Research Article

Habitat-Suitability Models for Cavity-Nesting Birds in a Postfire Landscape

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ABSTRACT Models of habitat suitability in postfire landscapes are needed by land managers to make timely decisions regarding postfire timber harvest and other management activities. Many species of cavity-nesting birds are dependent on postfire landscapes for breeding and other aspects of their life history and are responsive to postfire management activities (e.g., timber harvest). In addition, several cavity nesters are designated as species at risk. We compare the ability of 2 types of models to distinguish between nest and non-nest locations of 6 cavity-nesting bird species (Lewis's woodpecker [*Melanerpes lewis*], black-backed woodpecker [*Picoides arcticus*], hairy woodpecker [*P. villosus*], northern flicker [*Colaptes auratus*], western bluebird [*Sialia mexicana*], and mountain bluebird [*S. currucoides*]) in the early postfire years for a ponderosa pine (*Pinus ponderosa*) forest in Idaho, USA. The 2 model sets consisted of 1) models based on readily available remotely sensed data and 2) models containing field-collected data in addition to remotely sensed data (combination models). We evaluated models of nesting habitat by quantifying the model's ability to correctly identify nest and non-nest locations and by determining the percentage of correctly identified nest locations. Additionally, we developed relative habitat-suitability maps for nesting habitat of black-backed and Lewis's woodpeckers from the best models. For all species except Lewis's woodpeckers, model performance improved with the addition of field-collected data. Models containing remotely sensed data adequately distinguished between nest and non-nest locations for black-backed woodpecker and Lewis's woodpecker only, whereas models containing both field-collected and remotely sensed data were adequate for all 6 species. Improvements in the availability of more accurate remote sensing technology would likely lead to improvements in the ability of the models to predict nesting locations. External validation with data from other wildfires is necessary to confirm the general applicability of our habitat-suitability models to other forests. Land managers responsible for maintaining habitat for cavity-nesting birds in postfire landscapes can use these models to identify potential nesting areas for these species and select areas in burned forests where postfire salvage logging is most likely to have minimal impacts on cavity-nesting bird habitats. (JOURNAL OF WILDLIFE MANAGEMENT 71(8):2600–2611; 2007)

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Fire is a natural component of coniferous forests in the western United States. Human activities such as livestock grazing, urban development in fire-prone areas, fire suppression, and global climate change have contributed to an increase in the intensity and frequency of wildfire in recent years (Beschta et al. 1995, Dombeck et al. 2004, Kauffman 2004). Recent legislation regarding postfire management policy (i.e., National Fire Plan [United States Department of Agriculture (USDA) 2000], Healthy Forest Restoration Act [USDA 2003], Healthy Forest Initiative [White House 2004]) focuses planning efforts on postfire salvage logging and fuels reduction projects. Currently, national forests are operating under the 1982 planning rule, which requires forests to provide habitat to maintain the viability of fish and wildlife populations (Federal Register 1982). New planning rules (Noon et al. 2005), when implemented, might modify existing regulations but will still require national forests to "provide for ecological conditions to support a diversity of native plant and animal species in the plan area" (Federal Register 2005:1047).

Many cavity-nesting birds are reliant on postfire forests for nesting and foraging (Bock et al. 1978, Raphael and White 1984, Hutto 1995, Haggard and Gaines 2001, Saab et al. 2004), and therefore these species are likely to be affected by postfire management activities (i.e., salvage logging). Land managers required to implement postfire management policies and concurrently meet the requirements of existing laws to maintain habitat for wildlife species associated with postfire habitats face significant challenges. Postfire management policies on public lands, and in particular, salvage logging (postfire timber harvest of dead or dying trees), are often at the center of legal controversies regarding postfire management decisions. Litigation over salvage logging often reflects the United States Forest Service's (USFS) struggles to demonstrate in a legally defensible manner that habitat is being maintained for sensitive species such as Lewis's woodpeckers (*Melanerpes lewis*) and black-backed woodpeckers (*Picoides arcticus*; USFS 2004*a*, *b*). These challenges are often the consequence of a lack of scientific planning tools available to land managers.

Previous researchers have recognized the importance of individual tree characteristics, such as diameter at breast height and densities of snags surrounding a tree, to cavity-nesting birds (Mannan et al. 1980, Schreiber and deCalesta 1992, Chambers et al. 1997, Saab et al. 2004). However, coarse-scale data are often more easily obtained from remote sensing maps than are fine-scale data collected in the field. Additionally, previous studies indicated that coarse-scale variables such as patch area, cover type, and prefire crown

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closure may be strongly associated with nest locations of cavity-nesting birds (Saab et al. 2002).

Developing predictive models that are accurate and incorporate data that are readily available to land managers is important for providing useful conservation tools (Stauffer 2002). Due to the likelihood of increased frequency, severity, and size of fires in the future as a consequence of global climate change and continued human landscape modifications (McKenzie et al. 2003, Pierce et al. 2004, Westerling et al. 2006), it is important to set achievable and appropriate goals for postfire management of public lands. We sought to quantify the difference in predictive ability between models containing data that are more expensive to obtain versus less costly data to provide land managers with efficient methods for identifying suitable habitat for 6 species of cavity-nesting birds (Lewis's woodpecker, black-backed woodpecker, hairy woodpecker [*P. villosus*], northern flicker [*Colaptes auratus*], western bluebird [*Sialia mexicana*], and mountain bluebird [*S. currucoides*]). We compared the ability of models containing remotely sensed data only versus models containing field-collected data in addition to remotely sensed data to identify potential nesting habitat of cavity-nesting birds in postfire landscapes.

STUDY AREA

The Star Gulch burn (12,467 ha) was created by a patchy, moderate-severity fire in August 1994 in western Idaho, USA (43°35′N, 115°42′W). Our study sites within this burned area were unlogged. Elevation ranged from 1,130 m to 2,300 m. Ponderosa pine (*Pinus ponderosa*) and Douglas-fir (*Pseudotsuga menziesii*) were the most common snag species in the burned area. Shrubs common in the understory and in forest openings included sagebrush (*Artemisia tridentada*), ninebark (*Physocarpus malvaceus*), and ceanothus (*Ceanothus velutinus*; Johnson et al. 2000, Saab et al. 2004).

METHODS

Data Collection and Classification

We surveyed in our unlogged study sites within the Star Gulch burn for occupied nest cavities using 21 rectangular (belt) transects each approximately 1.0 km long and 0.4 km wide (Dudley and Saab 2003). We surveyed for nests of the 6 bird species during May through June of 1995–1998. The area surveyed annually averaged 832 $\pm$ 67 ha (SE; Saab et al. 2007). We confirmed nest occupancy by monitoring nests on repeat visits.

We collected field data on the snag diameters and densities at all nest locations and 29 randomly selected non-nest locations after we completed nest surveys, from late July to mid-September of 1995–1998. We recorded the number and diameter of each snag and tree $>$1.37 m in height in a 0.04-ha circular plot surrounding the nest tree or central point of a random plot. We surveyed non-nest locations annually to confirm the absence of nesting birds and to remeasure vegetation variables.

