DENSITY AND HABITAT ASSOCIATIONS OF THE WOODHOUSE'S SCRUB-JAY IN CENTRAL TEXAS

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ABSTRACT—Woodhouse's scrub-jay (*Aphelocoma woodhouseii texana*) is a relatively understudied subspecies inhabiting juniper scrub and woodland in central Texas. We estimated density and examined habitat associations at the eastern edge of their breeding range. Scrub-jays were strongly associated with intermediate proportions of juniper land cover at a 100-m scale and showed lower density in areas of greater mixed oak-juniper woodland and greater urban land cover at a 1-km scale.

RESUMEN—El arrendajo de los matorrales (*Aphelocoma woodhouseii texana*) es una subespecie relativamente poco estudiada que habita en matorrales de enebro y bosques en el centro de Texas. Estimamos la densidad y examinamos las asociaciones de hábitat en el borde oriental de su área de reproducción. Los arrendajos se asociaron fuertemente con proporciones intermedias de cobertura de enebro a una escala de 100 metros y mostraron menor densidad en áreas de mayor bosque mixto de roble y enebro y mayor cobertura de tierra urbana en la escala de 1 kilómetro.

The Texas subspecies of Woodhouse's scrub-jay (*Aphelocoma woodhouseii texana*; hereafter scrub-jay) is mostly restricted to the Edwards Plateau of central Texas and is a distinct population almost disconnected from other subspecies to the west (Curry et al., 2017). The scrub-jay is generally associated with pinyon (*Pinus* species) and juniper (*Juniperus* species) scrub and woodland throughout its range (Curry et al., 2017). However, little information exists on the specific habitat associations of scrub-jays within central Texas woodlands. To our knowledge, only two previous studies have reported on habitat relationships of scrub-jays in Texas. Scrub-jays were found in both shrub-scrub and juniper woodland habitat in west-central Texas and were typically closer to habitat edges than expected (Klassen and Mathewson, 2014), and the species was considered a habitat generalist in mixed juniper-oak woodlands in central Texas (Burt, 1996). However, neither of these studies evaluated scrub-jay density in relation to specific features of the woodland habitat.

In addition to establishing baseline population data, we consider it important to identify habitat preferences of scrub-jays in Texas because its breeding range overlaps the breeding range of the endangered golden-cheeked warbler (*Setophaga chrysoparia*; hereafter warbler). Both species occupy the juniper-oak (*Quercus* species) woodlands of central Texas and scrub-jays are frequent predators of warbler nests (Petyk, 2004; Stake et al., 2004; Reidy et al., 2008). Warblers are more abundant in closed-canopy, tall, mixed juniper-oak woodland, suggesting this is preferred habitat, but also occur in shorter, open-canopy and juniper-dominated woodlands (Klassen et al., 2012; Peak and Thompson, 2013; Reidy et al., 2016). Warbler nest survival is lower near woodland edges (Peak, 2007; Reidy et al., 2009) and it is speculated that predation is higher because dominant nest predators such as rat snakes and scrub-jays may be more abundant near habitat edges (Peak, 2007; Reidy et al., 2009; Sperry et al., 2009; Klassen and Mathewson, 2014). Therefore, we consider more knowledge of scrub-jay habitat preferences as an important step to guiding effective habitat management for the warbler.

We conducted point count surveys across a large urban preserve in Austin, Texas, which supports breeding populations of scrub-jays and warblers. We estimated density of scrub-jays and evaluated relationships between scrub-jay density and vegetation structure at three spatial scales. At the patch scale, we predicted scrub-jays were associated with greater juniper density, intermediate canopy cover and canopy height, and lower shrub density. At the 100-m forest scale, we predicted scrub-jays were associated with intermediate to high proportions of juniper woodland, intermediate to high, open edge density, and intermediate canopy height. At the 1-km landscape scale, we predicted scrub-jays were positively associated with juniper and open land cover. We based our predictions on habitat preferences reported elsewhere in the range and previous studies within central Texas (Klassen and Mathewson, 2014; Curry et al., 2017). We then compared the supported habitat relationships with known habitat relationships of warblers reported in the literature.

Materials and Methods—*Study Area and Study Species*—We surveyed for scrub-jays within the Balcones Canyonlands Preserve (BCP), Travis County, Texas (30°23′N, 97°47′W). The BCP is a 12,294-ha fragmented preserve situated along the eastern edge of the Edwards Plateau and breeding ranges of both species. The BCP was created to protect habitat for several endangered species and is increasingly surrounded by urban development. The BCP is predominately scrubby or mature juniper and mixed juniper-oak woodland. Scrub-jays and warblers co-occur within the BCP and, additionally, the breeding season of both species overlap, with nest initiation beginning in March and most nesting being completed before or during June (Ladd and Gass, 1999; Curry et al., 2017).

