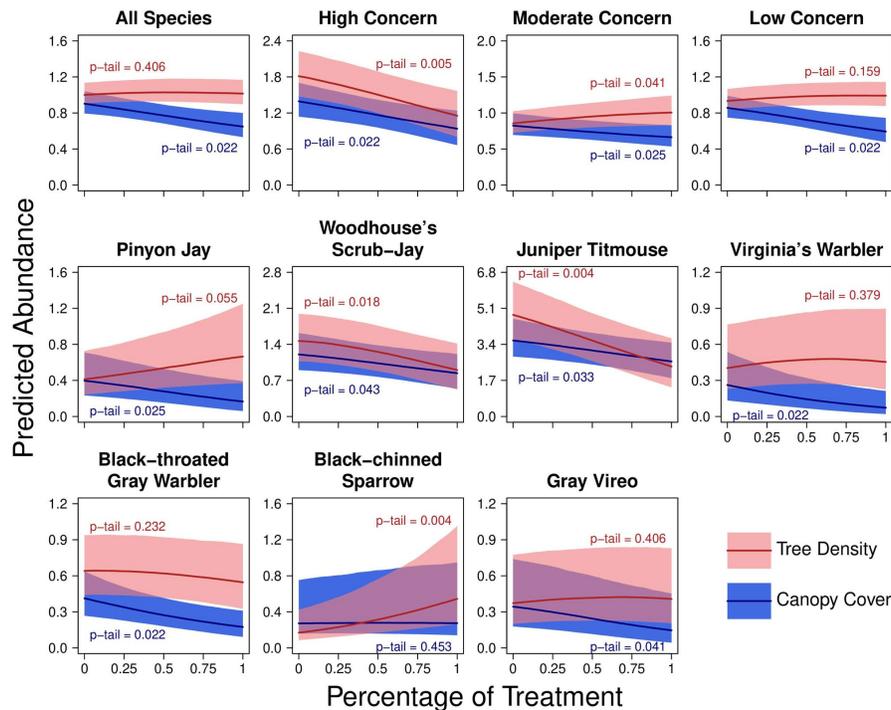
DISCUSSION

By using a path analysis, we were able to reveal multiple underlying pathways of the effects of piñon-juniper thinning on bird groups and species. Overall, we found that certain bird groups and species had negative relationships with piñon-juniper thinning in New Mexico. While reduced tree density and canopy cover can explain such negative relationships in some cases, some unmeasured factors may also play an important role and thus require further investigation.

The effects of piñon-juniper thinning and other environmental factors on bird community

Our results, which showed that species groups of high and moderate conservation concerns have negative relationships with thinning, are consistent with results from a growing body of empirical and model-derived studies that show piñon-juniper woodland birds generally have negative responses to piñon-juniper clear-cutting, thinning, burning, natural mortality, or a combination of these factors (O'Meara et al. 1981, Crow and Van Riper 2010, Bombaci and Pejchar 2016, Bombaci et al. 2017, Gallo and Pejchar 2017, Holmes et al. 2017, Fair et al. 2018, Johnson et al. 2018, Magee et al. 2019, Van Lanen et al. 2023a, 2023b, 2023c, 2024; Table 1). We further revealed that such a

Fig. 5. Response curves showing the explained effects (line: median, band: 80% Credible Interval) of piñon-juniper thinning through tree density and canopy cover on the abundance of all 40 bird species, each of the 3 species groups, and each of the 7 priority species. P-tail statistics for tree density and canopy cover are shown in the same color of the corresponding covariate.



negative effect of thinning, particularly for the species group of high concern, could be explained by the reduction in canopy cover and tree density caused by thinning.

We found a quadratic but overall positive relationship between the species group of high concern and canopy cover, which is consistent with other studies on the topic, both empirical and model-derived (Bombaci et al. 2017, Zeller et al. 2021, Van Lanen et al. 2023a, 2024). Canopy cover requirements differ by species, but because our results also show that many species have relatively narrow optimum ranges of canopy cover, even light thinning, resulting in a canopy cover reduction of less than 10%, particularly in areas with a canopy cover that is already lower than 30%, could negatively impact piñon-juniper birds.

The relationships between bird abundance, tree density, and diameter at root crown combined may further explain the relationship with canopy cover, particularly for species groups of high and moderate conservation concerns. It appears most (but not all) piñon-juniper birds select woodlands with higher levels of canopy cover composed of fewer, larger diameter trees. This means that the combination of tree density, diameter at root crown, and canopy cover is likely an appropriate way to measure habitat selection for piñon-juniper birds.

Another component of woodland structure, tree height, was also important for piñon-juniper birds in our study. We found a quadratic relationship with tree height for the species group of high concern and negative relationships for species groups of

moderate and low concerns. Taller trees may expose nests to higher predation, among other things, and one study on Pinyon Jays showed they avoided nesting in the tallest, emergent trees (Johnson and Sadoti 2023). This could also represent that these birds select piñon and juniper trees that tend to be short and avoid tall tree species such as ponderosa pine. Many thinning prescriptions focus on retaining the largest trees, in both diameter at root crown and height. Our results, however, suggest that a selection for leaving taller trees is likely detrimental for piñon-juniper birds.

Our results also showed that species groups of high and moderate concerns select woodlands with a higher proportion of piñon trees. This could be because piñon pines provide highly nutritious nuts and habitat for invertebrate prey, as well as areas for nesting and cover. The importance of piñon pine should not, however, be interpreted as justification for removing all or most juniper when thinning, as numerous studies have shown juniper to be an important habitat component for piñon-juniper birds (Pavlacky and Anderson 2001, 2004, Harris et al. 2020). Regarding understory vegetation, the species group of high concern tends to select woodlands with a higher grass coverage, higher herb coverage, and lower shrub coverage. Our results suggest that management actions designed to increase grass and herbaceous cover, such as properly managed grazing, invasive species removal and soil erosion control are important for piñon-juniper bird species of high concern.

Fig. 6. Response curves showing the effects of tree density (number of trees per hectare) on the abundance of all 40 bird species, each of the 3 species groups, and each of the 7 priority species (line: median, band: 80% Credible Interval).

