Landscape Ecol (2014) 29:803–815
DOI 10.1007/s10980-014-0013-3

RESEARCH ARTICLE

Integrating single-species management and landscape conservation using regional habitat occurrence models: the northern goshawk in the Southwest, USA

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Received: 8 October 2013 / Accepted: 28 February 2014 / Published online: 18 March 2014

Abstract Conservation planners and land managers are often confronted with scale-associated challenges when assessing the relationship between land management objectives and species conservation. Conservation of individual species typically involves site-level analyses of habitat, whereas land management focuses on larger spatial extents. New models are needed to more explicitly integrate species-specific conservation with landscape or regional scales. We address this challenge with an example using the northern goshawk (*Accipiter gentilis*), a forest raptor with circumpolar distribution that is the focus of intense debate regarding forest management on public lands in the southwestern USA. To address goshawk-specific habitat conservation across a management area of 22,800-km^2 in northern Arizona, we focused on the territory scale rather than individual nest sites. We compiled a 17-year database of 895 nest sites to estimate territory locations. We then estimated the likelihood of territory occurrence for the entire management area using multiple logistic regression within an expert-driven, spatially balanced, and information-theoretic framework. Our occurrence model incorporated forest structure variables that were derived from USFS Forest Inventory and Analysis plots and high-resolution satellite imagery. Results indicated that high canopy-bulk density, intermediate canopy-base heights, and low variation in tree density were strong predictors of territory occurrence. We used model-averaged parameter estimates for these variables to map and explore patterns of territory distribution across multiple land jurisdictions and ecological subregions. Our iterative modeling approach complements previous demographic studies in the region. It also provides a robust framework for integrating species conservation and landscape management in ongoing and future regional planning efforts.

Keywords *Accipiter gentilis* · Forest management · Multi-model inference · *Pinus ponderosa* · Restoration · Spatial model

Electronic supplementary material The online version of this article (doi:10.1007/s10980-014-0013-3) contains supplementary material, which is available to authorized users.

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Introduction

Stewardship of natural resources is guided in part by the goal of conserving biological diversity while pursuing compatible land uses or management strategies that generate benefits for society (Angermeier 2000). On public lands in the United States, planning for persistence of native species is a requisite component of responsible land management, motivated in part by federal laws and regulations (Noon et al. 2009). Spatially explicit analyses of habitat quality and the viability of indicator or umbrella species (i.e., a single-species focus) are often central components of planning and management (Carroll et al. 2001; Noon et al. 2009). These efforts are, by nature, complex because they address dynamic factors affecting abundance and distribution of organisms over large and often heterogeneous areas. Thus, it seems clear that if analyses of species and habitats are to prove practical in support of planning and management, they must be conducted across broad spatial extents, where many of the drivers of environmental change (e.g., forest restoration) are manifest (Sisk et al. 2005).

Despite rapid advances in methods, outcomes based on species-level analyses and modeling can engender considerable debate and controversy, including administrative appeals and litigation of management actions on public lands (Teich et al. 2004). The northern goshawk (*Accipiter gentilis*; hereafter, goshawk) is illustrative of current conflicts between species conservation and the management of large landscapes (Beck et al. 2011). In the western U.S., the goshawk has become an icon in the debate over retention of large or old-growth trees and dense-canopy conditions (sensu Binkley et al. 2003). The focus on conserving goshawk habitat has slowed management responses to a widely recognized need for active restoration and hazardous fuels reduction in dry-site ponderosa pine (*Pinus ponderosa*) and mixed conifer forests (Allen et al. 2002; Hessburg et al. 2005), because hazardous fuel reduction creates open forest conditions that are believed to conflict with goshawk habitat needs. Ironically, concerns about possible conflicts between restoration and species conservation has resulted in deferral of management actions intended to reduce the likelihood of destructive wildfires that arguably represent the greatest risk to goshawks and other species.

In the southwestern United States, the impact of forest management on goshawks is a contentious subject that continues to slow management decisions across ~9-million ha of U.S. Forest Service (USFS) National Forest System lands (Youtz et al. 2008). The goshawk was designated a sensitive species by the USFS Southwestern Region (Region 3) in 1982. In addition, it is a Management Indicator Species (MIS) for several national forests in the region, largely because of its association with mature ponderosa pine and mixed-conifer vegetation that provide a primary source of commercial timber (Crocker-Bedford 1995; Boyce et al. 2006). These designations require that goshawk populations be monitored in relation to changes in habitat, and consideration of the results is a mandatory element in all management decisions (NFMA Planning Rule 36 CFR 219.19(a)(6)). After designation as an MIS, the goshawk became the subject of forest plan appeals and litigation, resulting in the near cessation of large tree harvest across the USFS Southwest Region. The conflict prompted an unprecedented field study by the USFS Rocky Mountain Research Station that encompassed >20 years, which produced numerous scientific and technical papers, management guidelines, and workshops (Peck 2000). This field study, however, was limited to the Kaibab Plateau and did not address the likelihood of goshawk territories beyond the study area, nor how these territories might be impacted by the change in USFS focus from commercial timber harvest to hazardous fuels reduction over broad spatial extents.

To address the challenge of incorporating the conservation of a single species into broad scale land management, we developed a reproducible spatial modeling framework and applied it to the case of the goshawk in Arizona. In a series of workshops with goshawk experts, we derived statistical models reflecting their knowledge of forest conditions used by goshawks (Andersen et al. 2005; Reynolds et al. 2006) and factors that influence the likelihood of territory occurrence. Our integration of expert opinion, extensive data on nest occurrence, novel environmental datasets, and statistical modeling techniques was designed to complement, not replace, detailed demographic analyses.

