FINAL REPORT

Incorporating pyrodiversity into wildlife habitat assessments for post-fire management and recovery

JFSP PROJECT ID: 19-1-01-5

September 2021

Morgan Tingley
Ecology and Evolutionary Biology
University of California, Los Angeles

Andrew Stillman
Ecology and Evolutionary Biology
University of Connecticut

Rodney Siegel
Institute for Bird Populations

Sarah Sawyer
USDA Forest Service

Table of Contents

List of Figures

Keywords

abundance, black-backed woodpecker, habitat, occupancy, *Picoides arcticus*, wildlife,

Abstract

Pyrodiversity – spatiotemporal variation of characteristics within a fire regime – plays an important role in structuring wildlife communities after fire, yet there is a need to better incorporate pyrodiversity into predictive models of animal distributions and abundance. For species that associated with post-fire forests, predictive models often must be implemented rapidly to guide time-sensitive decisions about where and how to manage forests following fire. Black-backed woodpeckers are species of conservation concern that are strongly associated with post-fire forests, and emerging evidence on the importance of pyrodiversity for this species highlights the need for updated management approaches. Our objectives were to leverage a long-term dataset of annual black-backed woodpecker surveys to assess the relationship between occupancy and pyrodiversity and to integrate this new information into predictive models for habitat management after fire. We show that black-backed woodpecker occupancy responds positively to increased pyrodiversity in the montane conifer forests of California. In addition, we found that the relationship between occupancy and high burn severity changes over time, with strong positive effects shortly after fire diminishing to largely neutral effects by ten years after fire. These results demonstrate the importance of pyrodiversity for this species and support the hypothesis that particularly large, severe megafires may pose a threat to black-backed woodpecker populations. We incorporated these relationships into an integrated space-use and occupancy model that can be used to predict black-backed woodpecker density and abundance rapidly after fire – without requiring lengthy on-the-ground surveys. To make this decision-support tool more available to managers, we built an online "Shiny" application to run this model using a point-and-click interface to produce management-friendly data products within minutes.

Objectives

Objective 1: *Investigate the relationship between pyrodiversity and black-backed woodpecker occupancy using a spatially hierarchical occupancy model.*

Our work was motivated by the hypothesis that black-backed woodpecker occupancy patterns respond to spatial patterns in burn severity. While this hypothesis has received support from recent field studies in California (Stillman et al. 2019a, 2019b, 2021), it had not been tested at broader spatial scales using population-level survey data. Below, we present results from a temporal autologistic occupancy model built using 11 years of statewide surveys in California.

Objective 2: *Test how the black-backed woodpecker responses to burn severity change as years since fire increases.*

Black-backed woodpeckers are strongly tied to the availability of standing dead trees (snags) after fire, which they use for nesting and foraging. As these resources decline with time since fire, we hypothesized that black-backed woodpeckers would show shifts in their patterns of habitat use. Our model results show evidence for the prediction that black-backed woodpecker habitat associations change with time since fire.

Objective 3: *Use the new knowledge gained from this study to update an existing management tool that predicts black-backed woodpecker density and abundance in burned forests.*

We incorporated our results into an integrated space-use and occupancy model used to inform habitat management decisions in post-fire forest (Tingley et al. 2016b). To make this decision-support tool more available to managers, we built a freely-available online application to run the model using a point-and-click interface and user-inputted data layers.

Background

Variation in the spatial effects of fire, collectively termed "pyrodiversity," has received considerable attention as a potential management goal for fire-prone forests in the western U.S. (Hessburg et al. 2016, Kelly et al. 2017). Recent studies indicate that pyrodiverse landscapes retain and cultivate greater post-fire biodiversity over time (Ponisio et al. 2016, Tingley et al. 2016a, Beale et al. 2018, Steel et al. 2019), yet the recent surge of atypically large, severe wildfires has prompted concerns about the future of post-fire wildlife communities and forest recovery (Jones et al. 2016, Steel et al. 2018). Managers need a more nuanced understanding of how pyrodiversity affects fire-associated species in order to manage for key pyrodiversity metrics in the wake of these homogeneously severe fires and to make post-fire forest management decisions that will benefit wildlife populations.

The black-backed woodpecker is highly associated with burned forest in the western U.S., where it is used as a management indicator species for post-fire wildlife habitat (Hutto 2008, Tarbill et al. 2018). Local black-backed woodpecker populations follow a "boom and decline" cycle in the 10 years following wildfire. Individuals rapidly colonize new fires, but populations decline in older (5+ years) post-fire areas (Saracco et al. 2011, Tingley et al. 2018). Previous research has demonstrated negative effects of post-fire logging on black-backed woodpeckers (Hanson and North 2008), and the species' rarity has prompted lawsuits to halt or alter specific post-fire management plans. Recent evidence suggests that individual black-backed woodpeckers select for pyrodiverse habitat within recent fires (Stillman et al. 2019b, 2019a), and that access to less-severely burned or unburned areas can increase juvenile survival (Stillman et al. 2021). However, information is lacking on the population-level effects of pyrodiversity on black-backed woodpecker abundance across California and how this relationship might change between fires and at different stages of post-fire recovery.

Materials and Methods

Study area and survey methods

The survey data used for this JFSP project were collected as part of a long-term effort (2009–2019) to monitor black-backed woodpecker populations in burned forests of California. For complete information on study design and sampling methods, please see Saracco et al. (2011), Tingley et al. (2018), and Tingley et al. (2020).

Briefly, we conducted surveys in National Forest System lands that had burned between 1 and 10 years prior to the sampling year. Our study area comprised ten contiguous National Forest units within the Sierra Nevada and southern Cascades ecoregions. Each year we randomly selected 50 fires to visit that met our established sampling protocol. Across all surveys between 2009 and 2019, we visited 133 fires ranging in burn year from 1999 to 2018.

We conducted single-visit surveys for black-backed woodpeckers using a removal design at 2–24 survey sites (median = 20) in each of the 50 burned areas selected each year. Survey points were spaced at least 250 m from each other and at least 50 m from the nearest road. We conducted surveys in the morning hours (0530-0930) between 4 May and 18 July each year. The data used in this JFSP project represented 2384 survey points and 8484 unique survey visits.