Additionally, we identified locations based on remotely sensed data that included prefire crown closure, burn severity, and cover type (methods detailed in Russell et al. 2006). We classified vegetation and burn severity using Landsat Thematic Mapper™ (Earth Resources Observation and Science, United States Geological Survey, Sioux Falls, SD) images representing pre- and postfire conditions. To take into account errors in remote sensing classification, we averaged burn severity, cover type, and prefire crown closure maps using a 3 $\times$ 3-pixel window, in which we assigned the center pixel the value of the most frequently occurring class (Booth and Oldfield 1989). We calculated burn severity as the change in the normalized burn ratio (ΔNBR) between pre- and postfire conditions (Cocke et al. 2005, Key and Benson 2006). In the Star Gulch wildfire, the ΔNBR for 10,582 pixels averaged 364 and ranged from unburned (−448) to high severity (1,106).

We used aerial photographs (1:16,000) from July 1988 and August 1996 to improve accuracy and assist in the classification of prefire crown closure and cover type (Johnson et al. 2000, Saab et al. 2002). Prefire crown-closure categories were 1) $<$40% (low), 2) $>$40–70% (moderate), and 3) $>$70% (high). Cover type categories were 1) ponderosa pine, 2) mixed conifer (mainly Douglas-fir), and 3) mesic (mountain shrubs and riparian).

We used landscape-level remotely sensed data to quantify prefire crown closure within a 1-km radius around plot centers. This area corresponded to the home-range sizes of most cavity-nesting birds that depend on snags for foraging and nesting (Saab et al. 2004). We calculated the percentage of 30 $\times$ 30-m pixels within a 1-km radius of the focal location (either the nest location or the center of the randomly selected plot) classified as each of the 3 prefire crown closure categories using the Spatial Analyst extension of ArcMap software. We calculated prefire patch area by determining the contiguous area of any conifer cover type (mixed or ponderosa) that incorporated the plot.

Statistical Analyses

We modeled nest versus non-nest locations as a function of covariates on 2 scales (field-collected and remotely sensed). Our goal was to compare performance of models containing field-collected and remotely sensed data (combination models) to models containing remotely sensed data only. We used a weighted regression, which allows the user to weight the response variables when the ratio of zeros (non-nest locations) to ones (nest locations) is not equal (Allison 1999; PROC Logistic [SAS Institute Inc., Cary, NC]). The intercept estimated from the weighted logistic model was not the true intercept (i.e., predicted values cannot be interpreted as probabilities of occupancy); therefore, predicted values from our models should be interpreted as relative indices of habitat suitability. When locations used for nesting by birds are incorrectly identified as nonused locations (in the field), evaluating a model on its ability to correctly identify nonused locations (contamination) may lead to false conclusions (Keating and Cherry 2004). We thoroughly searched all surveyed areas over the 4-year period and non-nest locations never contained a nest; therefore, we believe the rate of contamination in our study was low.

Models containing remotely sensed data included 1) pixel-level prefire crown closure class, prefire cover type, and burn severity; 2) patch area; and 3) landscape-level data, that is, percentages of each prefire crown closure and class measured within the 1-km radius around each plot center. For the combination models, we also included the number of snags in a plot and the diameter of the nest tree or a randomly selected focal tree at non-nest locations. Candidate models for remotely sensed data only included all possible combinations of 1–5 covariates (prefire crown closure on 2 scales, cover type, burn severity, and patch area). All variables we chose were identified by previous research as potentially important for nest-site selection of cavity-nesting birds (e.g., Raphael and White 1984, Li and Martin 1991, Saab et al. 2004). We were interested in generating models with the best ability to discriminate between nest and non-nest locations, and we used a best-subsets modeling approach to avoid excluding models that could be potentially useful to land managers. Consequently, we did not generate an a priori model set. Candidate models of combination data (field and remotely sensed data) for each species included only remotely sensed variables that appeared in top models from the first model selection exercise in addition to snag number and snag diameter. We included models containing only field-collected data (snag no. and snag diam) in the candidate model set of combination models for comparison purposes.

We first assessed models using information-theoretic approaches corrected for small sample sizes (i.e., Akaike's Information Criterion corrected for small sample size [AIC_c]; Burnham and Anderson 2002). We evaluated best models on their ability to correctly discriminate between nest plots, where we located $\geq$1 nest during the early years after fire (1–4 yr), versus random non-nest plots. We selected 2 top models for each species, one containing remotely sensed data only and one containing both remotely sensed and field-collected data.

Numerous methods have been developed for evaluating predictive models (Fielding and Bell 1997, Pearce and Ferrier 2000). Correctly identifying nest locations was our priority for developing habitat-suitability maps for sensitive woodpecker species. Therefore, we followed the suggestions of Gardner and Urban (2003) who recommended evaluating model sensitivity (using receiver operating characteristic [ROC] curves) as well as determining the number of correctly identified positives (in our case, correctly identified nest locations).

Model Diagnostics

Receiver operating characteristic curves.—Model diagnostics for predictive models quantify the ability of the model to distinguish between ones (nests) and zeros (non-nests). We used leave-one-out cross-validation methods to evaluate the number of correctly predicted nest versus non-nest locations for the 2 top models because of our relatively small sample size (Efron and Tibshirani 1993). In leave-one-out cross-validation, predicted values for a data point are generated from models developed without using that data point. Logistic regression models are evaluated by classifying observations as nest or non-nest on the basis of threshold values or cutoff points in the range of the predicted values, which range between zero and one (Fielding and Bell 1997, Pearce and Ferrier 2000). An observation with a predicted value below some threshold value (e.g., 0.5) is classified as a non-nest, whereas an observation with a predicted value above the threshold value is classified as a nest. This evaluation can be conducted over a wide range of values and be used to generate ROC curves that evaluate the relationship between the number of true positives and the number of false positives at different thresholds (e.g., Pearce and Ferrier 2000, Gardner and Urban 2003).

Area under the ROC curve (AUC) provides an index representing the model's ability to discriminate between positive and negative observations (Hanley and McNeil 1982). Swets (1988) suggested that an AUC between 0.5 and 0.7 reflects low accuracy, 0.7–0.9 reflects moderate accuracy, and $\geq$0.9 indicates excellent accuracy. When $>$1 model was equally plausible (i.e., within 2 ΔAIC_c points of the top model), we used AUC to select the model with the best discriminatory power for further evaluations.

Density plots.—We also used density plots of the predicted values for nest and non-nest locations to demonstrate the discriminatory ability of the models. Density plots are a generalization of the histogram and provide a measure of how often a particular predicted value is obtained for nest or non-nest locations. The greater the difference in the distributions, the greater the discriminatory ability of the models. We used the functions ldahist, roc.plot, and roc.area from the R libraries "mass" and "verification" to calculate area-under-the-curve statistics and generate density plots (R Core Development Team, R Foundation for Statistical Computing, Vienna, Austria).

Correct classification.—By adjusting the threshold value at which an observation was categorized as a nest or non-nest, we were able to calculate the threshold value needed to positively identify all nest locations correctly. At lower threshold values more non-nest locations will be incorrectly identified as nest locations (the rate of false positives will increase). Calculating the rate of false positives at thresholds where 100%, 75%, or 50% of the nests are correctly identified is important for land managers who need to minimize the amount of land incorrectly reserved as suitable habitat.