Field Data Collection—We recorded detections of individual scrub-jays detected during surveys for warblers (see Reidy et al., 2016 for details). We conducted surveys at 1,506 points spaced 250 m apart across the BCP from mid-April to mid-May 2011–2014, which coincided with the peak nesting period for scrub-jays (Curry et al., 2017) and warblers (Ladd and Gass, 1999). We surveyed points for 5 min beginning ~10 min post sunrise until ~1100 h central daylight time, when the temperature was >10°C, wind was <19 kph, and there was no, or light, precipitation. We recorded the distance to the initial detection of individual target birds and recorded multiple individuals at a point only if we were confident they were unique individuals (e.g., simultaneous detections) to avoid double-counting. We measured distances directly with a laser range-finder (Bushnell Yardage Pro, Bushnell, Overland Park, Kansas) or estimated distance when dense vegetation or steep topography made direct measurement difficult. Each point was surveyed once by one of eight observers (two per year), each of whom was trained in species identification and distance estimation prior to surveys.

We measured vegetation structure around the point for the patch scale. We recorded the diameter at breast height (DBH) of all living stems >2.5 cm at DBH within an 11.3-m radius of the point using a Biltmore stick. We converted these DBHs to total basal area and to tree density (stems/ha) in three size classes (<10 cm, 10–15 cm, and >15 cm) for junipers, live oaks (*Quercus fusiformis*), and deciduous trees. We chose these tree groups because juniper is a principal feature of central Texas woodlands, is a requisite tree for warbler breeding habitat (Ladd and Gass, 1999), and may be an important food source for scrub-jays (Curry et al., 2017); live oaks are the other dominant evergreen and produce edible mast that may be an important source of forage (Curry et al., 2017); and remaining species such as red oaks (*Quercus buckleyi*) and cedar elms (*Ulmus crassifolia*) may be less attractive to scrub-jays because of a lack of foraging opportunities. We measured average juniper and nonjuniper height in each quadrant with a clinometer and averaged these readings for a single measure of patch-level juniper and nonjuniper height. We estimated canopy cover by averaging the four cover readings from a spherical concave densiometer (one reading facing in each cardinal direction taken from the patch center). We counted live small woody stems (hereafter "shrubs") >10 cm tall and converted these counts to shrub density in three groups: junipers, live oaks, and all others.

We derived habitat covariates from two remotely sensed products for the forest and landscape scales. The Texas Ecological Systems Phase 1 Vegetation Classification (TESP1) provided land cover classification (https://www.tpwd.state.tx.us/landwater/land/maps/gis/tescp/index.phtml), and light detection and ranging imagery provided vegetation height (Hill and Thomson, 2005; Sexton et al., 2009). We intersected the TESP1 and light detection and ranging imagery data layers in ArcMap (ver. 10.0, ESRI, Redlands, California) to create a higher resolution (2 m) and more-current map (2012) of land cover. We categorized land cover as juniper woodland (≥70% of tree canopy is juniper and the mean canopy height is >3 m tall), mixed juniper-oak woodland (<70% of tree canopy is juniper and the mean canopy height is >3 m tall), urban land cover (low and high density), and open land cover (primarily shrubland, canopy <3 m tall; Jensen et al., 2013). We reduced the land cover types to these four categories to simplify the analysis and because these are the dominant habitat types found in and around the BCP. In addition, we were interested in determining if scrub-jays were more abundant in habitat preferred by the warbler. There is no information available on scrub-jays' territory size in this area, so we focused our analysis on the 100-m forest and 1-km landscape scales to enable comparison with results from previous studies on warblers (e.g., Reidy et al., 2017). We calculated the proportion of juniper woodland, mixed woodland, urban land cover, and open land cover within the 100-m and 1-km radius of points. We also calculated the mean and standard deviation of canopy height and open edge density within the 100-m radius around points as measures of successional state. We included the linear and the quadratic form of mean canopy height because we predicted scrub-jays were most abundant in areas of intermediate canopy height. We also included the standard deviation of canopy height as a measure of variation in canopy height. We defined open edge as the interface between all wooded and nonwooded habitat types (excluding urban). We included edge density at the 100-m scale because we predicted scrub-jays responded positively to increasing edge within wooded habitat.

Analysis—We fit hierarchical distance sampling models (Royle et al., 2004) in a four-stage process (described below) to the point count data to predict density and to evaluate the response of density to vegetation and landscape structure at the three spatial scales. We used distance sampling to estimate detection probability based on distances to detected scrub-jays and used Poisson regression to evaluate the effects of supported covariates on density (Buckland et al., 2001; Royle et al., 2004; Fiske and Chandler, 2011). We discarded detections beyond 125 m, which removed the farthest 10% of detections (Buckland et al., 2001), and grouped remaining detections into four unequal distance bins with break points at 38, 65, and 90 m to represent similar numbers of detections in each bin. We standardized continuous covariates prior to analysis (mean = 0, standard deviation = 1).