Occupancy modeling

We developed a temporally autologistic occupancy model in a Bayesian framework designed to examine the factors affecting occupancy rates while accounting for temporal dependence in survey sites with visits in consecutive years (MacKenzie et al. 2002, Tingley et al. 2016a). The observed detection/non-detection data, y_{jkt}, are assumed to be imperfectly observed representations of the true occupancy state for survey interval *k* at site *j* and year *t*. Here, *t* represents the number of years since the fire burned, ranging from 1 to 10. The true occupancy status for each site-year combination, z_{jt}, is assumed to be closed among all *k* survey intervals within the <12-minute survey period. Observed occurrence is modeled as a Bernoulli-distributed random variable

$$y_{jkt} \sim \text{Bernoulli}\left(z_{jt} p_{jkt}\right),$$

where p_{jkt} is the probability of detection for a given survey site, survey interval, and year. The true occurrence status, z_{jt}, is a latent variable modeled as

$$z_{j,t} \sim \text{Bernoulli}\left(\psi_{jt}\right),$$

where ψ_{jt} is the probability of occupancy of site *j* in year *t*. Using previous work in this system as a baseline (Saracco et al. 2011, Tingley et al. 2018, 2020), we modeled the probability of detection as a logit-linear function of three covariates: survey interval duration (2 minutes = 0, 3 minutes = 1), the ordinal day of the year, and the survey type (passive = 0, broadcast = 1).

The occupancy model included an autologistic component to account for the temporal dependence of z_{jt} on $z_{j,t-1}$. Thus, we modeled the probability of occupancy in year 1 after fire as

$$logit(\psi_{j,t=1}) = \beta X,$$

where β represents a vector of intercept and slope coefficients and X represents a design matrix including observed covariates. For subsequent years after fire, *t* = 2, … ,10, we modeled the probability of occupancy as

$$logit(\psi_{j,t>1}) = \beta X + \phi z_{jt},$$

where ϕ is a site-specific temporal autologistic parameter (Royle and Dorazio 2008). In both cases, we modeled the probability of occupancy as a function of 8 covariates based on previous studies and 5 covariates based on our updated *a priori* hypotheses about the post-fire habitat characteristics that influence occurrence (Saracco et al. 2011, Tingley et al. 2018, 2020). Covariates based on previous studies included (1) the number of years since the fire burned, (2) a quadratic effect of years since fire, (3) elevation, (4) a quadratic effect of elevation, (5) latitude, (6) the linear interaction between elevation and latitude, (7) burn severity, and (8) pre-fire canopy cover. Covariates meant to test our updated hypotheses included the following: (1) diversity in burn severity, (2) the interaction between burn severity and years since fire, (3) distance to low severity burn or unburned forest, (4) basal area of fir trees, and (5) the interaction between fir basal area and years since fire. Fir basal area was measured as the combined basal area of red fir (*Abies magnifica*) and white fir (*A. concolor*) within 100 m of a survey point. The occupancy model included an effect for habitat type, divided into 10 categories, which we included as a random intercept.

We used Landsat-derived burn severity data, measured as the percent change in canopy cover from before to after the burn, as the basis for three covariates in our model: burn severity, diversity in burn severity, and distance to low severity burn or unburned forest. Given that previous studies have documented strong relationships between black-backed woodpecker habitat selection and burn severity at multiple spatial scales (Hutto 2008, Stillman et al. 2019a, 2019b, Campos et al. 2020), we used an indicator variable selection approach to test which scales to use in our final model (Hooten and Hobbs 2015, McGarigal et al. 2016). Briefly, we fit the full occupancy model with burn severity and diversity in burn severity at two spatial scales. First, we measured these variables at a 100-m buffer around survey points to represent the assumed detection radius of surveys. Second, we measured these variables at a 500-m buffer around survey points to approximate home range size (Tingley et al. 2014). Each parameter of interest was written as the product of a binary indicator variable, I, the regression coefficient, and the observed data. For example, the burn severity variable was included as

$$\mathrm{I}_{severity} * \beta_{100m} * Severity_{100m} + (1 - \mathrm{I}_{severity}) * \beta_{500m} * Severity_{500m} \,.$$

Indicator variables came from a Bernoulli distribution $Bernoulli(\iota_{j,t})$, where $\iota_{j,t}$ is given a prior distribution of $Beta(\alpha = 1, \beta = 1)$. Here, posterior distributions of $\iota_{j,t}$ which tend toward 1 support the 100-m scale, and posterior distributions which tend toward 0 support the 500-m scale. The 100-m scale received strong support for burn severity and the 500-m scale received strong support for diversity in burn severity, so we used these scales in the final model.

We calculated diversity in burn severity to represent a fine-scale index of spatial pyrodiversity around each survey point. To calculate this metric, we first divided the percent change in canopy cover into 11 bins (0%, 1-10%, … 91-100%). Next, we calculated the inverse Simpsons diversity of all burn severity pixels within a 500-m buffer of survey points. In this case, the inverse Simpsons index ranges from 1 (all pixels equal) to 11 (pixels equally distributed between different severity classes). This metric conveys information about the representation and evenness of severity classes, providing a single metric of variation that may be useful to land managers (Ponisio et al. 2016). We used the average percent change in canopy cover within 100 m of survey points represent burn severity in our model, and we used a 25% change in canopy cover threshold to represent low severity when calculating the distance to low severity or unburned forest.

To control for spatial autocorrelation induced by surveying multiple points within a burn, we additionally included a random intercept term for fire area. Previous work suggests that black-backed woodpecker colonization rates are affected by fire-level characteristics such as fire size and ignition season (Tingley et al. 2018), so we sought to test the effects of these fire characteristics on occupancy patterns. Thus, we allowed a fire-specific random effect to arise from a hyper-distribution $\beta_{fire} \sim Normal(\mu_{fire}, \sigma_{fire})$, where μ_{fire} and σ_{fire} are hyper-parameters representing the mean and standard deviation across all fire areas. We modeled μ_{fire} as a linear function of two fire-level covariates: area burned by the fire, and fire ignition season. We included fire ignition season as a binary variable (0 = before 15 August, 1 = after 15 August). The August 15 cutoff represents the date that dispersing wood-boring beetles available for colonizing new fires typically decline (Costello et al. 2013), potentially leading to lower food availability for black-backed woodpeckers.