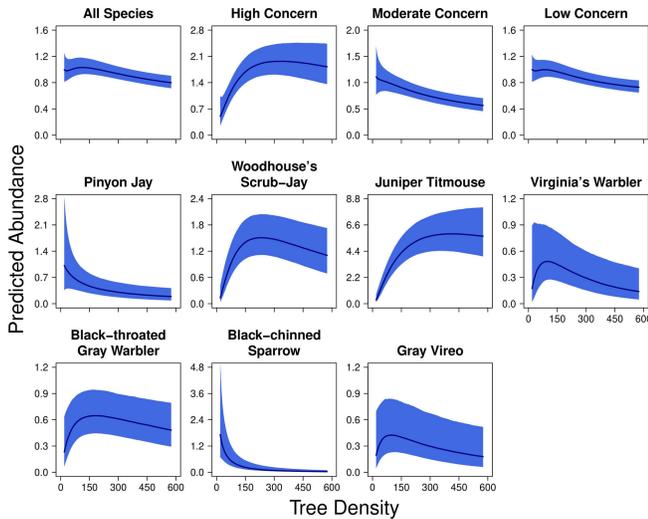
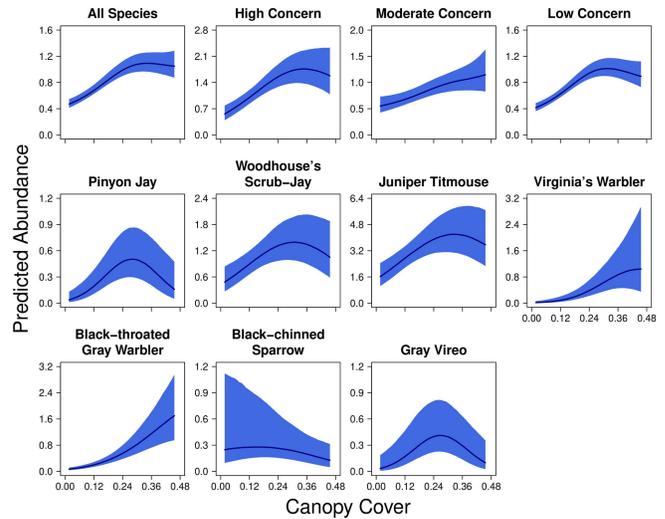


Fig. 7. Response curves showing the effects of canopy cover on the abundance of all 40 bird species, each of the 3 species groups, and each of the 7 priority species (line: median, band: 80% Credible Interval).



The responses of seven priority species to piñon-juniper thinning

Pinyon Jay

Our study took place during the time of year that Pinyon Jays in New Mexico are usually at the end of their breeding season or the beginning of their post-breeding season (mid- to late-May). Our results evaluating the influence of environmental covariates on Pinyon Jay abundance suggest good late-breeding or early post-breeding Pinyon Jay habitat likely includes, but is not necessarily limited to, lower density and moderate canopy cover woodlands composed of shorter, medium-diameter trees, a lower proportion of piñon pine, higher herbaceous cover, and higher shrub cover. Our results did not find grass cover to be important for Pinyon Jay; however, other research has found this to be important (Van Lanen et al. 2024). It is important to note that (Johnson and Sadoti 2019) found Pinyon Jay nesting habitat selection is relative and depends upon what is available in a flock's home range. Therefore, there is no "typical" nesting habitat, and the above information is likely not applicable for all nesting Pinyon Jays.

Our study showed Pinyon Jays have a negative relationship with thinning, which is consistent with other empirical and modeling studies (Johnson et al. 2018, Magee et al. 2019, Van Lanen et al. 2024). However, this negative relationship is inconsistent with what you would expect based upon the above-mentioned environmental covariates. Our Path analysis provides a plausible explanation for this inconsistency. It reveals that the Pinyon Jay's negative relationship with thinning should largely be explained by factors other than tree density and canopy cover. Factors that could affect Pinyon Jays after thinning may include overgrazing, invasive species infestation, and more. These actions could result in significantly lower invertebrate prey, and invertebrates are an important part of the Pinyon Jay diet (Sicich et al. 2025).

Woodhouse's Scrub-Jay

The negative relationship the Woodhouse's Scrub-Jay has with thinning is consistent with other studies (Bombaci et al. 2017, Magee et al. 2019). Our study suggests that good Woodhouse's Scrub-Jay habitat likely includes, but is not necessarily limited to, woodlands with moderately low tree density and height and moderately high canopy cover, with more piñon than juniper. Good breeding habitat also likely contains substantial grass and herbaceous cover. Because it is understudied, there is not a lot of other information regarding habitat needs of Woodhouse's Scrub-Jay.

Juniper Titmouse

The negative relationship with thinning for the Juniper Titmouse is consistent with other studies (Bombaci et al. 2017, Gallo and Pejchar 2017, Magee et al. 2019). Our study suggests good Juniper Titmouse habitat likely includes, but is not necessarily limited to, woodlands with higher canopy cover, higher densities of larger diameter, and moderate height trees. Good habitat also, according to this study, likely contains substantial amounts of piñon as compared to juniper, higher grass and herbaceous cover, and lower shrub cover. Our results are consistent with other studies that have found higher canopy cover, more piñon pine, higher grass cover, and lower shrub cover to be important for Juniper Titmouse (Pavlacky and Anderson 2001, 2004). These same studies determined that taller trees were important for Juniper Titmouse, while we found medium height trees were selected; more research is needed regarding tree height. These studies also evaluated environmental covariates that were not included in our study and found that Juniper Titmouse likely selects woodlands with lower seedling/sapling and bare ground/rock cover, as well higher dead limb density and senescent tree density (Pavlacky and Anderson 2001, 2004).

Table 1. Summaries of literatures that show the negative associations between birds and thinning in piñon-juniper woodland.