Our first step was to determine the best fitting key function by comparing support for the hazard-rate, uniform, and half-normal key function. We used the key function with the lowest Akaike information criterion for small sample sizes (AIC_c) to determine which best fit the distance data (Buckland et al., 2001). We then used that key function in subsequent steps. Second, we compared support for 26 detection models comprised of single and 2- and 3-way combinations of the variables of observer, slope, total tree basal area, minutes since sunrise, and day of year, as well as an intercept-only (null) model to determine which variables, if any, affected detectability. We considered observer because it is a well-documented source of variability in detection probability (Alldredge et al., 2007; Farmer et al., 2012; Reidy et al., 2016). We evaluated vegetation and terrain features because these may influence how bird song travels through space (Schiek, 1997; Pacifici et al., 2008; Sillett et al., 2012). We included time of day and day of year because singing rates often vary across these temporal variables (Skirvin, 1981; Kendrick et al., 2013). We included the most-supported detection covariates in the following density models evaluating vegetation and landscape covariates.

Third, we examined density and habitat relationships at three separate spatial scales using an information-theoretic approach (Burnham and Anderson, 2002). We compared support for models representing our a priori hypotheses about vegetation and landscape structure at the three spatial scales influencing scrub-jay density. We assessed multicollinearity between covariates by calculating tolerance values for all variables in the global model using PROC REG (SAS Institute, Cary, North Carolina; Allison, 1999); we found no excessive collinearity (<0.40) among covariates and proceeded with model selection. We examined 14 models at the patch scale composed of single and 2- and 3-way additive combinations of the variables representing tree density by size class (9 variables), canopy cover, juniper and nonjuniper height, and shrub density (3 variables), as well as a null model with the intercept only (Appendix). We examined 13 models at the forest scale comprised of single and additive combinations of the variables juniper woodland cover, mixed woodland cover, open land cover, edge density, mean canopy height, and standard deviation of canopy height, along with a null model that only included the intercept (Appendix). We included the quadratic form of juniper cover in every model except the null because we predicted that, at the forest scale, juniper cover would be the strongest predictor based on scrub-jay habitat associations elsewhere. We then added one or two additional variables to this base model that we predicted to be less influential than juniper woodland. We next evaluated 11 models at the landscape scale comprised of single and 2-way additive combinations of juniper, mixed, open, and urban land cover, as well as a site model (to capture effects otherwise not effectively measured) and the null model with the intercept only (Appendix). For our final step, we compared support for eight models composed of the most-supported variables from each spatial scale as determined in the step above to determine the scale that most influenced scrub-jay density.

We ranked support for models within each spatial scale and the final set comparing scales according to the Akaike weight (w_i; Burnham and Anderson, 2002). We evaluated goodness-of-fit of the most-supported model at each spatial scale with the Freeman-Tukey test based on a parametric bootstrap run for 100 simulations (Fiske and Chandler, 2011; Sillett et al., 2012). We plotted predicted densities from the final spatial scale model set as a function of covariates for which 95% confidence intervals did not overlap 0 by varying the variable of interest across its observed range while holding other covariates at their mean (Shaffer and Thompson, 2007). We fit all models in the R package "unmarked" using the distsamp function (Royle et al., 2004; Fiske and Chandler, 2011; Chandler, 2017).

Results—We surveyed 389, 341, 390, and 386 points and detected 105, 112, 26, and 107 scrub-jays in 2011, 2012, 2013, and 2014 respectively, for a total of 350 scrub-jays at 284 of the 1,506 survey points. Our points spanned a wide range of vegetation structure and landscape composition (Table 1). We detected no scrub-jays or warblers at 718 points, ≥1 scrub-jay and 0 warblers at 204 points, ≥1 warbler and 0 scrub-jays at 504 points, and ≥1 of both species at 80 points. The hazard-rate function was the most supported key function ($w_i = 0.85$) and was used in all subsequent models. The detection process was most influenced by observer (Fig. 1), tree basal area, and slope ($w_i = 0.74$), with detection increasing with decreasing total basal area ($\beta = -0.20$, $SE = 0.04$) and increasing slope ($\beta = 0.09$, $SE = 0.04$). These variables were used in the detection portion of all subsequent models examining density. The effective detection radius was ~94 m and the overall detection probability was 0.57.

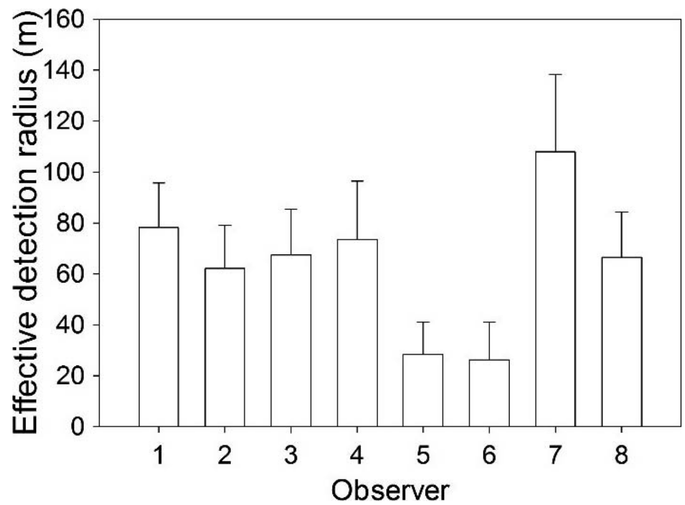

Fig. 1—Effective detection radius by observer for surveys estimating density of Woodhouse's scrub-jays across the Balcones Canyonlands Preserve, Austin, Texas, 2011–2014.