In this context, our principal objective was to integrate forest structure and biophysical attributes into a landscape model to predict regional occurrence of a species of conservation concern. Using the goshawk as a case study, our specific technical objectives were to: (1) estimate breeding territories from existing nest location data from across the region and years; (2) develop environmental variables characterizing forest structure and biophysical attributes; (3) confront these data in a formalized, expert-driven process of variable specification and model building within an information-theoretic framework; (4) apply a spatially explicit, statistical approach to estimate the likelihood of territory occurrence at a regional extent; and (5) explore territory occurrence patterns across multiple jurisdictions and ecological subregions at scales relevant to forest planning and management. For the Southwest region, our goal was to produce results that would allow managers to utilize this information in ongoing forest planning and monitoring efforts.

Methods

Study area

Dominant land cover types and vegetation patterns on our 22,800-km^2 study area were characteristic of decades of multiple-use management that included timber harvest, fire suppression, livestock grazing, road construction, and recreation. These management activities are common across the public lands of western North America. The study area encompassed the Kaibab, Coconino, and Apache-Sitgreaves National Forests, two Ranger Districts on the Tonto National Forest, and the North Rim of Grand Canyon National Park in northern Arizona (USA) (Fig. 1). We placed a 5-km buffer around each administrative unit to avoid edge effects introduced by the analysis extent (see below). The area was dominated by ponderosa pine and pine-oak (*Quercus gambelii*) forest at elevations of 1,820–2,500 m, but also included pinyon- (*Pinus edulis*) juniper (*Juniperus scopulorum* or *J. deppeana*) woodlands (1,370–2,280 m), mixed-conifer forest comprised of Douglas-fir (*Pseudotsuga menziesii*), aspen (*Populus tremuloides*), white fir (*Abies concolor*), corkbark fir (*Abies lasiocarpa*), blue spruce (*Picea pungens*), Engelmann spruce (*Picea engelmannii*), and white pine (*Pinus strobiformus*) (2,430–3,050 m), small areas of pure aspen (2,600–3,050 m), and spruce-fir forest (3,050–3,500 m).

Estimation of territories from nest location data

We focused our database development and analyses on the territory, the area exclusively occupied by a pair of goshawks during a breeding season (Reynolds et al. 2005). To estimate territories, we used the initial calculations of Reynolds et al. (2005) on the Kaibab Plateau portion of our total study area. Goshawk breeding pairs occupied all available habitat in this portion of the study area, suggesting habitat was saturated and the distance between breeding pairs could be used to approximate average territory size. Using 435 nest sites detected between 1991 and 2002, Reynolds et al. (2005) calculated each territory centroid as the arithmetic mean of all nests associated with each breeding pair. Territory sizes were represented by a circle with radius half the mean distance between neighboring centroids; 121 territories with a mean territory size of 1,134 ha were delineated (Reynolds et al. 2005). We applied this approach to the remainder of the study area after compiling and verifying a spatial database of 460 additional nest locations from 1991 to 2007 using a geographic information system (GIS; ArcGIS v9.3.a, ESRI, Redlands, CA). We used only previously identified nests for which geographic [i.e., Universal Transverse Mercator (UTM)] coordinates were recorded and $\geq$1 year of data on nest status were available. Approximately half of the territories contained only one known nest site and for these, we treated this location as the territory center.

Variable selection and model development

Because of the contentious context of goshawk ecology and management, we hosted a series of local workshops with goshawk experts and other stakeholders and implemented a formal, structured, and transparent elicitation effort to capture extensive knowledge regarding goshawk biology and conservation. Four individuals (co-authors R.T.R., S.S.R., M.F.I., and C.D.V.) with expertise on goshawk ecology and forest habitat management in the Southwest were tasked with framing models of territory occurrence that emphasized variables likely to be impacted by broad-scale fuel reduction or restoration treatments and fire. We applied their opinion in a standardized approach to compile a set of a priori candidate explanatory variables and models. Initially, we provided each expert with a comprehensive list of 'foundational' variables derived from previous collaborative efforts or from the outcome of our initial workshop (Appendix A in Supplementary material).