We fit the model to the data in R version 4.1.0 using JAGS version 4.3.0 and the package R2JAGS (Plummer 2003, R Core Team 2021, Su and Yajima 2021). We used agnostic priors with slight regularization, $Normal(\mu = 0, \tau = 0.2)$, on all fixed effects and a uniform prior (0.1, 3) on the standard deviation of random effects. We used a uniform prior (0.01, 0.99) to keep the detection model intercept between 0 and 1 on the probability scale. We ran 3 chains in parallel with 50000 iterations after a burnin of 30000 and a thin rate of 100, yielding a posterior sample of 1500 across all chains. We confirmed that the Gelman–Rubin statistic was <1.1 for every estimate and visually inspected traceplots to assess convergence (Gelman et al. 2004, Youngflesh 2018).

Integrated occupancy and space use model

The third objective of this JFSP project was to integrate the new knowledge gained from this study into an updated management tool to predict black-backed woodpecker density and abundance after fire. Full details on the modeling framework used in this tool are provided in Tingley et al. (2016b). The model framework can be conceptualized as fully packing a landscape with black-backed woodpecker home ranges based on habitat quality, and then subtracting home ranges based on a probabilistic process that accounts for the fact that heterogeneous landscapes are rarely occupied at maximum density. In addition to the occupancy model described above, the integrated occupancy and space use model includes two additional components:

Home range model. This model predicts black-backed woodpecker density across a burned area using the relationship between snag density and home range size (Tingley et al. 2014). We used the same model and data described by Tingley et al. (2016b).

Snag density model. We built a model to predict snag basal area across a burned area using freely-available satellite-derived data. Our model follows the same framework as Tingley et al. (2016b), but it incorporates additional data collected at occupancy survey sites. We modeled the log-transformed basal area of snags as a function of 8 covariates: burn severity at the survey point, quadratic effect of burn severity at the survey point, pre-fire canopy cover, the interaction between pre-fire canopy cover and burn severity, tree size class, elevation, latitude, and the interaction between elevation and latitude. We fit the model to the data in R version 4.1.0 using JAGS version 4.3.0 and the package R2JAGS (Plummer 2003, R Core Team 2021, Su and Yajima 2021). We used vague priors *Normal*($\mu = 0$, $\tau = 0.01$) on all fixed effects and a vague prior Gamma(0.001, 0.001) on the intercept. We ran 5000 iterations with a burnin of 1000 and a thin rate of 10, giving a posterior sample of 1200 across three chains.

Results and Discussion

We found strong relationships between post-fire habitat characteristics and black-backed woodpecker occupancy. As we predicted, occupancy rates decreased with increasing years since fire (Figure 1a) and, on average, occupancy was higher in areas burned at high severity (Figure 1b). However, the relationship between burn severity and occupancy interacted strongly with time since fire – burn severity showed a strong positive relationship 1 year after fire, but a neutral relationship 10 years after fire. This interaction effect indicates that black-backed woodpecker habitat preferences change over time, likely following resource dynamics tied to the availability of food (e.g., woodboring beetles) and nest sites in dead trees. This result also highlights the potential importance of areas burned at medium or low severity to the longer-term persistence of black-backed woodpeckers in post-fire areas (Stillman et al. 2019b). Moreover, we found a positive relationship between occupancy and diversity in burn severity, emphasizing the importance of pyrodiversity for black-backed woodpeckers (Figure 1c). We did not find a relationship between occupancy and the distance to low severity or unburned forest (Figure 2c), although we predict that this variable may yet be important but perhaps primarily in the large, severe megafires which have burned in recent years (and which are under-represented in our random sample of fires). Taken together, these results represent a major step forward in understanding the habitat associations of black-backed woodpeckers and provide meaningful information for managers interested in promoting black-backed woodpecker habitat after forest fire. These results relate directly to Objectives 1 and 2.

Moreover, we were able to test the hypothesis that black-backed woodpecker persistence in older post-fire forests is partially linked to the availability of fir trees, which decay at slower rates than pines and may retain beetle larvae for more years after fire. We found a strong positive effect of fir basal area on occupancy, and this effect increases (i.e., became more positive) as years since fire increased (Figure 1d). This result represents the first evidence for our hypothesis and suggests that habitat structure may indirectly influence black-backed woodpecker population dynamics in burned areas by regulating the abundance and availability of prey.

Black-backed woodpecker occupancy rates increased with increasing elevation and latitude (Figure 2a, b), but occupancy rates did not show a relationship with pre-fire canopy cover (Figure 2d). These results are largely consistent with previous findings in this study system (Saracco et al. 2011, Tingley et al. 2018). We did not find evidence for effects of fire size or ignition season on occupancy.