Peer-reviewed reference	Ecological communities and species	Year(s) of the study	Type of woodland change
Bombaci and Pejchar 2016	Piñon-juniper woodland bird community	n/a [†]	Thinning, clear cutting, burning
Bombaci et al. 2017	Piñon-juniper woodland bird community	2012–2013	Clear cutting
	Ash-throated Flycatcher (<i>Myiarchus cinerascens</i>)		
	Black-chinned Hummingbird (<i>Archilochus alexandri</i>)		
	Black-throated Gray Warbler (<i>Setophaga nigrescens</i>)		
	Blue-gray Gnatcatcher (<i>Polioptila caerulea</i>)		
	Broad-tailed Hummingbird (<i>Selasphorus platycercus</i>)		
	Cassin's Finch (<i>Haemorhous cassinii</i>)		
	Chipping Sparrow (<i>Spizella passerina</i>)		
	Dark-eyed Junco (<i>Junco hyemalis</i>)		
	Evening Grosbeak (<i>Hesperiphona vespertina</i>)		
	Hairy Woodpecker (<i>Leuconotopicus villosus</i>)		
	Juniper Titmouse (<i>Baeolophus ridgwayi</i>)		
	Mountain Bluebird (<i>Sialia currucoides</i>)		
	Mountain Chickadee (<i>Poecile gambeli</i>)		
	Mourning Dove (<i>Zenaid macroura</i>)		
	Northern Flicker (<i>Colaptes auratus</i>)		
	Plumbeous Vireo (<i>Vireo plumbeus</i>)		
	Red Crossbill (<i>Loxia curvirostra</i>)		
	Spotted Towhee (<i>Pipilo maculatus</i>)		
	Violet-green Swallow (<i>Tachycineta thalassina</i>)		
	White-breasted Nuthatch (<i>Sitta carolinensis</i>)		
	Woodhouse's Scrub-Jay (<i>Aphelocoma woodhouseii</i>)		
Crow and Van Riper 2010	Piñon-juniper woodland bird community	2005–2006	Thinning
	Brown-headed Cowbird (<i>Molothrus ater</i>)		
	Chipping Sparrow (<i>Spizella passerina</i>)		
	Gray Vireo (<i>Vireo vicinior</i>)		
Fair et al. 2018	Piñon-juniper woodland bird community	2003–2013	Natural mortality, thinning
Gallo and Pejchar 2017	American Robin (<i>Turdus migratorius</i>)	2013–2014	Thinning
	Cassin's Finch (<i>Haemorhous cassinii</i>)		
	Dark-eyed Junco (<i>Junco hyemalis</i>)		
	Juniper Titmouse (<i>Baeolophus ridgwayi</i>)		
	Mountain Chickadee (<i>Poecile gambeli</i>)		
	Mourning Dove (<i>Zenaid macroura</i>)		
	Plumbeous Vireo (<i>Vireo plumbeus</i>)		
	Spotted Towhee (<i>Pipilo maculatus</i>)		
	Vesper Sparrow (<i>Poocetes gramineus</i>)		
	Violet-green Swallow (<i>Tachycineta thalassina</i>)		
	White-breasted Nuthatch (<i>Sitta carolinensis</i>)		
Holmes et al. 2017	Gray Flycatcher (<i>Empidonax wrightii</i>)	2013–2014	Clear cutting
Johnson et al. 2018	Pinyon Jay (<i>Gymnorhinus cyanocephalus</i>)	2017–2018	Thinning
Magee et al. 2019	Ash-throated Flycatcher (<i>Myiarchus cinerascens</i>)	2014–2015	Thinning
	Black-headed Grosbeak (<i>Pheucticus melanocephalus</i>)		
	Black-throated Gray Warbler (<i>Setophaga nigrescens</i>)		
	Blue-gray Gnatcatcher (<i>Polioptila caerulea</i>)		
	Broad-tailed Hummingbird (<i>Selasphorus platycercus</i>)		
	Brown-headed Cowbird (<i>Molothrus ater</i>)		
	Bushtit (<i>Psaltriparus minimus</i>)		
	Clark's Nutcracker (<i>Nucifraga columbiana</i>)		
	Gray Flycatcher (<i>Empidonax wrightii</i>)		
	Juniper Titmouse (<i>Baeolophus ridgwayi</i>)		
	Mountain Chickadee (<i>Poecile gambeli</i>)		
	Mourning Dove (<i>Zenaid macroura</i>)		
	Northern Flicker (<i>Colaptes auratus</i>)		
	Pinyon Jay (<i>Gymnorhinus cyanocephalus</i>)		
	Plumbeous Vireo (<i>Vireo plumbeus</i>)		
	Steller's Jay (<i>Cyanocitta stelleri</i>)		
	Townsend's Solitaire (<i>Myadestes townsendi</i>)		
	Virginia's Warbler (<i>Leiothlypis virginiae</i>)		
	Western Tanager (<i>Piranga ludoviciana</i>)		
	Western Wood-Pewee (<i>Contopus sordidulus</i>)		
	White-breasted Nuthatch (<i>Sitta carolinensis</i>)		
	Yellow-rumped Warbler (<i>Setophaga coronata</i>)		
O'Meara et al. 1981	Piñon-juniper woodland bird community	1977	Clear cutting
	Black-throated Gray Warbler (<i>Setophaga nigrescens</i>)		
	Chipping Sparrow (<i>Spizella passerina</i>)		
	Gray Flycatcher (<i>Empidonax wrightii</i>)		

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	Hermit Thrush (<i>Catharus guttatus</i>)		
	Juniper Titmouse (<i>Baeolophus ridgwayi</i>)		
	Mountain Bluebird (<i>Sialia currucoides</i>)		
	Mountain Chickadee (<i>Poecile gambeli</i>)		
	Northern House Wren (<i>Troglodytes aedon</i>)		
	Northern Flicker (<i>Colaptes auratus</i>)		
	Plumbeous Vireo (<i>Vireo plumbeus</i>)		
	White-breasted Nuthatch (<i>Sitta carolinensis</i>)		
	Williamson's Sapsucker (<i>Sphyrapicus thyroideus</i>)		
Van Lanen et al. 2023a	Pinyon Jay (<i>Gymnorhinus cyanocephalus</i>)	2008–2020 [‡]	Conifer removal [§]
Van Lanen et al. 2023b	Bewick's Wren (<i>Thryomanes bewickii</i>)	2008–2020 [‡]	Conifer removal [§]
	Gray Flycatcher (<i>Empidonax wrightii</i>)		
	Pinyon Jay (<i>Gymnorhinus cyanocephalus</i>)		
Van Lanen et al. 2023c	Bewick's Wren (<i>Thryomanes bewickii</i>)	2008–2020 [‡]	Conifer removal [§]
	Black-throated Gray Warbler (<i>Setophaga nigrescens</i>)		
	Gray Flycatcher (<i>Empidonax wrightii</i>)		
	Gray Vireo (<i>Vireo vicinior</i>)		
	Juniper Titmouse (<i>Baeolophus ridgwayi</i>)		
Van Lanen et al. 2024	Pinyon Jay (<i>Gymnorhinus cyanocephalus</i>)	2008–2020 [‡]	Conifer removal [§]

[†] Study was a literature review.

[‡] Study used data from the Bird Conservancy of the Rockies' Integrated Management in Bird Conservation Regions (IMBCR) program.