Relative Suitability Maps

We generated relative suitability maps for the entire burn area. Field-collected snag density and diameter at breast height were not available for most of the study area. Consequently, we used models containing only remotely sensed data to generate predicted values of habitat suitability. We generated maps only for species where we deemed the fit of models containing remotely sensed data adequate (AUC $>$ 0.70). We calculated relative habitat suitability for each pixel by using the parameter estimates generated from best fitting remotely sensed data models.

Table 1. Model selection results for models containing remotely sensed data only, based on weighted logistic regression associating nest habitat and non-nest habitat to plot-level variables on an unlogged burn in Idaho, USA (1–4 yr postfire), 1995–1998, for 6 cavity-nesting bird species.

Species	No. of nests	Model	K[a]	ΔAIC_c[b]	AIC_c wt	AUC[c]
Lewis's woodpecker (min. $AIC_c = 25.70$)	49	Burn severity, patch area	3	0.00	0.61	0.97
Hairy woodpecker (min. $AIC_c = 78.82$)	130	Burn severity	2	0.00	0.27	0.68
		Burn severity, patch area	3	0.33	0.23	0.70
Black-backed woodpecker (min. $AIC_c = 61.47$)	37	Pixel-level and landscape-level prefire crown closure, patch area	6	0.00	0.13	0.80
		Burn severity, pixel-level prefire crown closure, patch area	5	0.13	0.12	0.80
		Burn severity, pixel-level and landscape-level prefire crown closure, patch area	7	0.31	0.11	0.84
		Pixel-level prefire crown closure, patch area	4	0.47	0.10	0.79
		Pixel-level prefire crown closure	3	1.17	0.07	0.72
		Burn severity, pixel-level prefire crown closure	4	1.55	0.06	0.73
		Pixel-level prefire crown closure, landscape-level prefire crown closure	5	1.81	0.05	0.73
Northern flicker (min. $AIC_c = 83.07$)	91	Burn severity	2	0.00	0.20	0.57
		Patch area	2	0.89	0.13	0.55
		Landscape-level prefire crown closure	3	1.09	0.12	0.59
		Burn severity, patch area	3	1.46	0.10	0.60
Western bluebird (min. $AIC_c = 74.55$)	52	Burn severity, patch area	3	0.00	0.32	0.74
		Burn severity	2	0.33	0.27	0.70
Mountain bluebird (min. $AIC_c = 81.47$)	112	Burn severity	2	0.00	0.21	0.64
		Pixel-level prefire crown closure	3	1.29	0.11	0.61
		Burn severity, pixel-level prefire crown closure	4	1.89	0.08	0.64

[a] K = no. of parameters.
[b] AIC_c = Akaike's Information Criterion corrected for small sample sizes.
[c] AUC = area-under-the-curve statistics from receiver operating characteristic curves.

RESULTS

Model Selection by AIC_c and AUC

For models containing remotely sensed data only, burn severity was included in ≥1 plausible model (within 2 AIC_c points of the best model) for all species (Table 1). Best models, as determined by information-theoretic approaches (AIC_c) and the ability of the model to distinguish between nest and non-nest locations (AUC), included burn severity and patch area for all species except mountain bluebird (Table 1). The 2 best models for mountain bluebird nesting habitat were identical based on AUC, and included burn severity only and burn severity and prefire crown closure together. Consequently, we selected the most parsimonious model (burn severity only) as the best model. The best model of black-backed woodpecker nest locations included prefire crown closure on the pixel and landscape scales, as well as burn severity and patch area. All species were positively

Table 2. Model selection results for models containing remotely sensed and field-collected data based on weighted logistic regression associating nest habitat and non-nest habitat to remote sensing variables on an unlogged burn in Idaho, USA, (1–4 yr postfire), 1995–1998, for 6 cavity-nesting bird species.

Species	No. of nests	Model	K[a]	ΔAIC_c[b]	AIC_c wt	AUC[c]
Lewis's woodpecker (min. $AIC_c = 23.00$)	49	Burn severity, patch area, snag diam	4	0.00	0.59	0.96
Hairy woodpecker (min. $AIC_c = 66.55$)	130	Snag diam, snag no.	3	0.00	0.33	0.82
		Burn severity, snag diam, snag no.	4	0.09	0.31	0.83
		Patch area, snag diam, snag no.	4	1.17	0.18	0.82
		Burn severity, patch area, snag diam, snag no.	5	1.38	0.16	0.84
Black-backed woodpecker (min. $AIC_c = 38.17$)	37	Pixel-level prefire crown closure, landscape-level prefire crown closure, snag no., snag diam	7	0.00	0.38	0.95
		Pixel-level prefire crown closure, snag no., snag diam	5	0.17	0.35	0.92
Northern flicker (min. $AIC_c = 67.38$)	91	Snag diam, snag no.	3	0.00	0.38	0.81
		Patch area, snag no., snag diam	4	1.24	0.2	0.81
		Burn severity, snag no., snag diam	4	1.38	0.19	0.82
Western bluebird (min. $AIC_c = 70.92$)	52	Burn severity, patch area, snag no.	4	0.00	0.23	0.79
		Burn severity, snag no.	3	0.20	0.21	0.75
		Burn severity, patch area, snag diam, snag no.	5	0.33	0.2	0.80
		Burn severity, snag no., snag diam	4	0.38	0.19	0.74
Mountain bluebird (min. $AIC_c = 73.92$)	112	Snag no., snag diam	3	0.00	0.59	0.76
		Burn severity, snag diam, snag no.	4	1.26	0.31	0.77

[a] K = no. of parameters.
[b] AIC_c = Akaike's Information Criterion corrected for small sample sizes.
[c] AUC = area-under-the-curve statistics from receiver operating characteristic curves.