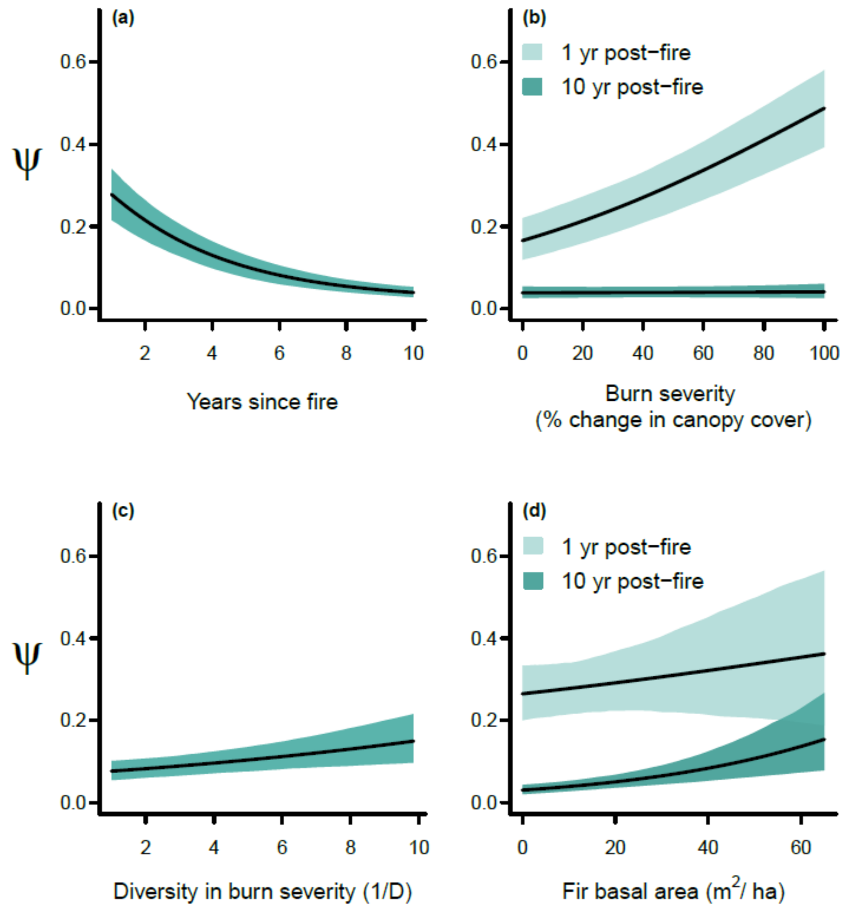

Figure 1. Modeled relationships between black-backed woodpecker occupancy and four habitat characteristics which relate to Objectives 1 and 2: (a) years since fire, (b) burn severity, (c) diversity in burn severity, (d) fir basal area. Panels (b) and (d) show interaction effects between years since fire and habitat, with relationships visualized at 1 and 10 years post-fire.

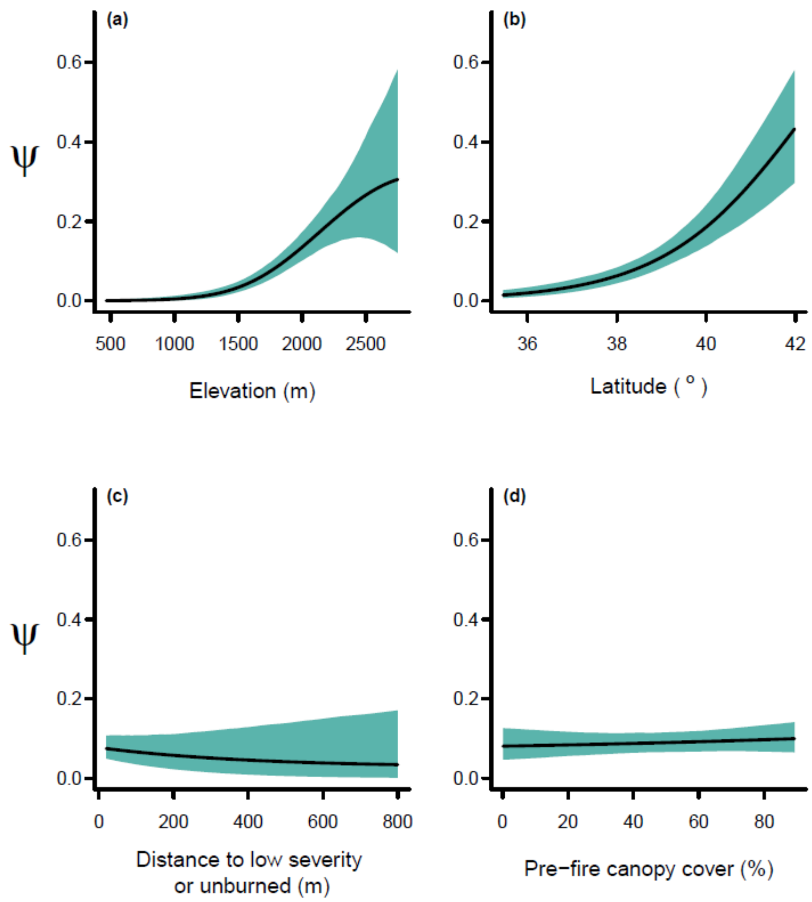

Figure 2. Modeled relationships between black-backed woodpecker occupancy and habitat characteristics including (a) elevation, (b) latitude, (c) distance to low severity or unburned forest, and (d) pre-fire canopy cover.

Science delivery: Incorporating pyrodiversity into a tool for post-fire management

We incorporated the occupancy relationships assessed in Objectives 1 and 2 into an integrated occupancy and space use model to predict black-backed woodpecker relative abundance and density after fire (Tingley et al. 2016b). The expected users for this tool include land managers, conservation scientists, and other natural resource practitioners who are interested in incorporating information on black-backed woodpecker populations into their management decisions within the black-backed woodpecker's range in California. We have made the model code, including code for all component models, available on Github: https://github.com/andrewstillman/IntegratedAbundance_model. This repository also includes data to run the model for an example fire.

To make this decision-support tool more available to managers, we built an online application to run the predictive model using a point-and-click interface to produce results within minutes (Figure 3). This online tool requires user inputs specific to the particular area of interest within a burned forest (≤ 10 years post-fire). To begin, users provide two files that are freely available within months of a fire burning: (1) a gridded spatial dataset (raster) of burn severity measured as percent change in canopy cover from before to after fire, and (2) a polygon shapefile giving the outline of either the full fire or a management area of interest (one or more polygons) within the fire. The tool then uses the integrated occupancy and space use model to predict black-backed woodpecker abundance across the area of interest and produce spatially explicit predictions of potential pair density at approximately 30x30 m resolution. These predictions can then be used to inform post-fire forest management decisions by predicting their potential effects on black-backed woodpecker abundance, without requiring on-the-ground black-backed woodpecker surveys. Predictions are specific to a single post-fire year (i.e., 1–10 years after fire), allowing users to explicitly account for the temporal dynamics of black-backed woodpecker populations. The tool is built using RShiny and hosted by the Institute for Bird Populations: https://bird-populations.shinyapps.io/Black-backed_Woodpecker_Portal/.

The online application includes 6 tabs in a point-and-click interface:

- *Home*: Information on the expected audience, suggested uses, and purpose of the application (Figure 3a).
- *Instructions and Uses*: Step-by-step instructions on how to run the app, including information on where to find the necessary input data.
- *Upload Data*: Information and instructions for the data upload process. This tab includes buttons to browse your computer for the spatial input data and collects user input on years since fire, fire season, and year of the fire (Figure 3b).
- *Run the Model*: This tab runs the predictions and allows the user to select and download the desired outputs.
- *FAQ*: Frequently asked questions and additional information helpful for users. This section includes additional information on the variables used to make predictions behind the scenes.
- *About this Site*: Contact information for project personnel, literature cited, and releases.