At the patch scale, the most-supported model predicting scrub-jay density included the nine variables representing tree density by species group and size and three variables representing shrub density by species group ($w_i = 0.36$; Appendix). Density of scrub-jays increased from 0.07 (95% CI: 0.06, 0.10) to 0.14 (95% CI: 0.10, 0.22) individuals/ha when density of small juniper trees increased from 0 to 4,075 stems/ha, whereas density decreased from 0.10 (95% CI: 0.08, 0.13) to 0.04 (95% CI: 0.02, 0.08) when density of large deciduous trees increased from 0 to 275 stems/ha and from 0.10 (95% CI: 0.08, 0.13) to 0.04 (95% CI: 0.02, 0.09) individuals/ha when small deciduous trees increased from 0 to 900 stems/ha. Density of scrub-jays increased from 0.08 (95% CI: 0.07, 0.10) to 0.13 (95% CI: 0.09, 0.19) individuals/ha when juniper shrub density increased from 0 to 4,978 stems/ha, but decreased from 0.10 (95% CI: 0.08, 0.13) to 0.04 (95% CI: 0.02, 0.08) individuals/ha when deciduous shrub density increased from 0 to 18,161 stems/ha.

At the forest scale, density of scrub-jays was best

Table 1—Descriptive statistics of survey conditions, vegetation structure, and landscape composition at 1,506 points surveyed for Woodhouse's scrub-jays (*Aphelocoma woodhouseii texana*) at Balcones Canyonlands Preserve in Travis County, Texas, 2011–2014. DBH = diameter at breast height.

Model and variable	Description	Mean	*SD*	Min	Max
Detection					
Day	Day of year	118.5	8.7	97	135
Mins	Minutes since sunrise	117.8	66.4	6	296
Total basal area	Basal area of all live stems	19.8	10.5	0.0	65.3
Slope	Slope in percent	9.8	8.1	0.00	47.00
Density—patch					
Large juniper	Juniper stem density <10 cm DBH	208.65	178.82	0.00	975.00
Medium juniper	Juniper stem density 10–15 cm DBH	356.51	238.74	0.00	1,525.00
Small juniper	Juniper stem density >15 cm DBH	1,204.17	906.17	0.00	5,125.00
Large live oak	Live oak stem density <10 cm DBH	37.93	67.62	0.00	500.00
Medium live oak	Live oak stem density 10–15 cm DBH	25.01	56.78	0.00	700.00
Small live oak	Live oak stem density >15 cm DBH	28.80	70.76	0.00	750.00
Large deciduous	Deciduous stem density <10 cm DBH	38.35	66.57	0.00	475.00
Medium deciduous	Deciduous stem density 10–15 cm DBH	27.59	51.96	0.00	375.00
Small deciduous	Deciduous stem density >15 cm DBH	107.14	200.03	0.00	2,100.00
Juniper shrub	Juniper shrub density	1,076.38	1,364.52	0.00	15,240.00
Live oak shrub	Live oak shrub density	380.07	1,599.69	0.00	37,973.00
Other shrub	Deciduous shrub density	2,412.92	4,233.35	0.00	53,594.00
Canopy cover	Canopy cover	67.02	34.72	0.00	100.00
Juniper height	Mean juniper height around the point	6.21	2.15	0.00	19.00
Nonjuniper height	Mean nonjuniper height around the point	5.38	3.45	0.00	20.57
Density—forest					
Canopy height	Canopy height (m) – 100 m	4.78	1.81	0.00	9.23
Canopy height SD	Canopy height *SD* – 100 m	2.10	0.86	0.00	16.39
Edge	Open edge density (m/ha) – 100 m	109.41	59.39	0.00	267.10
Mixed	Mixed forest cover – 100 m	0.25	0.23	0.00	0.93
Juniper	Juniper forest cover – 100 m	0.44	0.23	0.00	0.99
Open	Open land cover – 100 m	0.33	0.11	0.08	0.70
Density—landscape					
Urban1k	Urban land cover – 1 km	0.30	0.12	0.06	0.77
Mixed1k	Mixed forest cover – 1 km	0.19	0.10	0.05	0.46
Juniper1k	Juniper forest cover – 1 km	0.27	0.07	0.04	0.48
Open1k	Open land cover – 1 km	0.23	0.09	0.06	0.57

predicted by the proportion of juniper woodland and open land cover ($w_i = 0.73$; Appendix). Density of scrub-jays peaked at 0.14 (95% CI: 0.11, 0.17) when juniper cover was ~0.55 of the land cover at the 100-m scale and declined to almost zero when the proportion of juniper woodland was 0.00 or 0.91. Density increased from 0.05 (95% CI: 0.03, 0.06) to 0.25 (95% CI: 0.18, 0.34) as the proportion of open land cover increased from 0.00 to 0.76.