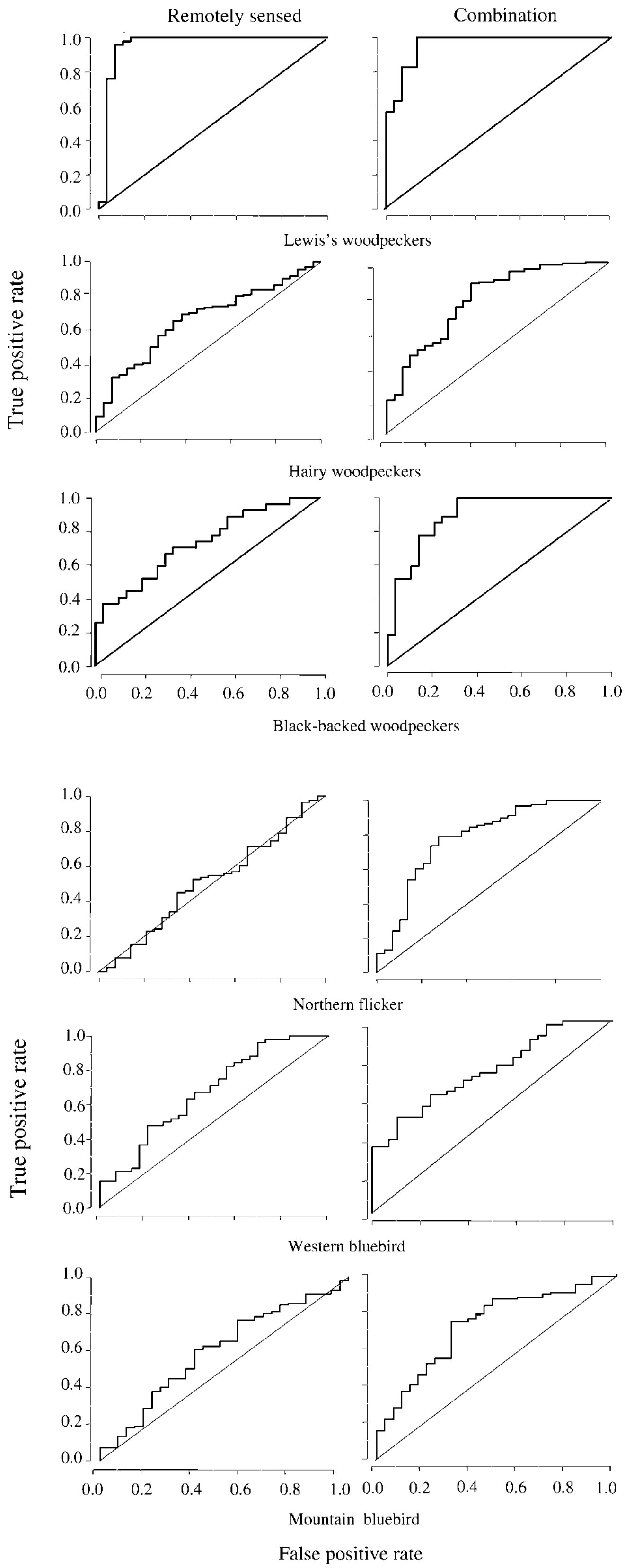

Figure 1. Receiver operating characteristic curves (ROC curves) for weighted logistic regression models distinguishing between nest and non-nest locations for 6 species of cavity-nesting birds in an unlogged burn in Idaho, USA, 1995–1998 (1–4 yr postfire). Remotely sensed models contained variables derived from remote sensing only; combination models included field-collected variables and remotely sensed data.

associated with burn severity and patch area, except mountain bluebird, which was positively associated with burn severity only (see Appendixes A and B for parameter estimates). Burn severity (ΔNBR) at nest locations ranged from an average of 422.13 ± 18.27 (SE) for northern flickers to 540.85 ± 27.35 (SE) for Lewis's woodpeckers (Appendix C). In contrast, burn severity at non-nest locations was 357.72 ± 40.59 (SE). Average patch area ranged from 70.93 ± 9.47 ha (SE) for mountain bluebirds to 341.63 ± 7.49 ha (SE) for Lewis's woodpeckers, versus an average patch area of 67.05 ± 22.12 ha (SE) at non-nest locations (Appendix C). Additionally, black-backed woodpeckers were positively associated with pixels classified as moderate or high prefire crown closure versus low prefire crown closure and with pixels surrounded by larger amounts of high and moderate prefire crown closure areas (landscape-level crown closure; Appendix A). Only 11% of black-backed woodpecker nests were located in pixels identified as 0–40% prefire crown closure versus 48% of non-nest plots. Additionally, on average within a 1-km radius of black-backed woodpecker nests 55% of the area was identified as having a prefire crown closure >40%. In non-nest locations, 47% of the landscape with a 1-km radius was >40% prefire crown closure (Appendix C).

Best combination models (remotely sensed and field-collected data) for all species except black-backed woodpeckers included burn severity (Table 2). Models containing only snag diameters and snag numbers but no remotely sensed variables appeared in top model sets for mountain bluebirds and northern flickers (Table 2). Best combination models included both snag diameters and snag numbers for all species except Lewis's woodpeckers, whose best model contained snag diameters only. All species were positively associated with increasing snag densities and snag diameters; however, only snag diameter appeared in best models for Lewis's woodpeckers (see Appendix B for parameter estimates). Average snag densities at nest locations ranged from 170.27 ± 12.46 per ha (SE) for mountain bluebirds to 312.22 ± 27.66 per ha (SE) for black-backed woodpecker, and averaged 164.91 ± 24.18 per ha (SE) at non-nest random locations (Appendix C). Snag diameters ranged from an average of 51.43 ± 3.03 cm (SE) for Lewis's woodpeckers to 35.28 ± 3.30 cm (SE) for mountain bluebirds. Snag diameters at non-nest locations averaged 29.09 ± 3.53 cm (SE; Appendix C). Minimum AIC_c values were always lower (between 2.75 AIC_c points for Lewis's woodpecker and 23.3 AIC_c points for black-backed woodpeckers) for combination models than for models containing remotely sensed data only, indicating a better model fit when field-collected data were included.

Evaluating Model Diagnostics

When evaluating graphs of ROC curves, the farther the curve is from the 1-to-1 line in the center of the graph, the larger the AUC, and the better the model's ability to discriminate between nest and non-nest locations (Fig. 1). Overlapping density plots indicated that predicted values for both nest and non-nest locations were similar, and therefore the model cannot discriminate between the 2 types of