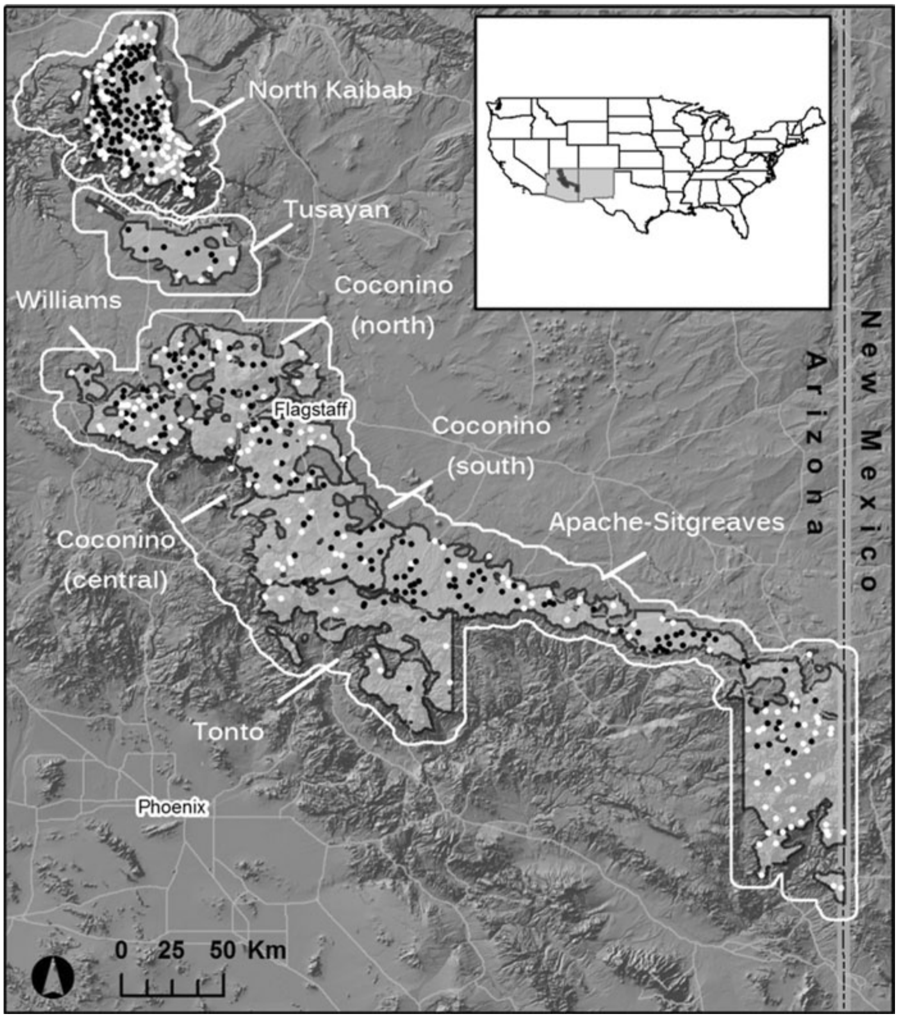

Fig. 1 The 22,800-km^2 study area (*white polygon*) used to model the likelihood of northern goshawk territory occurrence in northern Arizona, USA. *Black* and *white circles* indicate known (1991–2007) territories and ecologically based pseudo-absence locations, respectively. *Grey shaded area* defines the analysis envelope and *black-bounded polygons* encompass the jurisdictional zones

In some cases, experts suggested modifications to these variables, e.g., inclusion of interaction or higher order terms. Experts specified up to 6 candidate models of territory occurrence; each model had $\leq$12 parameters.

Initial input from the experts resulted in multiple possible models of goshawk territory occurrence that were evaluated in a hypothesis-driven framework. Although several models emerged from this effort, we assured participants that this initial suite of models would serve principally to guide further model formulation and would not be published. Rather, this iterative exercise was predicated on collaborative development of a single, more parsimonious 'consensus' model (see methods below).

In response to recommended goshawk-habitat relation models identified above, we derived forest structure and environmental variables from USFS Forest Inventory and Analysis (FIA) plot data, and terrain-corrected and radiometrically calibrated multi-date Landsat Thematic Mapper (TM) imagery (30-m resolution; US Geological Survey EROS Data Center, http://edc.usgs.gov/). We developed variables using images acquired in early September (leaf on) and late October (leaf off) of 2006 to contrast FIA plots and spectral values for areas dominated by coniferous trees or deciduous vegetation. We also mapped the location of large disturbance events (e.g., forest treatments, fire, insect outbreaks) over the course of the study. We used the imagery and 4 additional terrain variables related to biophysical attributes to derive 31 spectral variables (Appendix B in Supplementary material) using the ENVI software package (Version 4.7, ITT Visual Information Solutions, Boulder, CO). We related these spectrally derived (i.e., predictor) variables to 781 spatially referenced FIA plots measured on the study area from 1995 to 2005. These data were "grown forward" to late 2006 conditions for consistency of use with 2006 Landsat using the Central Rockies variant of the Forest Vegetation Simulator (Dixon 2002). To produce continuous map layers of forest structure variables and validate model estimates, we used a Random Forest regression tree approach (Breiman 2001) and the randomForest package in the R statistical environment (R Development Core Team, www.R-project.org).

We used derivatives of the National Elevation Dataset (NED), obtained from the interagency LANDFIRE Project website (www.landfire.gov), to model multiple terrain features, including elevation, slope, and aspect (see Appendix A in Supplementary material). Data and methods used to derive additional foundational variables are provided in Appendix A (Supplementary material).

Within each goshawk territory, we generated descriptive statistics for each environmental variable using a GIS-based moving window analysis with 8-cell nearest neighbors around the focal pixel. We then extracted and related these values to each territory center, and to each of the pseudo-absence locations described below. However, we first standardized and rescaled values for all continuous environmental variables to mean of zero and unit variance prior to model runs. We diagnosed univariate correlations using a simple correlation matrix and multicollinearity among variables using variance inflation factors (VIF; Neter et al. 1996). If necessary, less interpretable variables with VIF > 10.0 or a Pearson's correlation coefficient >0.60 were excluded from analyses.