At the landscape scale, the mixed woodland and urban land cover model received overwhelming support ($w_i = 1.00$; Appendix). Density of scrub-jays decreased from 0.20 (95% CI: 0.16, 0.26) to 0.03 (95% CI: 0.02, 0.04) individuals/ha as the proportion of mixed woodland increased from 0.00 to 0.42 and from 0.20 (95% CI: 0.16, 0.26) to 0.02 (95% CI: 0.01, 0.04) individuals/ha as the proportion of urban land cover increased from 0.10 to 0.68.

Among spatial scales, the patch + forest + landscape model received strong support ($w_i = 0.58$) followed by the forest + landscape model ($w_i = 0.37$; Table 2). Predicted scrub-jay density was strongly associated with density of large deciduous trees and shrubs at the patch scale, juniper woodland at the forest scale, and mixed and urban land cover at the landscape scale (Fig. 2; Table 3). The remaining variables showed weaker relationships, with confidence intervals overlapping 0 and P values > 0.05 (Table 3). Overall mean scrub-jay density was 0.08 individuals/ha (95% CI: 0.07, 0.10).

Discussion—We provide the first estimate of Woodhouse's scrub-jay density and habitat associations in central Texas. This species is not considered a species of concern; recent Breeding Bird Survey data showed a slight, but likely negligent, trend of a declining population in the Edwards Plateau region (Sauer et al., 2017).

TABLE 2—Final model support for each spatial scale from the final model selection steps investigating Woodhouse's scrub-jay (*Aphelocoma woodhouseii texana*) density within the Balcones Canyonlands Preserve (BCP), Travis County, central Texas, 2011–2014. Each spatial scale here includes the most-supported variables from a prior step investigating variables within a spatial scale (results shown in the Appendix). The Akaike information criterion (AIC_c) of the most supported model was 2,495.98. These models also include the covariates of observer, tree basal area, and slope estimating the detection process. W_i = Akaike weight.

Model	K	ΔAIC_c	W_i
Patch[a] + forest[b] + landscape[c]	29	0.00	0.58
Forest + landscape	17	0.88	0.37
Patch + forest	27	5.05	0.05
Forest	15	9.51	0.00
Patch + landscape	26	15.20	0.00
Landscape	14	21.96	0.00
Patch	24	54.30	0.00
Null	12	102.71	0.00

[a] Patch model includes the variables densities of large, medium, and small juniper trees (three variables); densities of large, medium, and small live oak trees (three variables); densities of large, medium, and small other tree species (three variables); and shrub densities of juniper, live oak, and other species (three variables).

[b] Forest model (100-m) includes the variables juniper cover, juniper cover^2, open land cover.

[c] Landscape model (1-km) includes the variables mixed land cover and urban land cover.

We were unable to find comparable density estimates for the scrub-jay elsewhere in the breeding range, but the Breeding Bird Survey data suggests that the relative abundance in the Edwards Plateau is similar to that of populations in the Southern Rockies and Colorado Plateau region and the Sierra Madre Occidental (Sauer et al., 2017).

This population was strongly associated with juniper woodland, with density peaking at intermediate proportions at the 100-m forest scale (~0.55) and declining to almost zero across the end ranges of proportion of juniper woodland. Scrub-jays avoided landscapes with greater proportions of mixed juniper-oak woodland and urban land cover, the former coinciding with the negative relationship the species showed with increasing deciduous tree and shrub density at the patch scale. Scrub-jays preferred habitat dominated by young, immature junipers, and density declined significantly with increasing amounts of mature deciduous trees. We did not find direct evidence that scrub-jays were associated with increasing edge density, as suggested by Klassen and Mathewson (2014). However, there was a quadratic relationship with proportion of juniper cover within 100 m that showed densities peaked at intermediate levels of juniper cover. This suggests some heterogeneity in land cover preference at this relatively fine scale, and hence edge, was preferred.

TABLE 3—Parameter estimates, *SE*, 95% confidence intervals (*LCL*, *UCL*), and *P* values (*P*) for variables included in the most supported spatial model (patch + forest + landscape) evaluating habitat associations of Woodhouse's scrub-jays (*Aphelocoma woodhouseii texana*) within the Balcones Canyonlands Preserve (BCP), Travis County, central Texas, 2011–2014. These models also include the covariates of observer, tree basal area, and slope estimating the detection process.