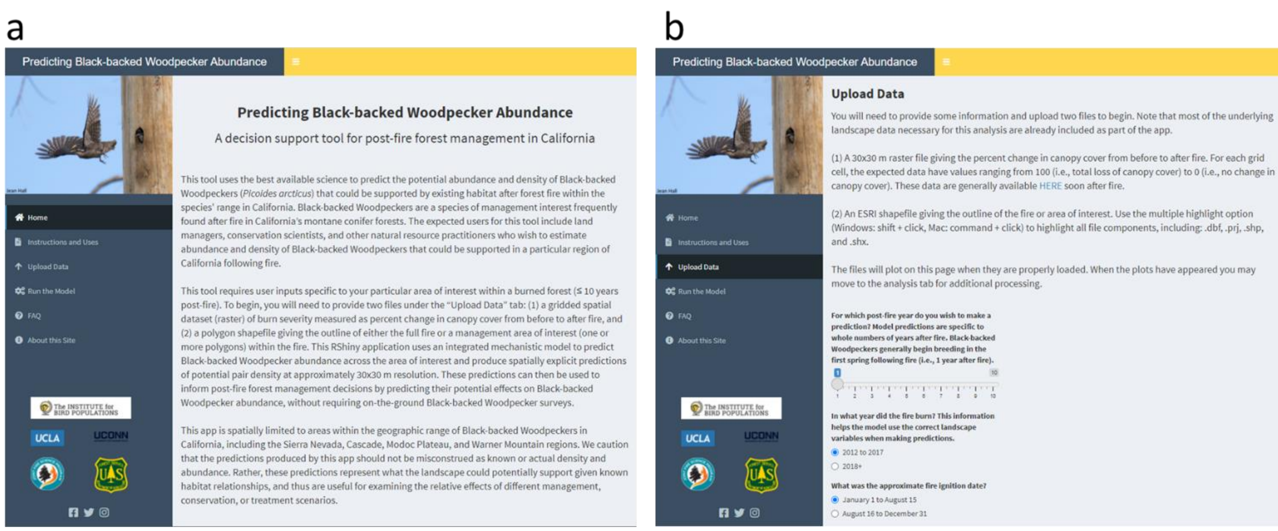

Figure 3. We created an RShiny application, available freely online, to run the decision-support tool using a point-and-click interface. (a) shows the landing page for the app, and (b) shows the page where users upload data from the area of interest in preparation for running the model.

The predictive model will produce different data products depending on the analysis option that the user selects. Alternatively, a user can use the "Select All" feature to produce all outputs simultaneously. The outputs of the online application are as follows:

Option: "Predict abundance"

1) A histogram plot showing the Bayesian posterior estimate of black-backed woodpecker pair abundance potentially supported by the landscape within the input polygon shapefile. The best estimate is displayed as the highest posterior density along with its 95% credible interval (Figure 4).

2) A .csv file (viewable in Microsoft Excel) giving the predicted abundance results for 1000 posterior draws from the model. This file allows the user to summarize or plot the abundance predictions and uncertainty according to their preferences (e.g., when writing a report).

Option: "Predict mean density"

1) A .tif raster file giving mean predicted density of black-backed woodpecker pairs that could be supported at roughly 30x30m resolution across the input shapefile. Units are in pairs/pixel.

2) A plot of the output raster showing predicted mean density converted to potential pairs per acre (Figure 5).

Option: "Estimate uncertainty in density predictions"

1) A .tif raster file giving a categorical representation of the model's confidence in black-backed woodpecker pair density predictions: "Good", "Fair", and "Poor".

2) A .tif raster file displaying areas with high, medium, and low relative density, masked to areas where prediction confidence = "Good". Relative density categories are assigned using quantiles from the total distribution of cells. Cells with value = 1 (low density) represent the lower quartile (0%-25%], cells with value = 2 (medium density) represent the middle quantiles (25%-75%], and cells with value = 3 (high density) represent the higher quartile (75%-100%). Areas with no prediction and areas where prediction confidence is "Fair" or "Poor" are given NA values (Figure 6).

3) Two plots to visualize the output rasters.

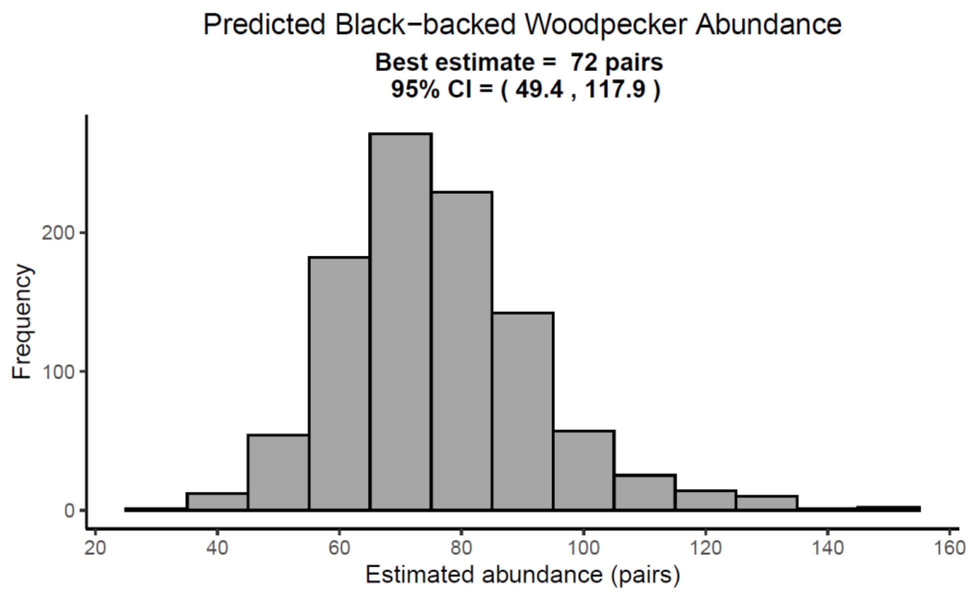

Figure 4. When users select the “Predict abundance” option, the app with produce a histogram showing the Bayesian posterior estimate of black-backed woodpecker pair abundance potentially supported by the landscape within the input polygon shapefile. The best estimate is displayed as the highest posterior density along with its 95% credible interval. Example data come from the 2012 Reading Fire in Lassen National Forest.