[§] Study evaluated importance of piñon-juniper cover for individual bird species and speculated that conifer removal, through any means, would negatively affect birds that need higher levels of piñon-juniper cover.

Virginia's Warbler

The negative relationship that Virginia's Warbler had with thinning is consistent with other studies (Magee et al. 2019, Latif et al. 2020). According to this study, good Virginia's Warbler habitat includes, but is not necessarily limited to, woodlands with higher canopy cover but lower tree density, trees that are shorter but larger in diameter, and high shrub cover. The positive relationship of Virginia's Warbler with shrub cover is likely due to the fact that abundant shrubby Gambel oak is an important habitat component for this species (Rosenstock 1998, Jentsch et al. 2008).

Black-throated Gray Warbler

The negative relationship with thinning for the Black-throated Gray Warbler is consistent with other studies (O'Meara et al. 1981, Bombaci et al. 2017, Magee et al. 2019). According to this study, good Black-throated Gray Warbler habitat includes, but is not necessarily limited to, woodlands with higher canopy cover consisting of shorter, smaller diameter trees, with more piñon than juniper. It also includes lower levels of herbaceous cover. Our results are consistent with other studies that showed the Black-throated Gray Warbler selects higher canopy cover, shorter trees, and more piñon pine (Pavlacky and Anderson 2001, 2004). These studies also evaluated environmental covariates that were not included in our study and found that Black-throated Gray Warblers likely also select lower grass cover, greater seedling/sapling cover, and greater rock/bare ground cover (Pavlacky and Anderson 2001, 2004).

Black-chinned Sparrow

This study found no relationship of this species with thinning. We did not find any other studies evaluating Black-chinned Sparrow response to thinning, so this is an area where additional research is needed. According to this study, good Black-chinned Sparrow habitat includes, but is not necessarily limited to, lower canopy cover and lower density woodlands with trees of moderate height and diameter, as well as a higher proportion of piñon. Additionally, good habitat also likely includes higher shrub cover, lower grass cover, and lower herbaceous cover. Other studies

suggest the Black-chinned Sparrow is primarily a shrub bird (Pandolfino et al. 2024), so our study is consistent with these findings. The Black-chinned Sparrow is an understudied species, and more research is needed regarding its habitat needs.

Gray Vireo

The positive relationship with thinning found in this study is inconsistent with other studies (Crow and Van Riper 2010), but this relationship is mostly unexplained by the environmental factors we considered, indicating that more research is needed regarding the effects of thinning on Gray Vireo. According to our study, good Gray Vireo habitat likely includes, but is not necessarily limited to, low density woodlands with moderate canopy cover composed of shorter, larger diameter trees. Our research is consistent with other studies that found larger diameter trees are important for Gray Vireo, but inconsistent with studies that found taller trees are important for Gray Vireo and a larger proportion of juniper is important for Gray Vireo (Harris et al. 2020). Due to these inconsistencies, more research evaluating important Gray Vireo habitat components is needed.

CONCLUSIONS

Overall, according to our study, thinning in piñon-juniper woodlands results in negative responses for woodland birds in New Mexico, with high concern species being the most negatively impacted. Our results are consistent with the available literature, which shows piñon-juniper woodland birds generally have negative responses to piñon-juniper clear-cutting, thinning, burning, natural mortality, or a combination of these factors (O'Meara et al. 1981, Crow and Van Riper 2010, Bombaci and Pejchar 2016, Bombaci et al. 2017, Gallo and Pejchar 2017, Holmes et al. 2017, Fair et al. 2018, Johnson et al. 2018, Magee et al. 2019, Van Lanen et al. 2023a, 2023b, 2023c, 2024; Table 1). Furthermore, our study improved our understanding about how piñon-juniper thinning affects avian biodiversity through various environmental factors such as tree density and canopy cover. Our results showed that the pathways of the effects of piñon-juniper thinning on avian biodiversity were complicated and multifaceted, and indicated that a reevaluation of thinning in

piñon-juniper woodlands outside of the wildland urban interface might be needed, especially in persistent piñon-juniper woodlands that contain the declining, keystone Pinyon Jay, which has been petitioned for listing under the United States Endangered Species Act (Defenders of Wildlife 2022).

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1 **Appendix 1.** Additional tables and figures. Detailed descriptions of the tables and figures could
2 be found in the captions below.

3

4 **Table S1.** The list of all 40 species considered in this study, their common English names, Latin
5 names, level of conservation concern, the highlights of the 7 priority species, and their counts at
6 treatment and control sites. The level of conservation concern is defined according to the New
7 Mexico Avian Conservation Partners (NMACP) conservation lists (New Mexico Avian
8 Conservation Partners 2016).

Common English name	Latin name	Concern	Priority	Treatment	Control
Ash-throated Flycatcher	<i>Myiarchus cinerascens</i>	low		240	314
Black-chinned Hummingbird	<i>Archilochus alexandri</i>	low		10	11
Black-chinned Sparrow	<i>Spizella atrogularis</i>	moderate	yes	31	24
Bewick's Wren	<i>Thryomanes bewickii</i>	low		46	104
Blue-gray Gnatcatcher	<i>Polioptila caerulea</i>	low		15	10
Black-headed Grosbeak	<i>Pheucticus melanocephalus</i>	low		66	108
Broad-tailed Hummingbird	<i>Selasphorus platycercus</i>	moderate		74	62
Black-throated Sparrow	<i>Amphispiza bilineata</i>	low		13	31
Black-throated Gray Warbler	<i>Setophaga nigrescens</i>	moderate	yes	73	130
Bushtit	<i>Psaltriparus minimus</i>	moderate		138	196
Cassin's Kingbird	<i>Tyrannus vociferans</i>	low		134	32
Canyon Towhee	<i>Melospiza fusca</i>	moderate		22	23
Chipping Sparrow	<i>Spizella passerina</i>	low		199	175
Dusky Flycatcher	<i>Empidonax oberholseri</i>	low		13	7
Gray Flycatcher	<i>Empidonax wrightii</i>	low		214	232
Gray Vireo	<i>Vireo vicinior</i>	moderate	yes	12	16
Green-tailed Towhee	<i>Pipilo chlorurus</i>	moderate		59	25
Hairy Woodpecker	<i>Dryobates villosus</i>	low		18	11
Hepatic Tanager	<i>Piranga flava</i>	low		24	36
Hermit Thrush	<i>Catharus guttatus</i>	low		1	9
House Finch	<i>Haemorhous mexicanus</i>	low		156	47
House Wren	<i>Troglodytes aedon</i>	low		17	5
Juniper Titmouse	<i>Baeolophus ridgwayi</i>	high	yes	121	186
Lark Sparrow	<i>Chondestes grammacus</i>	low		94	68
Lesser Goldfinch	<i>Spinus psaltria</i>	low		7	4
Mountain Chickadee	<i>Poecile gambeli</i>	moderate		10	19
Northern Flicker	<i>Colaptes auratus</i>	low		45	25
Pinyon Jay	<i>Gymnorhinus cyanocephalus</i>	high	yes	10	24
Plumbeous Vireo	<i>Vireo plumbeus</i>	low		91	104
Say's Phoebe	<i>Sayornis saya</i>	low		17	5
Spotted Towhee	<i>Pipilo maculatus</i>	low		600	520