Model and variable	Estimate	*SE*	*LCL*	*UCL*	*P*
Intercept	−2.53	0.10	−2.73	−2.34	
Patch					
Large juniper tree	−0.10	0.09	−0.29	0.07	0.26
Medium juniper tree	−0.06	0.07	−0.20	0.08	0.39
Small juniper tree	0.07	0.06	−0.05	0.19	0.27
Large live oak tree	−0.06	0.07	−0.20	0.08	0.44
Medium live oak tree	0.05	0.06	−0.7	0.18	0.42
Small live oak tree	0.00	0.06	−0.11	0.12	0.90
Large deciduous tree	−0.18	0.09	−0.35	−0.01	0.04
Medium deciduous tree	0.09	0.08	−0.06	0.24	0.23
Small deciduous tree	−0.10	0.10	−0.29	0.09	0.31
Juniper shrub	0.05	0.05	−0.04	0.14	0.29
Live oak shrub	0.03	0.05	−0.06	0.12	0.55
Deciduous shrub	−0.19	0.10	−0.39	0.01	0.06
Forest					
Juniper cover	1.28	0.30	0.70	1.89	<0.001
Juniper^2 cover	−1.17	0.29	−1.73	−0.61	<0.001
Open cover	0.02	0.11	−0.19	0.24	0.82
Landscape					
Mixed woodland cover 1k	−0.33	0.12	−0.56	−0.10	0.005
Urban land cover 1k	−0.31	0.11	−0.51	−0.10	0.003

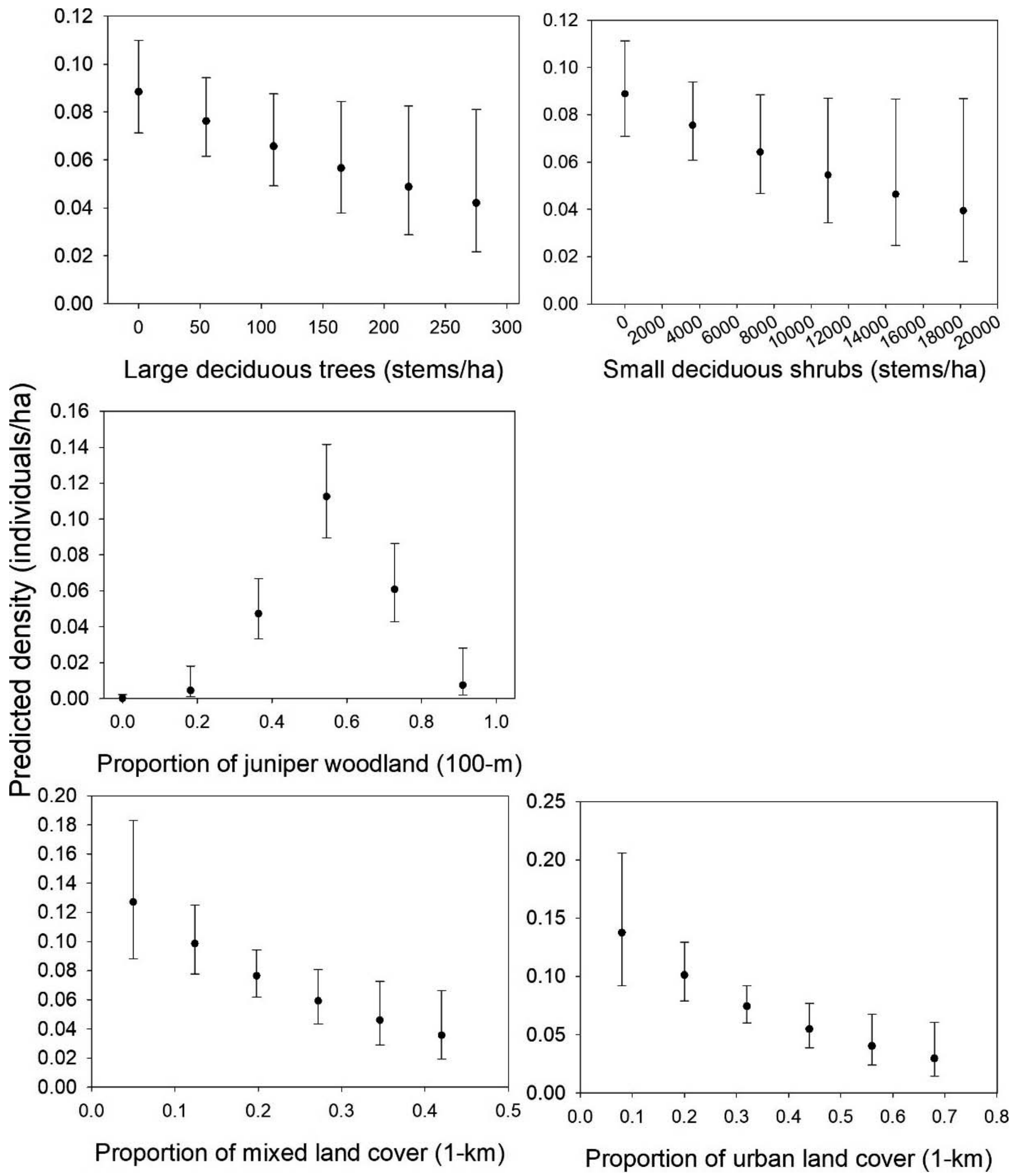

FIG. 2—Predicted density of Woodhouse's scrub-jays (individuals/ha) as a function of predictor variables at the patch scale (top), forest scale (middle), and landscape scale (bottom) from the most supported spatial model across the Balcones Canyonlands Preserve, Austin, Texas, during 2011–2014.