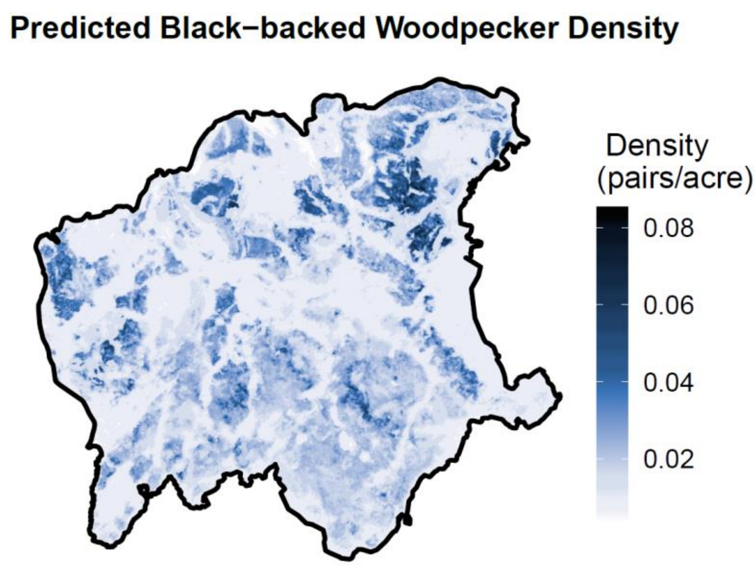

Figure 5. When users select the “Predict mean density” option, the app will produce a map showing predicted mean density converted to potential pairs per acre. Example data come from the 2012 Reading Fire in Lassen National Forest.

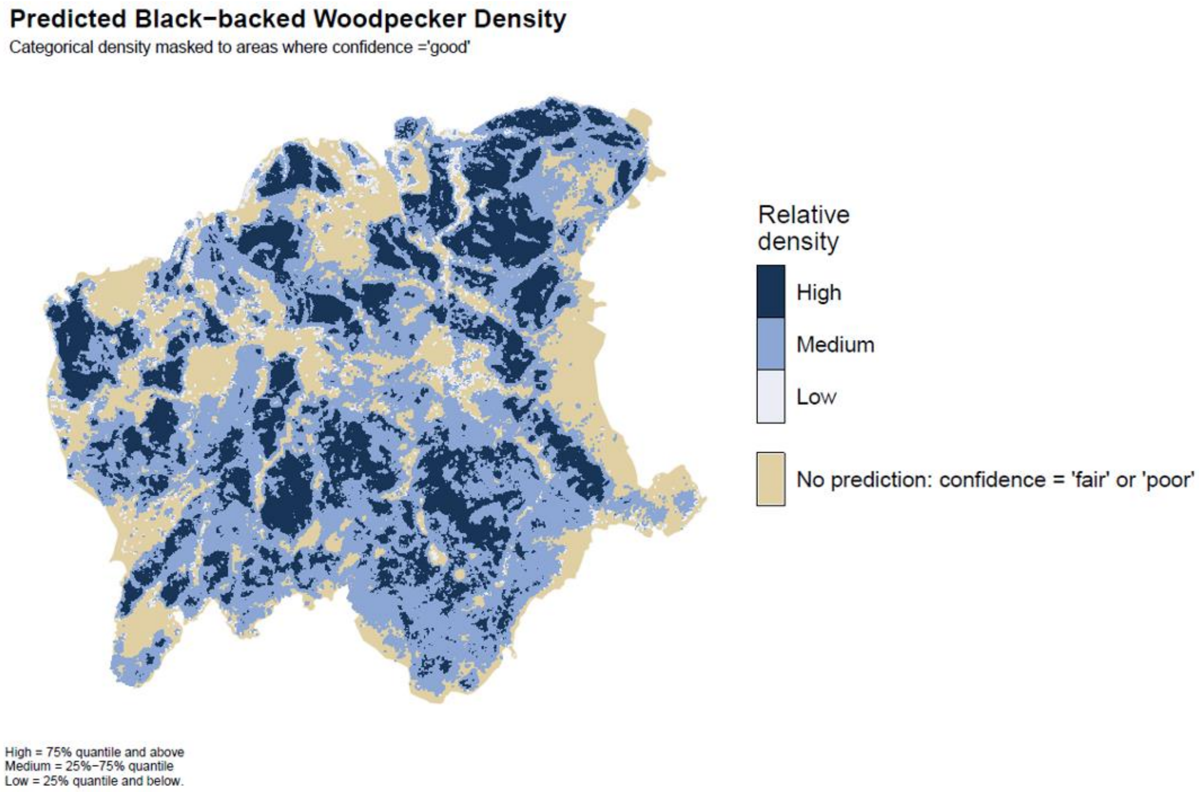

Figure 5. When users select the “Estimate uncertainty in density predictions” option, the app will produce a map showing the uncertainty in density estimates (not pictured) and a map (shown above) displaying areas with high, medium, and low relative density, masked to areas where prediction confidence = “Good”. Relative density categories are assigned using quantiles from the total distribution of cells. Example data come from the 2012 Reading Fire in Lassen National Forest.

Science delivery: Science communication and future development

The online application tool that we developed integrates our updated knowledge into predictions of black-backed woodpecker potential abundance and provides a streamlined interface for running the model. We are working with agency partners in Region 5 of the USDA Forest Service to distribute the app among management decision-makers and conservation practitioners. During the fall of 2021, we will present information on the app during a monthly joint meeting of National Forest biologists and identify opportunities for use in this year’s management planning cycle. During the winter of 2021/2022, we will pilot the app with a small group of National Forest biologists working to implement management treatments in recently burned forests. In order to provide more complete validation tests of the updated tool, we also plan to validate the occupancy portion of the tool using black-backed woodpecker survey data from a 2021 field season conducted using the same methods described above. Preliminary posterior predictive checks indicate that the occupancy model performs well. After this validation process is complete, we will continue working with partners at the USDA Forest Service to distribute the online application publicly to land managers at the state, district, and national forest levels.

To communicate the scientific findings within the wildlife management community, we are presenting the tool at the "Wildfire and Prescribed Fire Effects on Biodiversity in US Forests" symposium at the 2021 meeting of The Wildlife Society (November 2021). In addition, we are preparing a manuscript for submission to a peer-reviewed journal.