Likelihood of territory occurrence

Within an information-theoretic modeling framework (Burnham and Anderson 2002), we used multiple logistic regression and a spatially structured approach to estimate the likelihood of territory occurrence in our study area as a function of expert-defined environmental variables. Specifically, we defined territory occurrence as the predicted likelihood that a 1,134-ha circular area was a goshawk territory during the 17-year period of analysis. Because most goshawk surveys on our study area were not designed to confirm absence through repeated surveys, we used a habitat envelope model to constrain randomized placement of ecologically based pseudo-absence (Pearce and Boyce 2006; sensu Zarnetske et al. 2007) locations. Importantly, the use of a habitat envelope allowed us to minimize variability in our pseudo-absence locations that could introduce spurious model outcomes (Zarnetske et al. 2007). We used an equal ratio of presence and pseudo-absence locations. We used 30-m resolution data on existing vegetation obtained from LANDFIRE (rapid refresh) to compute the proportion of forest (ponderosa pine, mixed conifer) or woodland (pinyon-juniper) pixels within a 1,900-m radius of all territory centers, and used the minimum value to specify our analysis area (i.e., envelope). Because goshawks establish territories and nest in areas of woodland-dominated vegetation (Reynolds et al. 2006), we included areas with at least this minimum value in our modeling efforts. Moreover, because different management jurisdictions (e.g., USFS Ranger Districts or National Park Service management units) often used different survey protocols, we selected a number of pseudo-absence locations equal to the number of known territories in each of several jurisdictions (hereafter, jurisdictional zones; Fig. 1). We prevented our algorithm from placing pseudo-absence locations within a known territory, or within vegetation types that were altered by large-scale disturbance events (e.g., forest treatments, fire, beetle kill) that occurred from 1991 to 2007.

To account for any residual spatial autocorrelation in the presence-absence data, we used the empirical Huber–White "sandwich" estimator, which relaxed assumptions of independence between locations and known covariance structure (Williams 2000; Wooldridge 2009). We accounted for additional spatial structure using trend surface analysis of UTM coordinates (Legendre and Legendre 1998). We used Moran's I statistic to evaluate clustering in Pearson residuals (Haining 2003). To account for higher goshawk density and survey effort on the North Kaibab Ranger District and Grand Canyon National Park-North Rim (Reynolds et al. 2005), as well as differences in management history and environmental conditions, we distinguished the Kaibab Plateau from the rest of the study area using a binary fixed effect.

We used Akaike's Information Criterion (AIC; Burnham and Anderson 2002) and AIC difference (ΔAIC) values to compare our final consensus model to an intercept-only (i.e., null) model. We considered a final model with a ΔAIC > 10.0 units lower than the null model as one that fit and approximated the data well (Anderson 2008). We used multi-model inference and model-averaging techniques to rank and evaluate the relative importance of expert-specified environmental variables, given all possible models (i.e., all possible variable combinations; Burnham and Anderson 2002). Since all variables were assumed to be drivers of territory occurrence, all (plus spatial trend terms) were included in the final consensus model. For this model, we computed AIC weights as the weight of evidence in favor of each variable (Burnham and Anderson 2002). We summed AIC weights across all possible models in which a given variable (*j*) occurred and considered a cumulative AIC weight ($w_+(j)$) ≥ 0.50 to be strong evidence (Barbieri and Berger 2004) for a response of goshawks to that variable. We implemented all analyses using the GLIMMIX procedure in SAS (v9.2; SAS Institute, Cary, NC, USA).

Because we had a large sample size and AIC is asymptotically equivalent to common cross-validation and bootstrap techniques (Shtatland et al. 2004), we used AIC in all steps of model building and assessment. To evaluate model classification accuracy, we computed the area under the receiver operating characteristic (ROC) curve (Hosmer and Lemeshow 2000). This ROC value provided a likelihood-based measure of discrimination between predicted presences and absences. We considered ROC values > 0.70 as indicative of acceptable discrimination (Hosmer and Lemeshow 2000).

We used model-averaged parameter estimates to produce a continuous, spatially explicit model (i.e., surface) describing the likelihood of goshawk occurrence at the territory scale, then clipped this surface to the extent of our habitat envelope. We implemented this surface in the GIS and used a 10-quantile classification of pixel (i.e., occurrence) values for inference at the study area and jurisdictional zone levels.

Results

Territory and nest location data

Our spatial database consisted of 272 estimated territories that were derived from 895 nest sites (Table 1). Among jurisdictional zones, the Kaibab Plateau accounted for nearly half ($n = 112$) of the territory locations used in our models.

Specification of environmental variables and a consensus model

Initial input from the experts generated 11 candidate models of goshawk territory occurrence that were evaluated in an information-theoretic framework. Through the workshop process and subsequent discussions of intermediate results, experts agreed on a final consensus model of territory occurrence conditioned on 6 environmental parameters, including

Table 1 Descriptive statistics (mean of means and standard deviation [in parentheses]) for forest structure variables at known (presence) and pseudo-absence (absence) northern goshawk territory locations in each of 8 jurisdictional zones in northern Arizona, USA, 1991–2007

Jurisdic. zone	Area (km^2)	No. territories	Presence			Absence		
			CBD	CBH	TPH	CBD	CBH	TPH
Kaibab Plateau	2,252	112	0.051 (0.020)	11.4 (4.1)	1496.4 (631.3)	0.037 (0.020)	8.5 (4.0)	1300.0 (792.6)
Tusayan	954	7	0.033 (0.009)	10.9 (3.8)	1037.1 (395.8)	0.018 (0.010)	5.8 (3.3)	570.3 (370.9)
Williams	1,673	33	0.040 (0.018)	12.1 (4.4)	1317.8 (635.8)	0.035 (0.017)	10.9 (4.6)	1258.4 (680.4)
Coconino (north)	1,708	12	0.054 (0.021)	12.7 (3.7)	1374.4 (554.3)	0.034 (0.020)	10.3 (5.3)	1027.0 (637.4)
Coconino (central)	1,194	17	0.051 (0.018)	13.6 (3.9)	1537.5 (660.9)	0.036 (0.016)	11.0 (4.0)	1276.7 (675.3)
Coconino (south)	2,393	17	0.049 (0.016)	13.7 (3.9)	1543.1 (608.8)	0.035 (0.015)	11.1 (4.2)	1291.9 (676.7)
Tonto	2,580	7	0.032 (0.013)	13.2 (3.0)	1946.4 (722.3)	0.013 (0.008)	8.8 (4.2)	1048.7 (662.0)
Apache-Sitgreaves	6,391	67	0.054 (0.018)	12.7 (3.7)	1539.7 (625.6)	0.036 (0.017)	10.1 (3.9)	1386.3 (729.0)
Global mean:		34 (37.2)	0.046 (0.017)	12.5 (3.8)	1474.0 (604.7)	0.031 (0.015)	9.6 (4.2)	1144.9 (653.3)