Scrub-jays had strong habitat preferences that did not coincide with the preferred habitat of warblers. Warblers breed in both juniper and mixed woodland, but density is much higher in areas of greater mixed woodland and more-mature trees (Reidy et al., 2016, 2017). Therefore, management and conservation of closed-canopy mature mixed woodlands may reduce predation on warbler nests from scrub-jays. However, other nest predators may be more abundant in mixed woodland and negate the reduced predation risk from scrub-jays. It is unknown if other nest predators such as rat snakes or other predatory bird species show strong preference within woodland types.

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Literature Cited

Alldredge, M. W., T. R. Simons, and K. H. Pollock. 2007. Factors affecting aural detections of songbirds. Ecological Applications 17:948–955.

Allison, P. D. 1999. Logistic regression using SAS®: theory and application. SAS Institute, Cary, North Carolina.

Buckland, S. T., D. R. Anderson, K. P. Burnham, J. L. Laake, D. L. Borchers, and L. Thomas. 2001. Introduction to distance sampling. Oxford University Press, New York.

Burnham, K. P., and D. R. Anderson. 2002. Model selection and multimodel inference: a practical information—theoretic approach. Springer Verlag, New York.

Burt, D. B. 1996. Habitat-use patterns in cooperative and non-cooperative breeding birds: testing predictions with western scrub-jays. Wilson Bulletin 108:712–727.

Chandler, R. 2017. Distance sampling analysis in unmarked. Available at: https://cran.r-project.org/web/packages/unmarked/vignettes/distsamp.pdf. Accessed 5 January 2018.

Curry, R. L., A. T. Peterson, T. A. Langen, P. Pyle, and M. A. Patten. 2017. Woodhouse's scrub-jay (*Aphelocoma woodhouseii*), version 3.0. The birds of North America (P. G. Rodewald, editor). Cornell Lab of Ornithology, Ithaca, New York.

Farmer, R. G., M. L. Leonard, and A. G. Horn. 2012. Observer effects and avian-call-count survey quality: rare-species biases and overconfidence. The Auk 129:76–86.

Fiske, I., and R. B. Chandler. 2011. Unmarked: an R package for fitting hierarchical models of wildlife occurrence and abundance. Journal of Statistical Software 43:1–23.

Hill, R. A., and A. G. Thomson. 2005. Mapping woodland species composition and structure using airborne spectral and LiDAR data. International Journal of Remote Sensing 26:3763–3779.

Jensen, J. L. R., S. Irvin, and A. Duarte. 2013. Lidar-based detection of shrubland and forest land cover to improve identification of golden-cheeked warbler habitat. Papers in Applied Geography 36:74–82.

Kendrick, S. W., F. R. Thompson III, and J. L. Reidy. 2013. Eastern wood-pewee (*Contopus virens*) breeding demography across a gradient of savanna, woodland, and forest in the Missouri Ozarks. The Auk 130:355–363.

Klassen, J. A., and H. A. Mathewson. 2014. Occurrence of western scrub-jays (*Aphelocoma californica*) near forest edges in fragmented golden-cheeked warbler (*Setophaga chrysoparia*) habitat. Southwestern Naturalist 59:399–403.

Klassen, J. A., M. L. Morrison, H. A. Mathewson, G. G. Rosenthal, and R. N. Wilkins. 2012. Canopy characteristics affect reproductive success of golden-cheeked warblers. Wildlife Society Bulletin 36:54–60.

Ladd, C., and L. Gass. 1999. Golden-cheeked warbler (*Dendroica chrysoparia*), version 2. The birds of North America (A. Poole and F. Gill, editors). Cornell Lab of Ornithology, Ithaca, New York.

Pacifici, K., T. R. Simons, and K. H. Pollock. 2008. Effects of vegetation and background noise on the detection process in auditory avian point-count surveys. The Auk 125:600–607.

Peak, R. G. 2007. Forest edges negatively affect golden-cheeked warbler nest survival. Condor 109:628–637.

Peak, R. G., and F. R. Thompson III. 2013. Amount and type of forest cover and edge are important predictors of golden-cheeked warbler density. Condor 115:659–668.

Petyk, J. 2004. Predation of a golden-cheeked warbler nest by a western scrub-jay. Wilson Bulletin 116:269–271.

Reidy, J. L., M. M. Stake, and F. R. Thompson III. 2008. Golden-cheeked warbler nest mortality and predators in urban and rural landscapes. Condor 110:458–466.

Reidy, J. L., F. R. Thompson III, and L. O'Donnell. 2017. Density and nest survival of golden-cheeked warblers: spatial scale matters. The Journal of Wildlife Management 81:678–689.