Steller's Jay	<i>Cyanocitta stelleri</i>	moderate		20	11
Vesper Sparrow	<i>Pooecetes gramineus</i>	moderate		43	22
Virginia's Warbler	<i>Oreothlypis virginiae</i>	high	yes	5	10
Western Bluebird	<i>Sialia mexicana</i>	moderate		57	18
Western Tanager	<i>Piranga ludoviciana</i>	low		73	98
Western Wood-Pewee	<i>Contopus sordidulus</i>	low		85	78
Wild Turkey	<i>Meleagris gallopavo</i>	low		12	6
Woodhouse's Scrub-Jay	<i>Aphelocoma woodhouseii</i>	high	yes	74	107
White-winged Dove	<i>Zenaida asiatica</i>	low		20	9

9

10

11 **Table S2.** Results of a variance inflation factor (VIF) test for potential multicollinearity among
12 the covariates considered in the current study. A VIF value less than 6 is considered lack of
13 evidence for multicollinearity.

Variable	VIF
Proportion of treatment	1.37
Tree height	2.29
Tree diameter at root crown	1.22
Tree density	4.64
Proportion of piñon	2.34
Canopy cover	5.94
Grass coverage	1.58
Herb coverage	1.54
Shrub coverage	1.31

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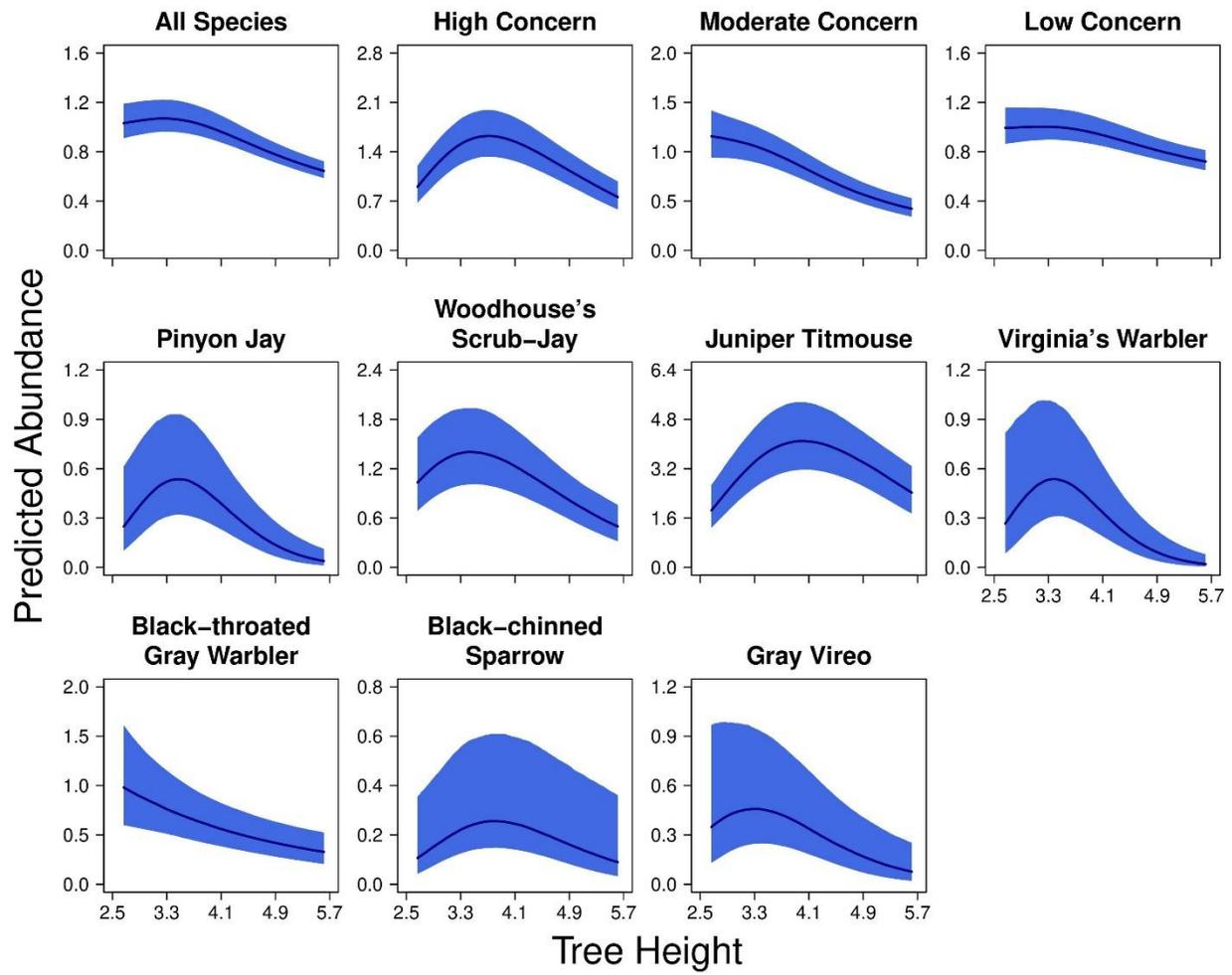