CBD canopy bulk density (kg/m^3), *CBH* canopy-base height (m), *TPH* trees per hectare. Variable descriptions are provided in Appendix A (Supplementary material) average canopy bulk density (linear form), average canopy-base height (linear and convex quadratic forms), variation (i.e., standard deviation) in tree density (linear form), northeastern aspect (transformed, linear form), and Kaibab Plateau (binary, continuous linear form). Canopy bulk density is a fuels metric (see Appendix A in Supplementary material) that also provides information about canopy structure and therefore could influence territory occurrence.

Likelihood of territory occurrence

Our 19,145-km^2 analysis envelope only included those pixels where existing forest or woodland vegetation types comprised ≥65 % of the surrounding 1,134-ha circular area. Within this envelope, our randomization algorithm resulted in spatially balanced placement of 272 pseudo-absence locations across the 8 jurisdictional zones (Table 1).

The model that best predicted goshawk territory occurrences included 11 environmental and spatial trend variables (Table 2) and was >205 AIC units better (i.e., lower) than the null model, indicating an excellent approximation of the data. The ROC value for this model was 0.84, indicating an acceptable level of discrimination. We did not detect spatial clustering among territory centers on the Kaibab Plateau (Moran's $I = 0.01$, Z-score $= 0.58$), nor across the remainder of the study area (Moran's $I = -0.02$, Z-score $= -0.77$).

All forest structure variables were strong predictors of territory occurrence (Table 2). The quadratic form of mean canopy-base height was strongest among them ($w_+(j) = 0.998$), followed by a negative relationship with variation in mean tree density (0.995) and a positive relationship with average canopy bulk density (0.721). The tendency of territories to be positioned on northeastern aspects was a strong predictor as well (0.997). The Kaibab Plateau was not an overly influential predictor of territory occurrence (0.547). We observed little broad-scale spatial trend in territory occurrence when (1) environmental covariates were considered simultaneously and (2) after accounting for any local-scale spatial structuring in the data. Estimated response functions suggested that high likelihoods of territory occurrence were predicted by each individual environmental variable in our model (Fig. 2).

Based on our spatially explicit model, estimates of territory occurrence across the study area ranged between 0.00 and 0.97 (mean = 0.40, SD = 0.29; Fig. 3). Typically, woodland-dominated areas near the perimeter of our habitat envelope model were characterized by a relatively low (<0.25) likelihood of occurrence. Mean likelihood of occurrence was highest (0.56, SD = 0.26) in the Peaks District of the Coconino National Forest (north) and lowest (0.18, SD = 0.17) in the Tonto National Forest (Fig. 4). Relative to other zones, the Tusayan (0.23) and North Kaibab (0.17) Ranger Districts in the Kaibab National Forest and the central zone of the Coconino National Forest (0.19) had the largest proportion of occurrence values in the upper quantile of the predicted distribution.

Table 2 Model-averaged regression coefficients ($\tilde{\bar{\beta}}$), unconditional standard errors (SE), and cumulative AIC (Akaike's Information Criterion) weights ($w_+(j)$) for environmental variables and trend surface terms used in a final model of northern goshawk territory occurrence in northern Arizona, 1991–2007

Environmental variable	$\tilde{\bar{\beta}}$	SE	$w_+(j)$
Canopy-base height (m)	4.533	0.811	1.000
Canopy-base height^2	−1.511	0.396	0.998
Northeast	0.632	0.174	0.997
Tree density (SD)	−0.811	0.255	0.995
Canopy bulk density (m)	0.307	0.267	0.721
Kaibab Plateau	−0.642	0.883	0.547
Longitude	0.258	0.464	0.521
Latitude	0.785	0.649	0.864
Longitude^2	−0.109	0.264	0.375
Latitude^2	0.033	0.196	0.326
Longitude × Latitude	−0.026	0.363	0.332

All estimates based on standardization and rescaling of continuous variables prior to analysis. Mean (m) and standard deviation (SD) next to variable names indicates variable statistic used. Squared term represents quadratic form of variable used for inference. Variable descriptions are provided in Appendix A (Supplementary material)

Discussion

In our study region, conservation of goshawks and management of their habitat plays a central role in USFS efforts to restore ecological integrity in southwestern ponderosa pine forests, often generating controversy as well as appeals or litigation (Ray 2011). Despite considerable investment in research