Conclusions

Implications for management

Pyrodiversity is an important component of post-fire landscapes, and managers are increasingly designing management actions with the goal of promoting or maintaining pyrodiversity both before and after fire (Hessburg et al. 2016). Recent studies indicate that pyrodiverse landscapes retain and cultivate greater post-fire biodiversity over time (Ponisio et al. 2016, Tingley et al. 2016a, Kelly et al. 2017). Localized field studies of black-backed woodpeckers have highlighted the importance of pyrodiversity for nest site selection, foraging, and juvenile recruitment in this species while uncovering potential mechanisms behind this species' association with pyrodiversity (Stillman et al. 2019b, 2019a, 2021). Here, we tested whether these mechanisms manifest in species-habitat relationships at a much larger scale using 11 years of state-wide occupancy surveys in California. Our results emphasize the need to incorporate pyrodiversity into management plans meant to promote black-backed woodpecker population persistence in burned areas. Given that black-backed woodpeckers are frequently used as a management indicator species for snag retention guidelines after fire (Saab et al. 2007, Hanson and North 2008, Tarbill et al. 2018), our results will directly inform post-fire planning for logging and restoration. By incorporating our new results into a decision support tool, we hope to reduce the resources and effort necessary for managers to assess the impact of planned treatments on black-backed woodpecker populations.

Implications for future research

The rise of atypically large, severe megafires in California has prompted concerns about the future of forest wildlife communities and forest recovery (Jones et al. 2016, Steel et al. 2018, 2021, Coop et al. 2020). More information on the effects of megafires on wildlife populations is urgently needed, particularly regarding the potential effects of high-severity fire when it occurs homogeneously over large, continuous areas. Our results highlight the need for additional research on the effects of megafires on black-backed woodpeckers, including potential effects on post-fire colonization and population persistence in large patches of high-severity burn. The changing characteristics of California's wildfires also creates a need to understand post-fire wildlife communities in areas that are reburned by multiple severe fire events.

Literature Cited

Beale, C. M., C. J. Courtney Mustaphi, T. A. Morrison, S. Archibald, T. M. Anderson, A. P. Dobson, J. E. Donaldson, G. P. Hempson, J. Probert, and C. L. Parr. 2018. Pyrodiversity interacts with rainfall to increase bird and mammal richness in African savannas. Ecology Letters 21:557–567.

Campos, B. R., Q. S. Latif, R. D. Burnett, and V. A. Saab. 2020. Predictive habitat suitability models for nesting woodpeckers following wildfire in the Sierra Nevada and Southern Cascades of California. The Condor:duz062.

Coop, J. D., S. A. Parks, C. S. Stevens-Rumann, S. D. Crausbay, P. E. Higuera, M. D. Hurteau, A. Tepley, E. Whitman, T. Assal, B. M. Collins, K. T. Davis, S. Dobrowski, D. A. Falk, P. J. Fornwalt, P. Z. Fulé, B. J. Harvey, V. R. Kane, C. E. Littlefield, E. Q. Margolis, M. North, M.-A. Parisien, S. Prichard, and K. C. Rodman. 2020. Wildfire-Driven Forest Conversion in Western North American Landscapes. BioScience 70:659–673.

Costello, S. L., W. R. Jacobi, and J. F. Negrón. 2013. Emergence of Buprestidae, Cerambycidae, and Scolytinae (Coleoptera) from mountain pine beetle-killed and fire-killed ponderosa pines in the Black Hills, South Dakota, USA. The Coleopterists Bulletin 67:149–154.

Gelman, A., J. B. Carlin, H. S. Stern, and D. B. Rubin. 2004. Bayesian data analysis. Second edition. Boca Raton, FL: Chapman & Hall, CRC.

Hanson, C. T., and M. P. North. 2008. Postfire woodpecker foraging in salvage-logged and unlogged forests of the Sierra Nevada. The Condor 110:777–782.

Hessburg, P. F., T. A. Spies, D. A. Perry, C. N. Skinner, A. H. Taylor, P. M. Brown, S. L. Stephens, A. J. Larson, D. J. Churchill, N. A. Povak, P. H. Singleton, B. McComb, W. J. Zielinski, B. M. Collins, R. B. Salter, J. J. Keane, J. F. Franklin, and G. Riegel. 2016. Tamm review: Management of mixed-severity fire regime forests in Oregon, Washington, and Northern California. Forest Ecology and Management 366:221–250.

Hooten, M. B., and N. T. Hobbs. 2015. A guide to Bayesian model selection for ecologists. Ecological Monographs 85:3–28.

Hutto, R. L. 2008. The ecological importance of severe wildfires: some like it hot. Ecological Applications 18:1827–1834.

Jones, G. M., R. J. Gutiérrez, D. J. Tempel, S. A. Whitmore, W. J. Berigan, and M. Z. Peery. 2016. Megafires: an emerging threat to old-forest species. Frontiers in Ecology and the Environment 14:300–306.

Kelly, L. T., L. Brotons, and M. A. McCarthy. 2017. Putting pyrodiversity to work for animal conservation. Conservation Biology 31:952–955.

MacKenzie, D. I., J. D. Nichols, G. B. Lachman, S. Droege, J. Andrew Royle, and C. A. Langtimm. 2002. Estimating site occupancy rates when detection probabilities are less than one. Ecology 83:2248–2255.

McGarigal, K., H. Y. Wan, K. A. Zeller, B. C. Timm, and S. A. Cushman. 2016. Multi-scale habitat selection modeling: a review and outlook. Landscape ecology 31:1161–1175.

Plummer, M. 2003. JAGS: A program for analysis of Bayesian graphical models using Gibbs sampling. Page Proceedings of the 3rd international workshop on distributed statistical computing. Vienna, Austria.

Ponisio, L. C., K. Wilkin, L. K. M'Gonigle, K. Kulhanek, L. Cook, R. Thorp, T. Griswold, and C. Kremen. 2016. Pyrodiversity begets plant–pollinator community diversity. Global Change Biology 22:1794–1808.

R Core Team. 2021. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Royle, J. A., and R. M. Dorazio. 2008. Hierarchical modeling and inference in ecology: the analysis of data from populations, metapopulations and communities. Academic Press, San Diego, California, USA.

Saab, V. A., R. E. Russell, and J. G. Dudley. 2007. Nest densities of cavity-nesting birds in relation to postfire salvage logging and time since wildfire. The Condor 109:97–108.

Saracco, J. F., R. B. Siegel, and R. L. Wilkerson. 2011. Occupancy modeling of Black-backed Woodpeckers on burned Sierra Nevada forests. Ecosphere 2:art31.