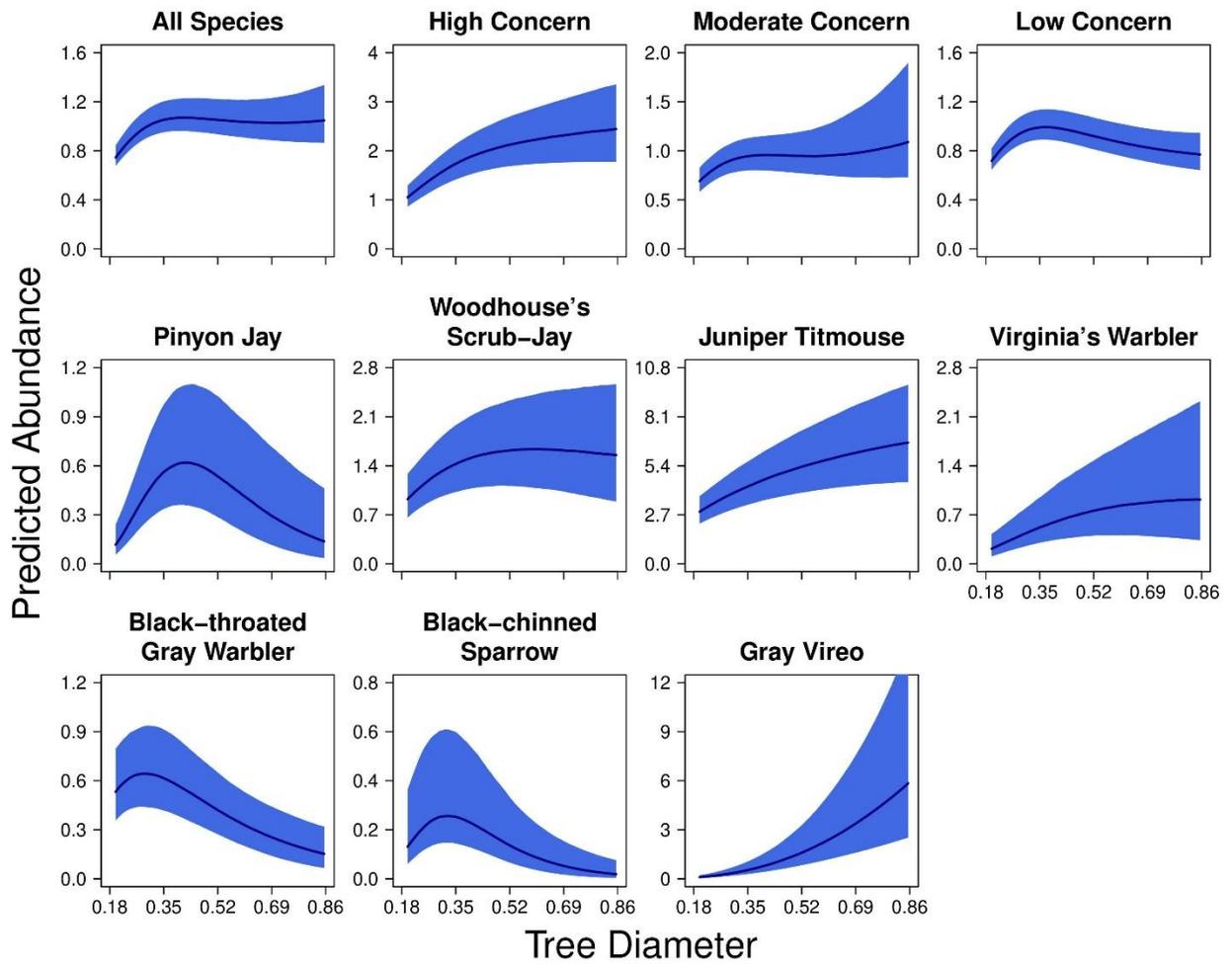


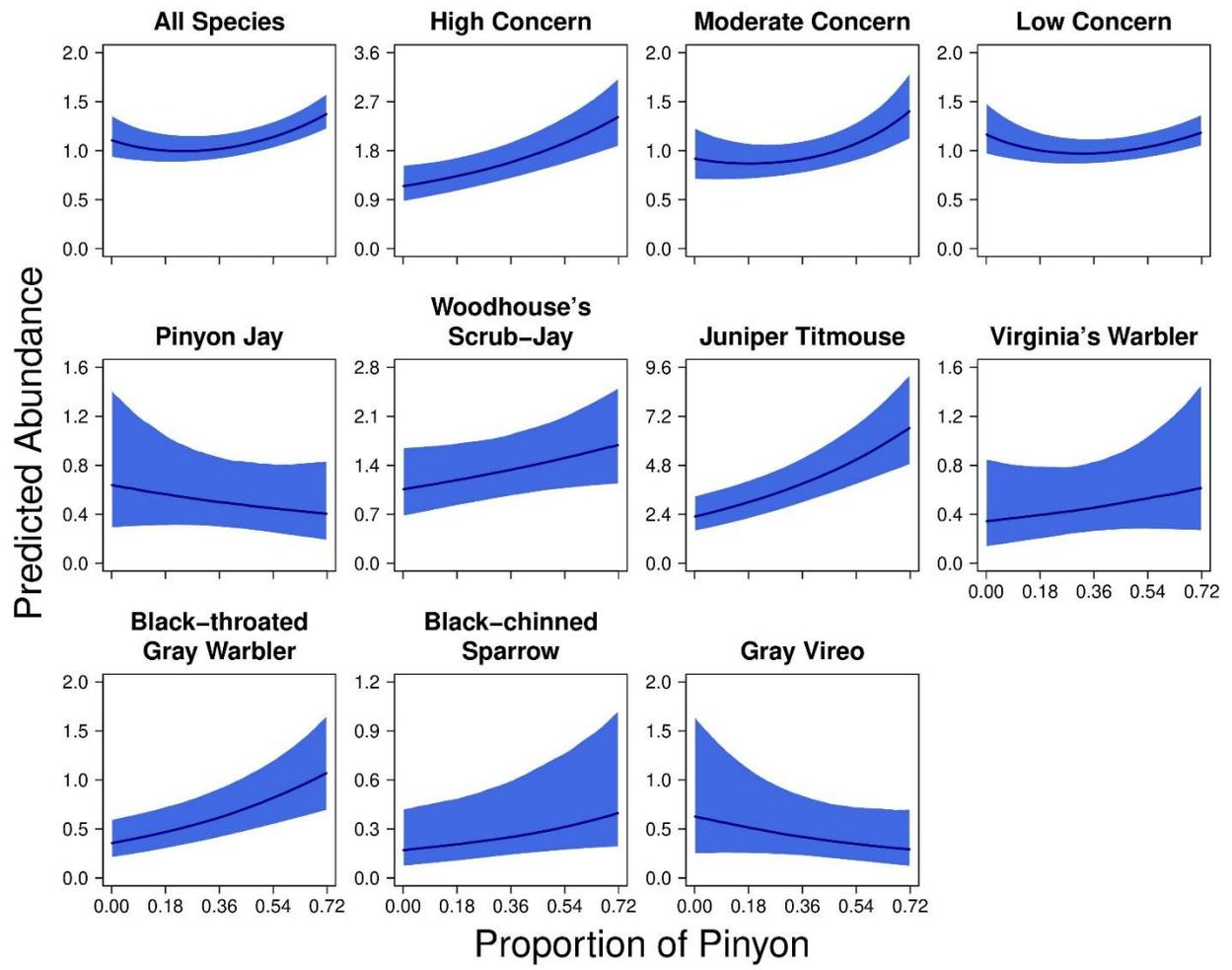
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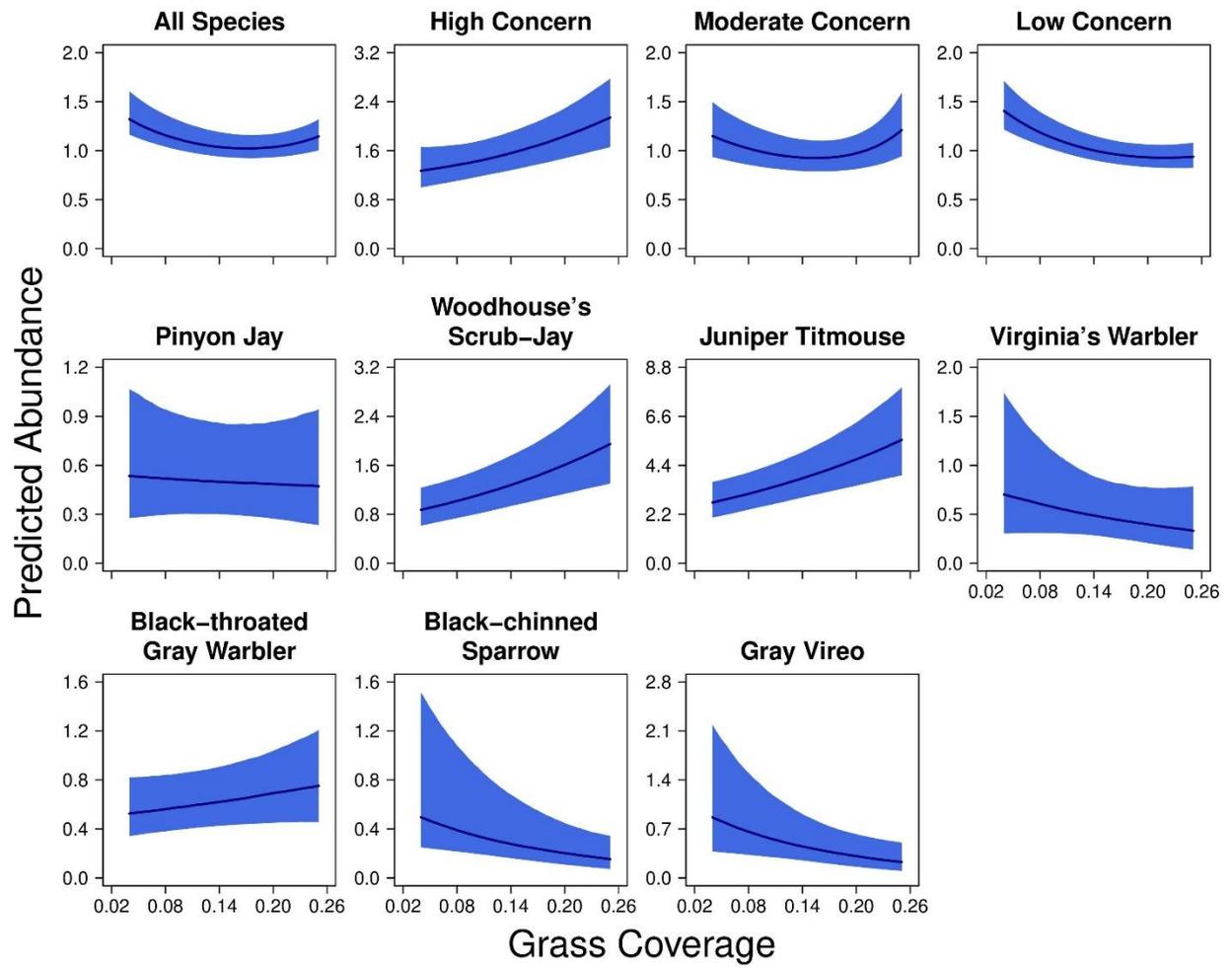
19 **Figure S1.** Example photos of some treatment sites. Treatments varied and included
20 prescriptions that created mosaics of thinned and unthinned patches of varying sizes, evenly-
21 spaced thinning, thinning that removed all juniper, thinning that preferentially retained tall trees,
22 and thinning that was followed with prescribed burning.