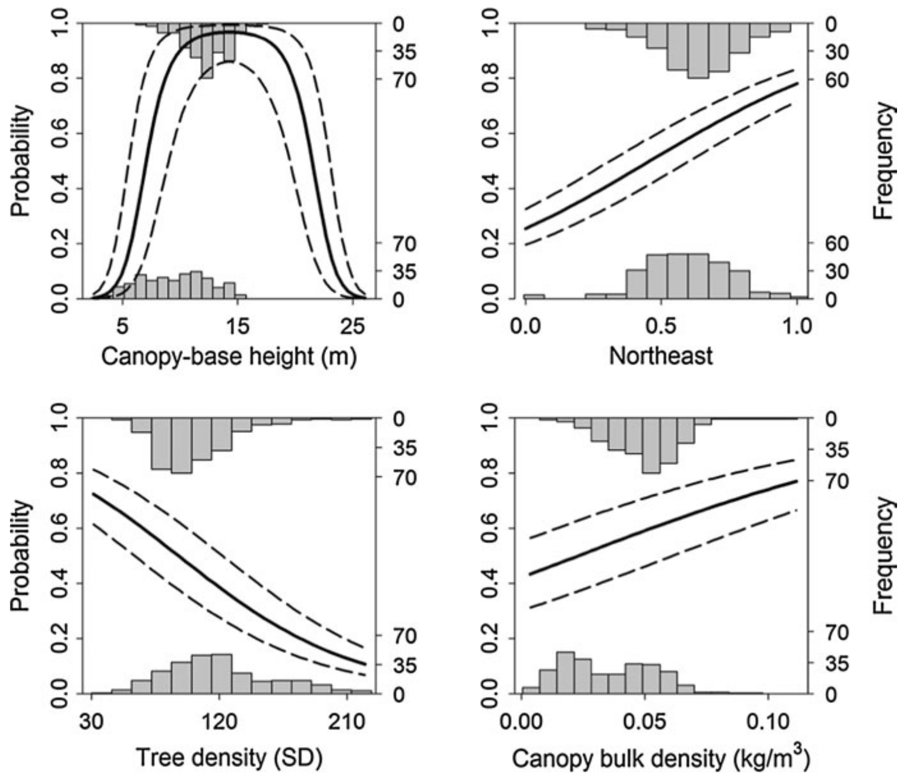

Fig. 2 Response functions for each continuous environmental (i.e., habitat) predictor variable included in final consensus model of northern goshawk territory occurrence in northern Arizona, USA, 1991–2007. Histogram on *top* and *bottom* of each panel represent frequency distributions of variable at territory presence and pseudo-absence locations, respectively

and attention, scientific consensus has been elusive, and conflicting interpretations of habitat requirements have led to ongoing debate and management uncertainty (Greenwald et al. 2005; Beier et al. 2008; Reynolds et al. 2008). Our quantitative and structured approach drawing on shared spatial data, opinion, and deliberation produced new inference that complements existing information on goshawk-habitat relationships. Rather than seeking a purely analytical result based on current data, we sought consensus on a parsimonious and practical model (i.e., hypothesis) that was likely to be robust to continuing debate and amenable to continuing improvement in the face of new monitoring and research.

For drawing management-relevant inference across landscapes for a wide-ranging species, our territory-scale approach provided a seamless assessment of goshawk territory distribution across an extensive study area. By ‘smoothing’ fine-scale habitat heterogeneity, we likely missed some conditions (e.g., relatively small clumps or groups of trees) that may influence goshawks at nest site or nest-area scales. Most species, including the goshawk, likely perceive and interact with their environment at multiple spatial scales (McGrath et al. 2003). However, a long-term study on the North Kaibab and adjacent portion of Grand Canyon National Park by Reynolds and Joy (2006) found that territories were relatively static over time, while nest sites varied, typically placed within the central portion of a territory. This pattern suggests that understanding forest structural attributes at the territory scale may lend important insight to questions about overall habitat quality and management (Klaver et al. 2012).

Forest structure variables in our consensus model were strong predictors of territory occurrence and represented both vertical and horizontal characteristics of forest structure. The convex quadratic (i.e., hump-shaped) form of average canopy-base height was the strongest predictor, suggesting that intermediate values (typically, 10–14 m) of this variable were more characteristic of known territories than were values from the pseudo-absence locations. Previous studies (Reynolds et al. 1992, 2006; McGrath et al. 2003; Boal et al. 2005) identified the importance of lifted crowns for goshawk nesting and foraging in mid-aged to old forests. Lifted crowns offer unobstructed foraging opportunities and foster development of an herbaceous