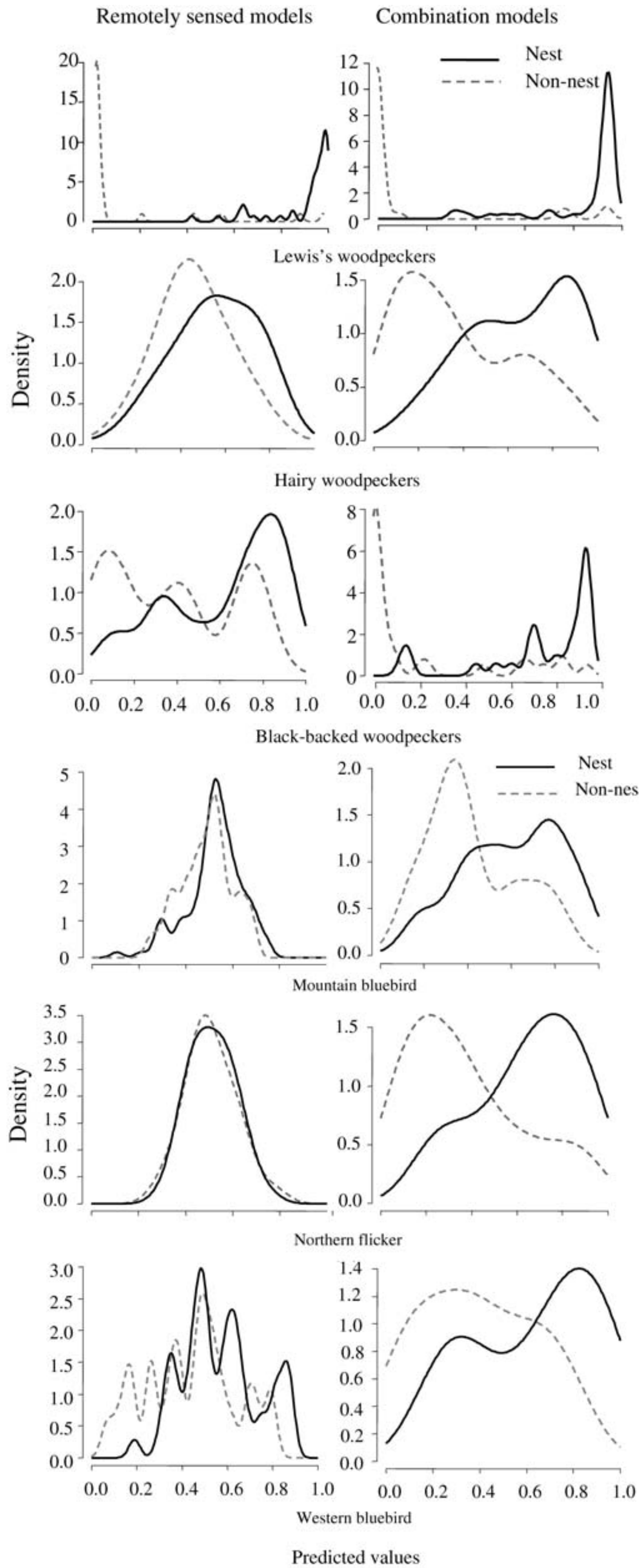

Figure 2. Density plots of predicted values for nest and non-nest locations from weighted logistic regression models distinguishing between nest and non-nest locations for 6 species of cavity-nesting birds in an unlogged burn in Idaho, USA, 1995–1998 (1–4 yr postfire). Remotely sensed models contained variables derived from remotely sensed imagery only; combination models included field-collected variables and remotely sensed data. Density plots represent a smoothed histogram for the frequency of occurrence of the predicted value in the sample (nest or non-nest).

locations (Fig. 2). Models with large AUC statistics have more separation in the density plots and are thus better at discriminating for nest and non-nest locations than models with smaller AUC.

The ability of the model to distinguish between nest and non-nest locations was greater for combination models of all species except Lewis's woodpecker, where discriminatory ability was equal for both models (i.e., AUC = 0.96; Fig. 1, Table 3). The overall discriminatory ability of remotely sensed data models was poor for mountain bluebirds (AUC = 0.60), northern flickers (AUC = 0.51), hairy woodpeckers (AUC = 0.66), and western bluebirds (AUC = 0.68). This is reflected in low AUC values (<0.7; Fig. 1; Table 3), ROC curves close to the 1-to-1 line (Fig. 1), and overlapping density plots for nest and non-nest locations (Fig. 2). For a land manager to correctly identify 100% of nest locations when only remotely sensed data are used, large numbers (>80%) of non-nest locations would be incorrectly identified as nest locations for all species except Lewis's woodpecker (Fig. 3; see Table 4 for threshold values). For Lewis's woodpecker, the remotely sensed data model performed well (AUC = 0.96), with large differences in the predicted values for nest and non-nest locations (Fig. 2). Also, at thresholds where 100% of Lewis's woodpecker nests are identified correctly, <20% of non-nest locations are identified incorrectly, indicating that few locations would be misidentified as nesting habitat when using this model (Fig. 3; Table 4).

Combination models generally represented an improvement in discriminatory ability over models containing remotely sensed data only (Table 3; Figs. 2, 3). To correctly identify 75% of black-backed woodpecker nests in our sample correctly using only remotely sensed data, 52% of non-nest locations were incorrectly identified as nest locations (Fig. 3); however, when using combination models, only 14% of non-nest locations in our sample were incorrectly identified. Models of western bluebird nest locations reflected the smallest increases in discriminatory ability (i.e., the smallest increases in AUC) when field-collected data were added (Fig. 3). The largest increases in discriminatory ability were obtained for models of black-backed woodpecker (AUC increased by 0.17), hairy woodpecker (AUC increased by 0.12), and northern flicker nest locations (AUC increased by 0.26) when field-collected data were included (Fig. 3). Additionally, misidentification of random locations when correctly identifying 75% of nest locations (rather than 100% of nest locations) decreased from 62% to 37% for hairy woodpeckers and from 78% to 25% for northern flickers when we included field-collected data in the models.

Relative Suitability Maps

Maps of relative habitat suitability for one study unit in the Star Gulch burn (Fig. 4) reflect the tendency of the Lewis's woodpecker model to predict values close to zero (no nest, white space on map) or close to one (nest occurrence, black space on map). White areas represented areas with predicted values below the lowest predicted value of any nest of that

Table 3. Evaluation of models predicting nest locations on an unlogged burn in Idaho, USA (1–4 yr postfire), 1995–1998, for 6 cavity-nesting bird species. Model performance is evaluated at the 0.5 threshold value for models containing remotely sensed data only and models including field-collected data and remotely sensed data (combination models).

Species	Remotely sensed models			Combination models		
	Correct nest[a]	Incorrect non-nest[b]	AUC[c]	Correct nest	Incorrect non-nest	AUC
Lewis's woodpecker	0.98	0.10	0.96	0.91	0.14	0.96
Hairy woodpecker	0.65	0.34	0.66	0.68	0.31	0.78
Black-backed woodpecker	0.67	0.31	0.73	0.85	0.24	0.90
Northern flicker	0.53	0.45	0.51	0.75	0.28	0.78
Western bluebird	0.58	0.38	0.68	0.65	0.34	0.74
Mountain bluebird	0.66	0.55	0.60	0.65	0.31	0.72

[a] Correct nest = proportion of nests correctly identified when a threshold of 0.5 is used to distinguish between nests and non-nests.
[b] Incorrect non-nest = proportion of non-nest random locations incorrectly classified as nest locations (i.e., predicted value > 0.5).
[c] AUC = area-under-the-curve statistics from receiver operating characteristic curves.

species in our sample (0.42 for Lewis's and 0.05 for black-backed woodpeckers; Table 4). Light gray, dark gray, and black areas together represent pixels that have predicted values above the lowest predicted value for either species (Table 4). Light gray areas represent pixels with predicted values above the lowest predicted value of any nest of that species in our sample and below the threshold value that identifies 75% of the nests (0.42–0.90 for Lewis's and 0.05–0.34 for black-backed woodpeckers; Table 4). Protection of dark gray and black areas would protect areas with relative habitat-suitability indices that were at least as high as the threshold value that would lead to correct identification of 75% of the nests in our sample (Table 4).