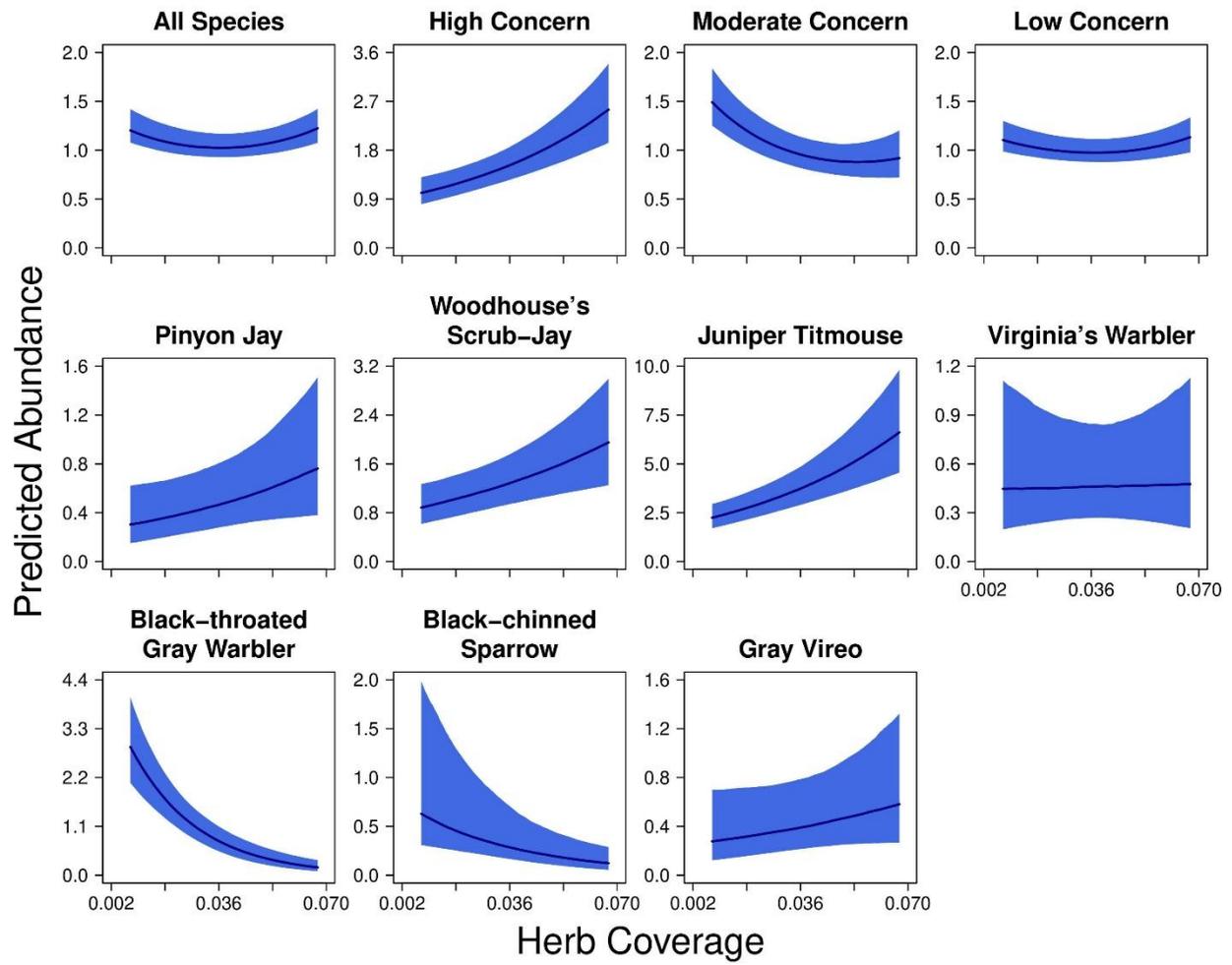
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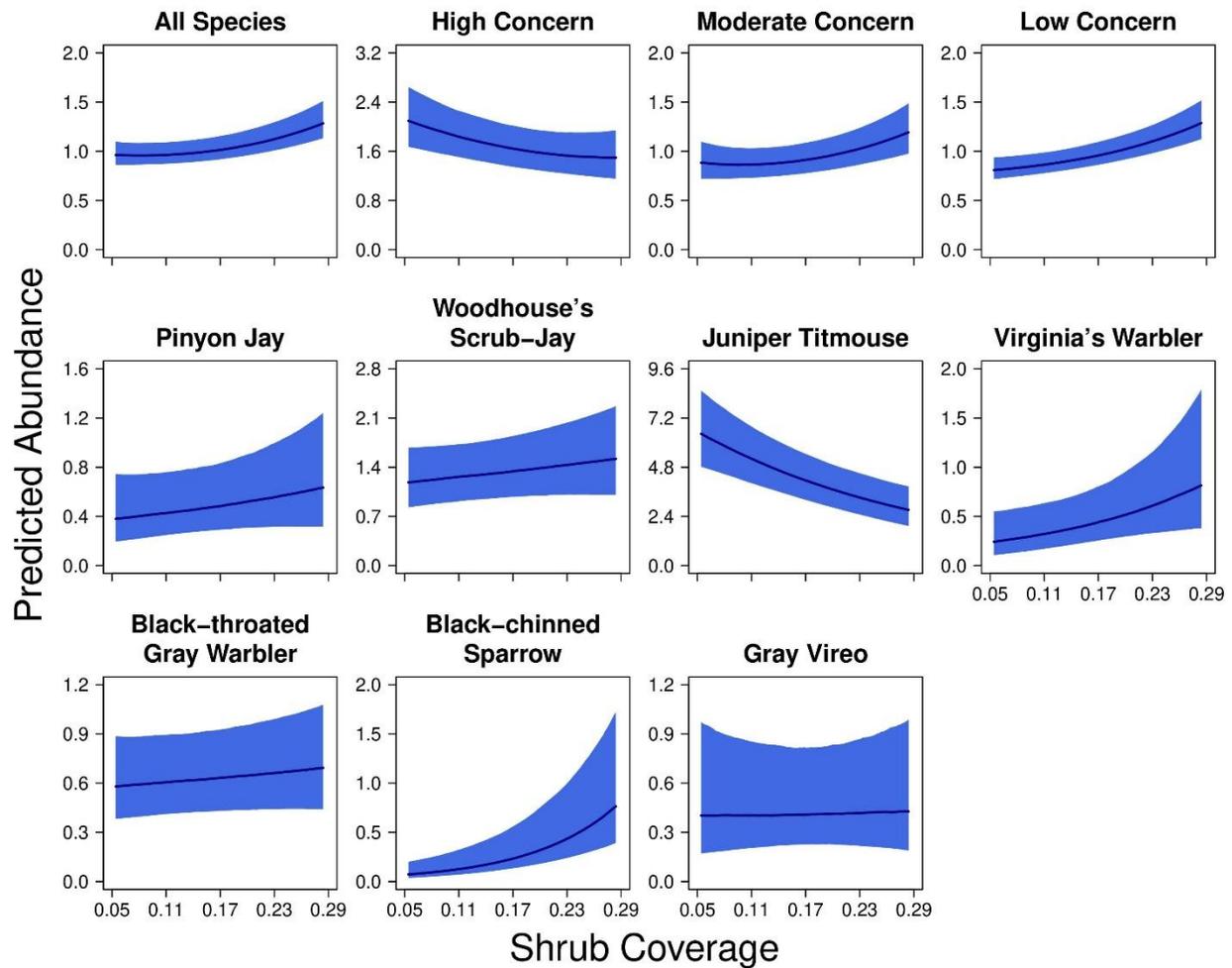












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30 **Figure S2.** Response curves showing the effects of tree height (meter), tree diameter at root
 31 crown (meter), the proportion of piñon in the piñon-juniper woodland, percent grass cover,
 32 percent herbaceous cover, and percent shrub cover on the abundance of all 40 bird species, each
 33 of the 3 species groups, and each of the 7 priority species (line: median, band: 80% Credible
 34 Interval).