Reidy, J. L., F. R. Thompson III, and R. G. Peak. 2009. Factors affecting golden-cheeked warbler nest survival in urban and rural landscapes. Journal of Wildlife Management 73:407–413.

Reidy, J. L., F. R. Thompson III, C. Amundson, and L. O'Donnell. 2016. Landscape and local effects on occupancy and densities of an endangered wood-warbler in an urbanizing landscape. Landscape Ecology 31:365–382.

Royle, J. A., D. K. Dawson, and S. Bates. 2004. Modeling abundance effects in distance sampling. Ecology 85:1591–1597.

Sauer, J. R., D. K. Niven, J. E. Hines, D. J. Ziolkowski, Jr, K. L. Pardieck, J. E. Fallon, and W. A. Link. 2017. The North American breeding bird survey, results and analysis 1966–2015. Version 2.07. 2017. USGS Patuxent Wildlife Research Center, Laurel, Maryland.

Schiek, J. 1997. Biased detection of bird vocalizations affects comparisons of bird abundance among forested habitats. Condor 99:179–190.

Sexton, J. O., T. Bax, P. Siqueira, J. J. Swenson, and S. Hensley. 2009. A comparison of lidar, radar, and field measurements of canopy height in pine and hardwood forests of southeastern North America. Forest Ecology and Management 257:1136–1147.

Shaffer, T. L., and F. R. Thompson III. 2007. Making meaningful estimates of nest survival with model-based methods. Studies in Avian Biology 34:84–95.

Sillett, T. S., R. B. Chandler, J. A. Royle, M. Kéry, and S. A. Morrison. 2012. Hierarchical distance-sampling models to estimate population size and habitat-specific abundance of an island endemic. Ecological Applications 22:1997–2006.

Skirvin, A. A. 1981. Effect of time of day and time of season on the number of observations and density estimates of breeding birds. Pages 271–274 in Estimating numbers of terrestrial birds (C. J. Ralph and J. M. Scott, editors). Studies in Avian Biology No. 6. Cooper Ornithological Society.

Sperry, J. H., D. A. Cimprich, R. G. Peak, and P. J. Weatherhead. 2009. Is nest predation on two endangered bird species higher in habitats preferred by snakes? Ecoscience 16:111–118.

Stake, M. M., J. Faaborg, and F. R. Thompson III. 2004. Video identification of predators at golden-cheeked warbler nests. Journal of Field Ornithology 75:337–344.

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Appendix—Model support within each spatial scale investigating Woodhouse's scrub-jay density within the Balcones Canyonlands Preserve (BCP), Travis County, central Texas during 2011–2014. The Akaike information criterion (AIC_c) of the most-supported model was 2,550.28, 2,505.49, and 2,517.95 for the patch, forest, and landscape scales, respectively. These models also include the covariates of observer, tree basal area, and slope estimating the detection process. W_i = Akaike weight.

Model	K	ΔAIC_c	W_i
Patch			
Tree density + shrub density	24	0.00	0.36
Tree density + canopy cover + shrub density	25	0.31	0.31
Tree height + shrub density	19	1.89	0.14
Tree density + tree height + shrub density	28	2.88	0.09
Canopy cover + shrub density	16	4.51	0.04
Tree density + canopy cover	22	4.96	0.03
Tree density + tree height	25	6.68	0.01
Tree density	21	7.69	0.01
Tree density + canopy cover + tree height	26	8.23	0.01
Shrub density	15	12.71	0.00
Canopy cover + tree height	17	19.65	0.00
Tree height	16	21.03	0.00
Canopy cover	13	30.71	0.00
Null	12	48.41	0.00
Forest (100-m)			
Juniper + open	15	0.00	0.73
Juniper + open + canopy height *SD*	16	1.99	0.27
Juniper + open + canopy height	16	10.23	0.00
Juniper + canopy height	15	15.63	0.00
Juniper + edge + canopy height	16	16.30	0.00
Juniper + mixed	15	25.98	0.00
Juniper + mixed + canopy height *SD*	16	27.79	0.00
Juniper + edge	15	34.76	0.00
Juniper + mixed + canopy height	16	36.57	0.00
Juniper + edge + canopy height *SD*	16	36.64	0.00
Juniper	14	47.00	0.00
Juniper + canopy height *SD*	15	49.00	0.00
Null	12	93.20	0.00
Landscape (1-km)			
Mixed1k + urban1k	14	0.00	1.00
Juniper1k + mixed1k	14	27.32	0.00
Juniper1k + open1k	14	34.21	0.00
Mixed1k	13	47.68	0.00
Open1k + urban1k	14	48.41	0.00
Mixed1k + open1k	14	49.56	0.00
Juniper1k + urban1k	14	53.51	0.00
Juniper1k	13	55.14	0.00
Urban1k	13	61.33	0.00
Open1k	13	75.04	0.00
Null	12	80.75	0.00