A map of relative suitability that combines the habitat requirements of both species, indicates the large amount of area required to reserve ≥75% of nests for both species (Fig. 5). Black areas on the habitat-suitability map correspond to areas with predicted values >0.42 for Lewis's woodpeckers and >0.34 for black-backed woodpeckers (Fig. 5). Light

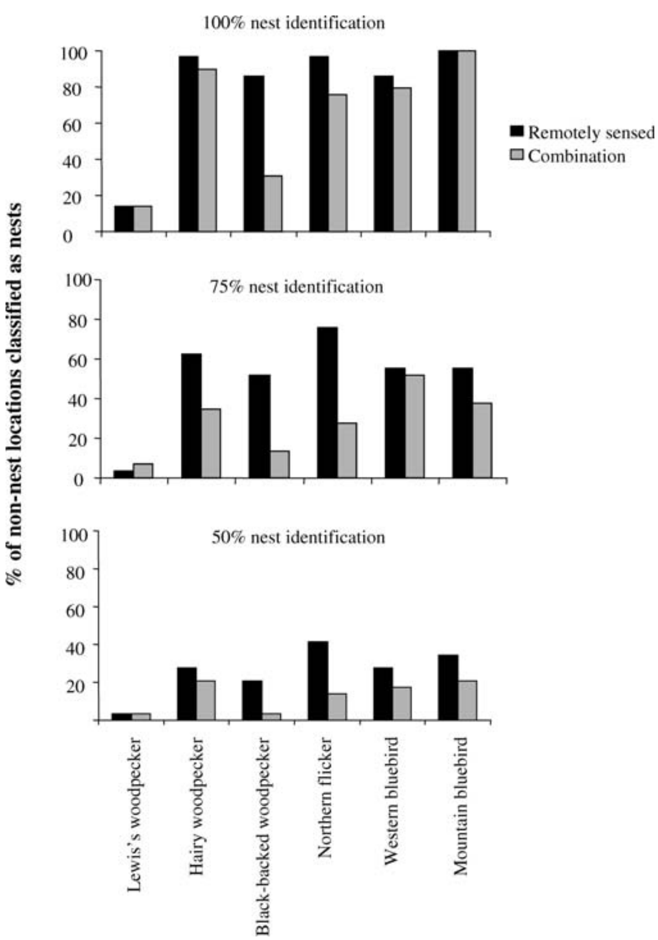

Figure 3. Percentage of non-nest locations incorrectly identified as nest locations for thresholds that correctly identify 100%, 75%, and 50% of nests in an unlogged burn in Idaho, USA, 1995–1998 (1–4 yr postfire). Results are reported for models containing remotely sensed variables only, and combination models that included field-collected and remotely sensed data. Threshold values increase as the percentage of correctly classified nest locations decrease.

Table 4. List of threshold values from models predicting nest locations on an unlogged burn in Idaho, USA (1–4 yr postfire), 1995–1998, for 6 cavity-nesting bird species. Correct nest identification (%) indicates the percentage of nests in our sample that would be correctly identified as nests if the corresponding threshold value for remotely sensed models or combination models was used.

Species	Threshold value[a]		
	Correct nest identification (%)	Remotely sensed models	Combination models
Lewis's woodpecker	100	0.42	0.32
	75	0.9	0.93
	50	0.96	0.99
Hairy woodpecker	100	0.13	0.08
	75	0.4	0.45
	50	0.55	0.65
Black-backed woodpecker	100	0.05	0.13
	75	0.34	0.73
	50	0.72	0.92
Northern flicker	100	0.29	0.15
	75	0.44	0.49
	50	0.51	0.68
Western bluebird	100	0.18	0.13
	75	0.45	0.37
	50	0.55	0.7
Mountain bluebird	100	0.1	0.08
	75	0.47	0.42
	50	0.53	0.6

[a] A threshold value indicates the predicted value below which a location is identified as a non-nest location and above which a location is identified as a nest location.

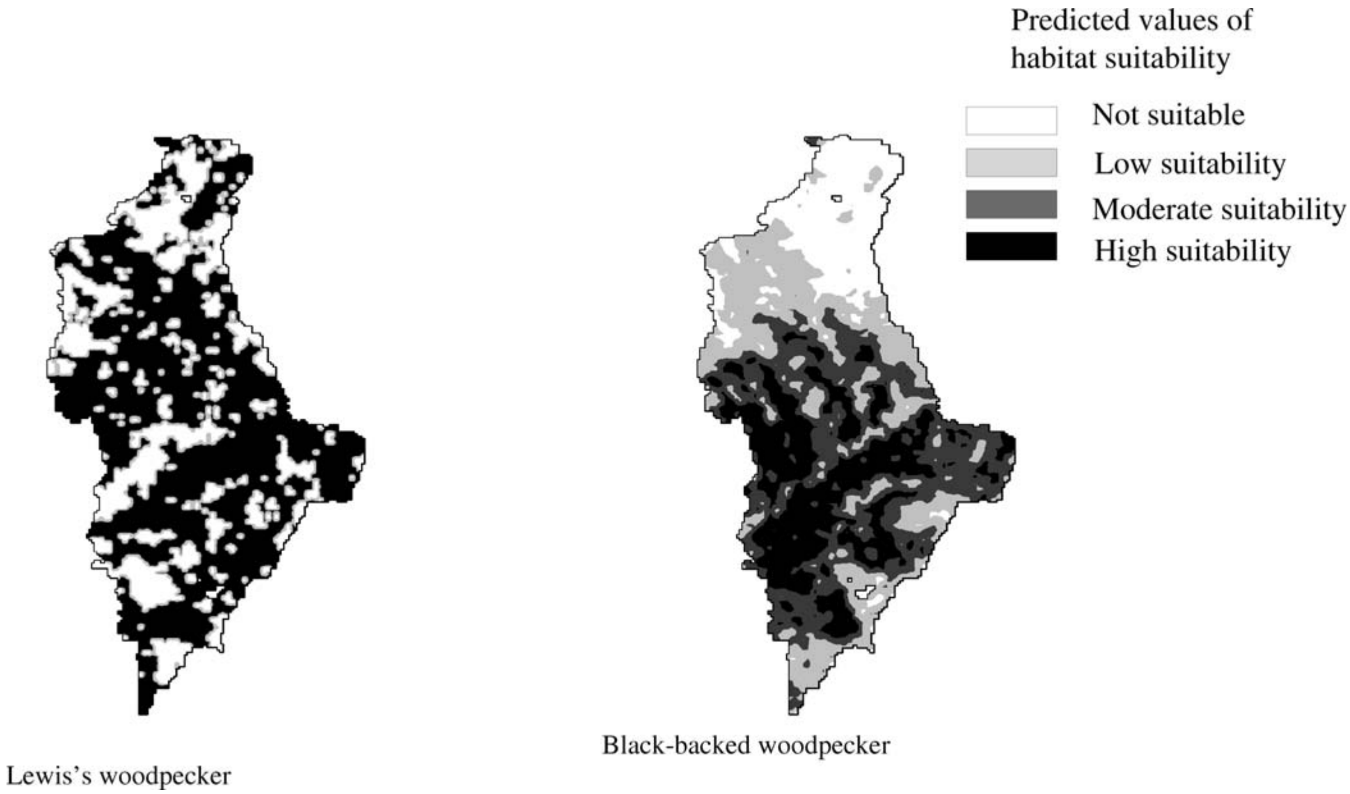

Figure 4. Suitability maps for black-backed and Lewis's woodpeckers in one unit of an unlogged burn in Idaho, USA, based on data collected from 1995–1998 (1–4 yr postfire). White areas represent areas with predicted values below the lowest predicted value of any nest for that species in our sample. Light gray, dark gray, and black areas together represent pixels that have predicted values above the lowest predicted value for either species. Light gray areas represent pixels with predicted values above the lowest predicted value of any nest for that species in our sample and below the threshold value that identified 75% of the nests. Dark gray and black areas represent areas with habitat-suitability indices that were at least as high as the threshold value that would correctly identify 75% of the nests in our sample.

gray areas indicate areas with predicted values that are below these values for both species and contain ≤25% of nests.