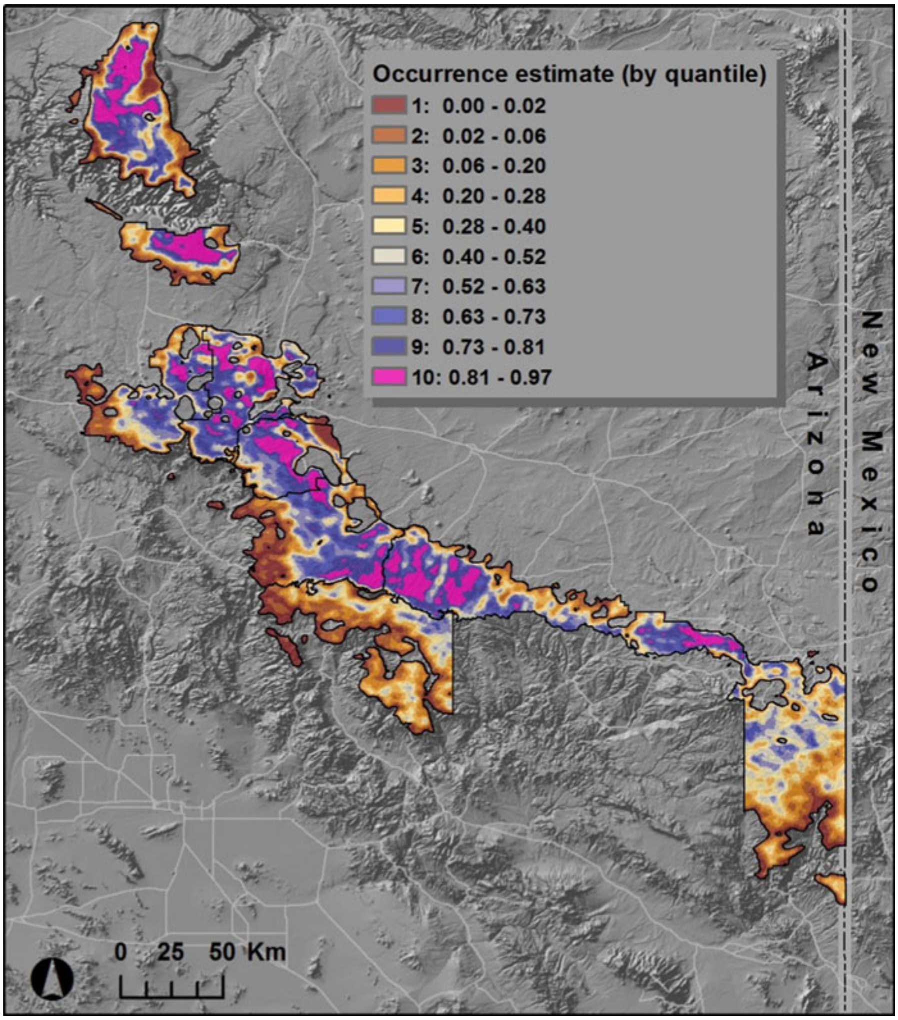

Fig. 3 Spatially explicit model of likelihood of territory occurrence for northern goshawk in northern Arizona, USA, 1991–2007. *Black-bounded* polygons correspond to the 8 jurisdictional zones identified in Fig. 1

understory, improving habitat quality for some prey species (i.e., rabbits, ground squirrels) (Reynolds et al. 1992, 2006). Territories with average canopy-base heights >14 m may represent the point at which the value of unobstructed foraging conditions is outweighed by conditions that are too open.

Goshawk territories in our study were characterized by higher values for canopy bulk density. Other studies (Penteriani et al. 2001; Finn et al. 2002) also have reported higher canopy volume or depth in goshawk nest areas compared to surrounding areas. When coupled with our result for canopy-base height, it seems reasonable to suggest that higher canopy bulk density values were not associated with trees with low canopy-base heights, such as small-diameter 'pole-size' trees or species with low-hanging live branches (e.g., pinyon, juniper). Rather, higher canopy bulk densities likely occurred in areas characterized by an abundance of larger trees interspersed with dense groups of younger trees. High canopy bulk density provides protected environments for goshawk nests and is a proxy measure of habitat available to several arboreal prey species (i.e., tree squirrels, foliage and bark-gleaning birds) (Reynolds et al. 1992, 2006).

We found a relatively strong negative relationship between goshawk territory occurrence and variability in tree density, suggesting that territories were established in areas with more contiguous forest structure. However, our derived density variable did not discriminate among tree species and was too coarse to identify finer-scale characteristics of forest structure (e.g., small groups or clumps of trees at the sub-hectare scale) considered important to goshawks and their prey. Higher occurrence of goshawk territories in

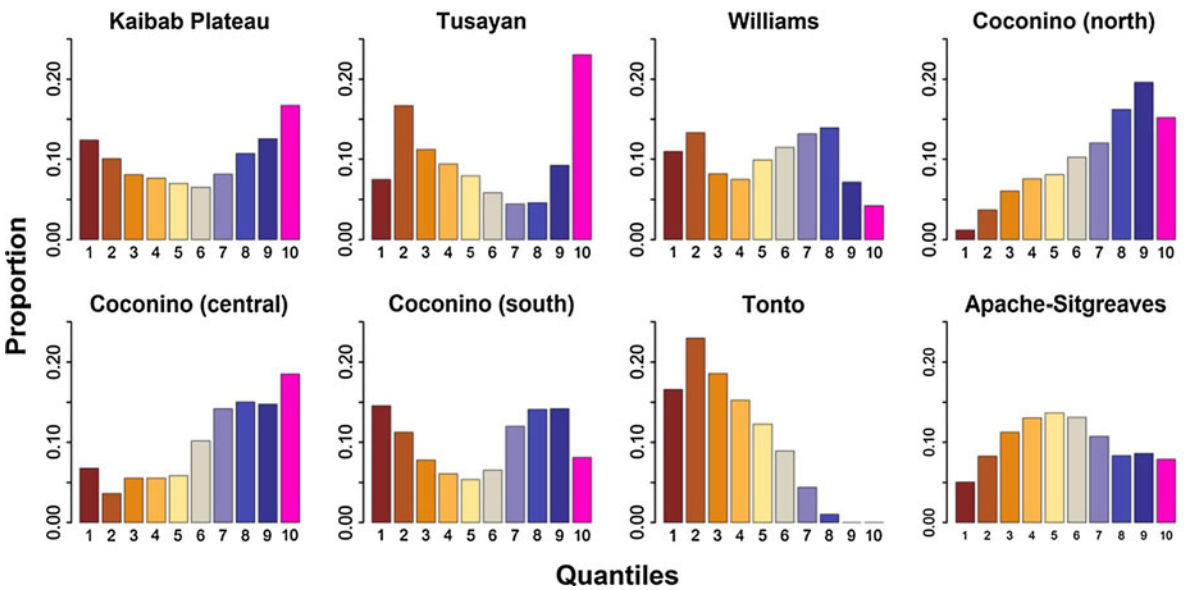

Fig. 4 Proportional distribution (10 quantiles) of goshawk territory occurrence values in each of 8 jurisdictional zones in northern Arizona, USA, 1991–2007. The distributions for each zone are based on the final territory occurrence model and associated environmental variables presented in Table 2

areas characterized by more contiguous forest may reduce competition with other forest raptors [e.g., red-tailed hawks (*Buteo jamaicensis*)] associated with open forest conditions (Crannell and DeStefano 1992; La Sorte et al. 2004).