Steel, Z. L., B. Campos, W. F. Frick, R. Burnett, and H. D. Safford. 2019. The effects of wildfire severity and pyrodiversity on bat occupancy and diversity in fire-suppressed forests. Scientific Reports 9:16300.

Steel, Z. L., A. M. Fogg, R. Burnett, L. J. Roberts, and H. D. Safford. 2021. When bigger isn't better—Implications of large high-severity wildfire patches for avian diversity and community composition. Diversity and Distributions n/a.

Steel, Z. L., M. J. Koontz, and H. D. Safford. 2018. The changing landscape of wildfire: burn pattern trends and implications for California's yellow pine and mixed conifer forests. Landscape Ecology 33:1159–1176.

Stillman, A. N., T. J. Lorenz, P. C. Fischer, R. B. Siegel, R. L. Wilkerson, M. Johnson, and M. W. Tingley. 2021. Juvenile survival of a burned forest specialist in response to variation in fire characteristics. Journal of Animal Ecology 90:1317–1327.

Stillman, A. N., R. B. Siegel, R. L. Wilkerson, M. Johnson, C. A. Howell, and M. W. Tingley.

2019a. Nest site selection and nest survival of Black-backed Woodpeckers after wildfire. The Condor: Ornithological Applications 121:duz039.

Stillman, A. N., R. B. Siegel, R. L. Wilkerson, M. Johnson, and M. W. Tingley. 2019b. Age-dependent habitat relationships of a burned forest specialist emphasise the role of pyrodiversity in fire management. Journal of Applied Ecology 56:880–890.

Su, Y.-S., and M. Yajima. 2021. R2jags: using R to run “JAGS”. R package version 0.7-1.

Tarbill, G. L., A. M. White, and P. N. Manley. 2018. The persistence of Black-backed Woodpeckers following delayed salvage logging in the Sierra Nevada. Avian Conservation and Ecology 13:16.

Tingley, M. W., V. Ruiz-Gutiérrez, R. L. Wilkerson, C. A. Howell, and R. B. Siegel. 2016a. Pyrodiversity promotes avian diversity over the decade following forest fire. Proceedings of the Royal Society of London B: Biological Sciences 283:20161703.

Tingley, M. W., A. N. Stillman, R. L. Wilkerson, C. A. Howell, S. C. Sawyer, and R. B. Siegel. 2018. Cross-scale occupancy dynamics of a postfire specialist in response to variation across a fire regime. Journal of Animal Ecology 87:1484–1496.

Tingley, M. W., A. N. Stillman, R. L. Wilkerson, S. C. Sawyer, and R. B. Siegel. 2020. Black-backed woodpecker occupancy in burned and beetle-killed forests: Disturbance agent matters. Forest Ecology and Management 455:117694.

Tingley, M. W., R. L. Wilkerson, M. L. Bond, C. A. Howell, and R. B. Siegel. 2014. Variation in home-range size of Black-backed Woodpeckers. The Condor 116:325–340.

Tingley, M. W., R. L. Wilkerson, C. A. Howell, and R. B. Siegel. 2016b. An integrated occupancy and space-use model to predict abundance of imperfectly detected, territorial vertebrates. Methods in Ecology and Evolution 7:508–517.

Youngflesh, C. 2018. MCMCvis: Tools to visualize, manipulate, and summarize MCMC output. Journal of Open Source Software 3:640.

Appendix A: Contact Information for Key Project Personnel

Morgan Tingley, Associate Professor, University of California – Los Angeles.
mtingley@ucla.edu

Andrew Stillman, Postdoctoral Associate, Cornell Lab of Ornithology.
stillman.andrewn@gmail.com

Rodney Siegel, Executive Director, Institute for Bird Populations.
rsiegel@birdpop.org

Sarah Sawyer, Regional Wildlife Ecologist, Pacific Southwest Region, USDA Forest Service.
sarah.sawyer@usda.gov

Appendix B: List of Completed/Planned Scientific/Technical Publications/Science Delivery Products

Ph.D. Dissertation:
Stillman, Andrew. Black-backed Woodpecker Resource Selection and Demographic Responses to Variation in Fire Characteristics. Department of Ecology and Evolutionary Biology, University of Connecticut, 2021.

Publications in prep:
Stillman, A.N., D.R. Kaschube, R.L. Wilkerson, R.B. Siegel, S.C. Sawyer, and M.W. Tingley. (*in prep*). Incorporating pyrodiversity into wildlife habitat assessments for post-fire management.

Presentations:
Stillman, A.N., D.R. Kaschube, R.L. Wilkerson, R.B. Siegel, S.C. Sawyer, and M.W. Tingley. Incorporating pyrodiversity into wildlife habitat assessments for post-fire management: lessons from the black-backed woodpecker. The Wildlife Society, 2021.

Stillman, A.N. Ecology in action through wildfire, woodpeckers, and 300,000 eagles. Ornithology Seminar guest speaker, Cornell University, 2021.

Decision support tool:
Portal for the online application:
https://bird-populations.shinyapps.io/Black-backed_Woodpecker_Portal/

Code and example data to run the predictive model and component models:
https://github.com/andrewstillman/IntegratedAbundance_model

Undergraduate mentorship:
Sonia Aronson. Developing a scalable workflow to measure fire severity from satellite imagery in Google Earth Engine. University of California – Los Angeles, 2021.

Appendix C: Metadata

All metadata will be archived with the Forest Service Research Data Archive in accordance to our data management plan. In addition, all code and example data necessary to run the predictive model and component models are available on Github: [https://github.com/andrewstillman/IntegratedAbundance_model.](https://github.com/andrewstillman/IntegratedAbundance_model)

/IntegratedAbundance_model: data and code to run the integrated space use and occupancy model to predict black-backed woodpecker abundance across an example fire (fire data contained in /ReadingFire_data). Predictions come from three component models: (1) A model of the relationship between snag density and home range size. Available at https://github.com/mtingley/BBWO_abundance/tree/master/Model_HomeRange. (2) A model to predict snag denstiy given remote sensing data. (3) A temporal auto-logistic occupancy model based on data from a long-term population survey.

/Occupancy_model: data and code to run the occupancy model component.

/ReadingFire_data: example input data for the integrated abundance model.

/Snag_model: data and code to run the snag density model component.