DISCUSSION

In general, the habitat identified in our models as appropriate for cavity-nesting birds reflects previous research findings (Saab et al. 2002, 2004). Postfire management activities should be directed away from these areas to avoid impacting nesting habitat of cavity-nesting birds. Our models, however, were based on one moderate-severity burn in a ponderosa pine–Douglas-fir forest of Idaho. The ability of the model to generalize to other forests has not been tested. For example, Lewis's woodpecker used larger patches that were burned more severely than were other locations on the landscape in our study area. Potentially, in a high-severity burn, Lewis's woodpeckers may select more moderately burned areas in comparison to the average severity on the landscape (i.e., the direction of the association between Lewis's woodpecker nesting habitat and burn severity may become negative). Additionally, for forests containing many large conifer patches, patch area may become less important as a selective factor for nesting habitat. Validation of our habitat-suitability models with data generated from other areas is necessary for broader applications and for developing design criteria for postfire salvage logging that preserve breeding habitat of cavity-nesting birds at-risk.

Lewis's and black-backed woodpeckers are considered habitat specialists (Tobalske 1997, Dixon and Saab 2000, Haggard and Gaines 2001, Saab et al. 2002), which may explain the greater ability of the models to distinguish between nest and non-nest locations for these species. Models for the 2 bluebird species did not perform as well as the woodpecker models, likely because these species are non-excavators that rely on existing cavities for their nest placement (Cunningham et al. 1980, Power and Lombardo 1996, Guinan et al. 2000). Both bluebird species use cavities excavated by several woodpecker species that select a variety of snag and habitat conditions (Martin and Eadie 1999, Saab et al. 2004). Western and mountain bluebirds rely on the nest-site selection preferences of other species. Therefore, factors such as competition for cavities may be more important predictors of nest locations than habitat variables for these species.

Numerous models for some species were ranked with a $\Delta AIC_c < 2$, indicating large amounts of model selection uncertainty. Selection of the best model for predictive purposes may not reflect best models as selected by standard information-theoretic approaches. Selection of the most parsimonious model that adequately discriminates between nest and non-nest locations may be sufficient in some

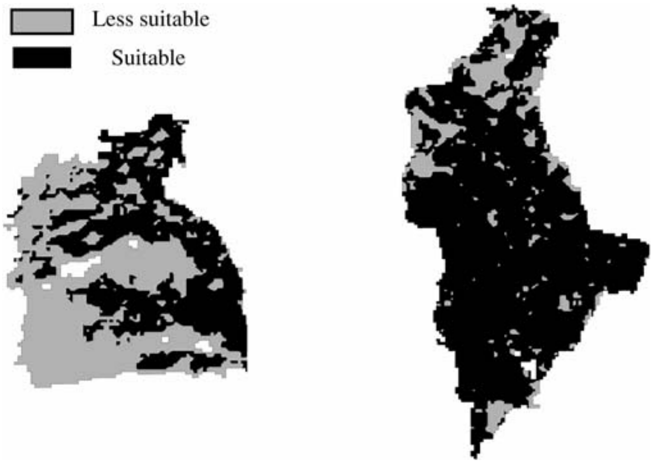

Figure 5. Habitat-suitability map for black-backed and Lewis's woodpecker for both units in an unlogged burn in Idaho, USA, based on data collected from 1995 to 1998 (1–4 yr postfire). Black areas on the habitat-suitability map for both the black-backed and Lewis's woodpeckers indicates areas needed to protect $\geq$75% of their nests that we located in the burn. These areas correspond to areas with predicted values >0.42 for Lewis's woodpeckers and >0.34 for black-backed woodpeckers. Light gray areas indicate areas with predicted values that are below these values for both species.

scenarios, but in other cases the need to maximize the discriminatory ability of the model regardless of how many additional variables are needed might be most important. Further exploration of the relationship between AIC_c, AUC, and the number of variables included in a model would be helpful for selecting best models for predictive purposes.

For most species that we studied, correct identification of 75% of nest locations would lead to >50% misclassification of non-nest locations when using remotely sensed data only. Therefore, by relying on remotely sensed data alone, land managers will have to accept a high degree of non-nest misclassification. It is possible that these misclassified locations were still suitable but not used because of low numbers of woodpeckers; therefore, our rates may overestimate misclassification of non-nest locations. Additionally, used sites may not be used in every year. However, high misclassification rates of non-nest locations is a serious detriment to land managers who are required to provide defensible reasons to protect an area from postfire management activities. Models that can predict snag densities and tree diameters from remotely sensed images with higher resolution than Landsat Imagery (e.g., QuickBird [Land Info Worldwide Mapping LLC, Highlands Ranch, CO] or Light Detection and Ranging data) would be most useful, but we are unaware of such models. Other vegetation mapping techniques such as direct gradient analysis and nearest-neighbor imputation provide promising advances in creating accurate vegetation maps of variables such as tree basal area and number of trees >100 cm (Ohmann and Gregory 2002). These techniques, if made readily available to land managers, would likely result in improved habitat mapping for cavity-nesting birds.

MANAGEMENT IMPLICATIONS

Land managers required to provide habitat for cavity-nesting bird species will likely maintain habitat for multiple species by reserving a range of suitable nesting areas characteristic of black-backed and Lewis's woodpeckers. Modifications to areas surrounding the pixels identified as suitable habitat will impact the overall suitability of the nesting habitat (i.e., cavity-nesting birds are unlikely to choose nesting habitat surrounded by unsuitable foraging habitat). Therefore, logging prescriptions should include a no-cut buffer zone surrounding suitable nesting habitat to ensure adequate foraging habitat adjacent to nests.

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Appendix A. Parameter estimates, standard error, Wald chi-square statistic, and *P*-value for parameter estimates from best models of nest versus non-nest locations for 6 species of cavity-nesting birds, modeled as a function of remotely sensed data, at an unlogged wildfire in Idaho, USA, 1995–1998 (1–4 yr postfire).