Considering our results for canopy-base height and canopy bulk density, and compared to pseudo-absence locations, areas with higher predicted occurrence of territories likely included forests comprised primarily of mid-aged to old trees. This forest condition also is consistent with the hypothesis that goshawk behavior (i.e., short-flight hunting tactic) and morphology (i.e., relatively short wings and long tail) are adapted to hunting in moderately dense, mature forest stands that allow unobstructed flight beneath the canopy (Reynolds et al. 1992; Reynolds et al. 2006; Beier and Drennan 1997). Territory occurrence and reproduction in the Southwest appear strongly related to prey abundance (Salafsky et al. 2005); therefore, the occurrence of territories is likely to be related to the amount and interspersion of these forest conditions.

The tendency of goshawk territories in our study area to favor northeastern exposures also was consistent with previous observations of the species. Carroll et al. (2006), and syntheses by McGrath et al. (2003) and Penteriani (2002), indicated that nest sites or areas typically were positioned on north or northeast aspects. In the high-elevation conifer forests of northern Arizona, these aspects provide the cool, mesic conditions under which plant productivity and diversity are highest (White and Vankat 1993). These conditions also provide important forage for many of the prey species that occur in a goshawk home range (Reynolds et al. 1992).

By modeling conditions for an extensive study area in a single analysis, we present a 'level playing field' of inference across jurisdictions that can inform allocation of limited research or management resources (Carroll et al. 2006; Beck et al. 2011). For example, relatively high likelihood of territories on the Tusayan Ranger District was unexpected, partly because little monitoring has been conducted on goshawks in this area. Our model predictions easily could be summarized according to jurisdictional boundaries, planning units, or other subareas of interest to planners and decision makers. Similarly, estimates of territory occurrence could be related to other habitat or forest structure attributes (e.g., canopy cover and basal area) which are more familiar to managers, improving their ability to inform planning efforts.

In addition to inference about habitat associations and species' distribution, our consensus model of territory occurrence presents a contemporary example and opportunity for evaluating forest restoration and management alternatives in a model- and scenario-based framework. For example, Ray (2014) used the model to explore how alternative approaches on the Kaibab Plateau might affect goshawk territory distribution. Proposed restoration approaches were used to project changes in forest structure across the digital landscape by altering the covariates used in our model, and then re-implementing the goshawk territory occurrence model on the resulting 'post-treatment' landscape. Initial applications of this approach have been promising, with estimates of goshawk territory occurrence articulating tradeoffs between forest restoration alternatives and consequences of large crown fire events (Ray 2014).

Conclusions

Our spatially extensive model of goshawk territories provides timely insight into perceived conflicts between species' habitat management and forest restoration, and how such conflicts might be minimized. Ponderosa pine forest restoration in the Southwest typically is aimed at reducing tree density and promoting the growth of large trees (Allen et al. 2002). The association of goshawk territories with intermediate values of canopy-base height in these forests suggests minimal conflict with restoration thinning practices that remove mostly younger trees with lower canopy-base height. Likewise, thinning activities are likely to increase canopy bulk density by removing trees with less canopy bulk and providing a growing environment conducive to canopy development for the remaining overstory. However, more intensive thinning prescriptions that result in large, long-term reductions in canopy bulk density could result in reduced likelihood of goshawk territories. Forest management in goshawk habitat should consider the scale of habitat selection for goshawks (Klaver et al. 2012). In other words, at the scale of nest site selection, forest management should favor the retention of trees that contribute disproportionately to higher levels of canopy biomass, while at the scale of territory selection, forest management should facilitate or mimic the effects of low-intensity understory surface fires typical of dry-site western pine forests. Moreover, forest management should promote higher values of canopy bulk density on north-eastern slopes where there is a higher likelihood of nest site selection.

As land and resource managers address the challenges of species-level assessment, habitat conservation planning, and monitoring of large landscapes, models like those we developed can integrate expert opinion and combine new or existing data sets to yield management-relevant inferences about forest and species' habitat conditions. Our current results are contributing to forest plan revisions and other large-scale forest management planning efforts in the Southwest, including the Four Forests Restoration Initiative (www.4fri.org) and the Kaibab Forest Health Focus (Sisk et al. 2009). On the Kaibab National Forest, the model also is being used to help identify areas of goshawk habitat and develop a comprehensive field sampling effort for broad-scale monitoring that is both efficient and statistically robust.

Our case study of the goshawk and forest management is far from unique. Similar conflicts between species conservation and landscape management objectives are evident across USFS lands and throughout the world. New models and technical advances alone will not solve this problem. Rather, analytical approaches that utilize species-level data to draw broad-scale inference are likely to improve the ability of planners to resolve perceived conflicts and identify management actions that can simultaneously achieve multiple conservation objectives.

Acknowledgments We thank biologists with the Kaibab, Coconino, Apache-Sitgreaves, and Tonto National Forests for providing historical goshawk location data. Funding was provided by the U.S. Forest Service, the Northern Arizona University Ecological Restoration Institute, The Grand Canyon Trust, and Northern Arizona University. C. Ray and two anonymous reviewers provided valuable comments on earlier drafts of this work.

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