Species	Model	Parameter scale	Estimate	SE	Wald χ^2	Pr > χ^2[a]
Lewis's woodpecker	Intercept		−9.764	3.483	7.86	0.005
	Burn severity	Pixel	0.008	0.004	5.07	0.024
	Patch area	Landscape	0.025	0.008	9.25	0.002
Hairy woodpecker	Intercept		−9.201	3.513	6.86	0.009
	Burn severity	Pixel	0.007	0.004	3.93	0.047
	Patch area	Landscape	0.021	0.008	6.81	0.009
Black-backed woodpecker	Intercept		−7.138	2.439	8.57	0.003
	Burn severity	Pixel	0.003	0.002	1.91	0.167
	Moderate vs. low prefire crown closure	Pixel	1.516	0.886	2.92	0.087
	High vs. low prefire crown closure	Pixel	2.927	1.224	5.72	0.017
	40–70% prefire crown closure	Landscape	0.078	0.039	3.92	0.048
	70–100% prefire crown closure	Landscape	0.094	0.064	2.2	0.138
	Patch area	Landscape	0.005	0.003	3.77	0.052
Northern flicker	Intercept		−0.838	0.644	1.7	0.193
	Burn severity	Pixel	0.002	0.001	1.59	0.207
	Patch area	Landscape	0.002	0.002	0.75	0.387
Western bluebird	Intercept		−2.362	0.849	7.74	0.005
	Burn severity	Pixel	0.005	0.002	7.86	0.005
	Patch area	Landscape	0.003	0.002	2.13	0.144
Mountain bluebird	Intercept		−0.881	0.589	2.24	0.135
	Burn severity	Pixel	0.002	0.001	2.89	0.089

[a] Probability that a particular Wald χ^2 test statistic is as large as, or larger than, what has been obs under the null hypothesis.

Appendix B. Parameter estimates, standard error, Wald chi-square statistic, and *P*-value for parameter estimates from best models of nest versus non-nest locations for 6 species of cavity-nesting birds, modeled as a function of field-collected and remotely sensed data, in an unlogged wildfire in Idaho, USA, 1995–1998 (1–4 yr postfire).

Species	Model	Parameter scale	Estimate	SE	Wald χ^2	Pr > χ^2[a]
Lewis's woodpecker	Intercept		−17.776	9.196	3.74	0.053
	Snag diam	Field collected	0.144	0.098	2.18	0.140
	Burn severity	Pixel	0.010	0.005	3.86	0.050
	Patch area	Landscape	0.031	0.015	4.32	0.038
Hairy woodpecker	Intercept		−4.542	1.308	12.05	0.001
	Snag diam	Field collected	0.050	0.02	6.08	0.014
	Snag no.	Field collected	0.169	0.062	7.40	0.007
	Burn severity	Pixel	0.002	0.002	2.00	0.157
	Patch area	Landscape	0.002	0.002	1.08	0.300
Black-backed woodpecker	Intercept		−19.082	6.224	9.4	0.002
	Snag diam	Field collected	0.483	0.169	8.15	0.004
	Snag no.	Field collected	0.143	0.054	6.94	0.008
	Moderate vs. low prefire crown closure	Pixel	4.623	1.823	6.43	0.011
	High vs. low prefire crown closure	Pixel	3.217	2.156	2.23	0.136
	40–70% prefire crown closure	Landscape	0.105	0.053	4.01	0.045
	70–100% prefire crown closure	Landscape	0.185	0.111	2.79	0.095
Northern flicker	Intercept		−4.014	1.218	10.86	0.001
	Snag diam	Field collected	0.063	0.019	11.32	0.001
	Snag no.	Field collected	0.123	0.059	4.31	0.038
	Burn severity	Pixel	0.002	0.002	0.89	0.344
Western bluebird	Intercept		−4.124	1.296	10.13	0.002
	Snag diam	Field collected	0.023	0.018	1.67	0.197
	Snag no.	Field collected	0.137	0.059	5.43	0.02
	Burn severity	Pixel	0.004	0.002	5.03	0.025
	Patch area	Pixel	0.004	0.002	2.24	0.135
Mountain bluebird	Intercept		−2.887	0.987	8.56	0.003
	Snag diam	Field collected	0.037	0.017	4.85	0.028
	Snag no.	Field collected	0.122	0.053	5.3	0.021
	Burn severity	Pixel	0.001	0.001	1.02	0.314

[a] Probability that a particular Wald χ^2 test statistic is as large as, or larger than, what has been obs under the null hypothesis.

Appendix C. Summary statistics of habitat covariates measured at nest and non-nest random locations in an unlogged wildfire in Idaho, USA, 1995–1998 (1–4 yr postfire).

	Aerial insectivores					
	Lewis's woodpecker (n = 49)		**Western bluebird (n = 52)**		**Mountain bluebird (n = 112)**	
Spatial scale (covariate)	$\bar{x}$	**SE**	$\bar{x}$	**SE**	$\bar{x}$	**SE**
Remotely sensed data						
0–40% prefire CC[a]	50.93	1.61	49.57	1.36	51.95	1.05
40–70% prefire CC[a]	38.66	1.46	41.08	0.98	37.25	0.73
70–100% prefire CC[a]	10.41	0.89	9.35	0.83	10.80	0.51
Patch area of conifer	341.63	7.49	114.73	21.69	70.93	9.47
Burn severity (ΔNBR)[b]	540.85	27.35	525.04	24.95	463.11	19.49
% of nests in 0–40% prefire CC[c]	34		31		35	
% of nests in 40–70% prefire CC[c]	59		52		40	
% of nests in 70–100% prefire CC[c]	7		17		25	
Field-collected data						
Dbh of nest tree	51.43	3.03	35.28	3.30	39.52	1.60
Density of snags[d]	294.65	13.55	170.27	12.46	280.14	16.02

	Bark insectivores					
	Hairy woodpecker (n = 130)		**Black-backed woodpecker (n = 37)**		**Northern flicker (n = 91)**	
Spatial scale (covariate)	$\bar{x}$	**SE**	$\bar{x}$	**SE**	$\bar{x}$	**SE**
Remotely sensed data						
0–40% prefire CC[a]	49.19	1.04	45.29	1.84	51.38	1.22
40–70% prefire CC[a]	40.59	0.78	43.54	1.13	37.96	0.90
70–100% prefire CC[a]	10.22	0.53	11.17	1.27	10.65	0.64
Patch area of conifer	121.51	13.80	112.47	32.64	93.56	13.60
Burn severity (ΔNBR)[b]	493.35	17.93	512.89	43.46	422.13	18.27
% of nests in 0–40% prefire CC[c]	32		11		46	
% of nests in 40–70% prefire CC[c]	49		63		42	
% of nests in 70–100% prefire CC[c]	19		26		12	
Field-collected data						
Dbh of nest tree	41.81	1.38	40.91	2.52	50.24	2.32
Density of snags[d]	304.28	14.72	312.22	27.65	217.34	15.41

	Star Gulch (non-nest n = 29)	
Spatial scale (covariate)	$\bar{x}$	**SE**
Remotely sensed data		
0–40% prefire CC[a]	53.42	2.43
40–70% prefire CC[a]	38.25	2.64
70–100% prefire CC[a]	8.33	0.95
Patch area of conifer	67.05	22.12
Burn severity (ΔNBR)[b]	357.72	40.59
% of plots in 0–40% prefire CC[c]	48	
% of plots in 40–70% prefire CC[c]	45	
% of plots in 70–100% prefire CC[c]	7	
Field-collected data		
Dbh of random tree	29.09	3.53
Density of snags[d]	164.91	24.18

[a] % of area within 1 km of central plot classified as a particular prefire crown closure (CC) category.
[b] ΔNBR = normalized burn ratio.
[c] Pixel level.
[d] In 11.3-m-radius plot.