Avian responses to climate change: projections for the Kaibab National Forest

Report

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Bird Conservancy of the Rockies

Connecting people, birds and land

Mission: Conserving birds and their habitats through science, education and land stewardship

Vision: Native bird populations are sustained in healthy ecosystems

Bird Conservancy of the Rockies conserves birds and their habitats through an integrated approach of science, education, and land stewardship. Our work radiates from the Rockies to the Great Plains, Mexico and beyond. Our mission is advanced through sound science, achieved through empowering people, realized through stewardship, and sustained through partnerships. Together, we are improving native bird populations, the land, and the lives of people.

Core Values:

1. **Science** provides the foundation for effective bird conservation.
2. **Education** is critical to the success of bird conservation.
3. **Stewardship** of birds and their habitats is a shared responsibility.

Goals:

1. Guide conservation action where it is needed most by conducting scientifically rigorous monitoring and research on birds and their habitats within the context of their full annual cycle.
2. Inspire conservation action in people by developing relationships through community outreach and science-based, experiential education programs.
3. Contribute to bird population viability and help sustain working lands by partnering with landowners and managers to enhance wildlife habitat.
4. Promote conservation and inform land management decisions by disseminating scientific knowledge and developing tools and recommendations.

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Introduction

Management planning by the U.S. Forest Service (USFS) is increasingly challenged by ongoing climate change and changes in wildfire dynamics caused by human land use and exacerbated by climate change. The 2012 planning rule includes mandates for forest plans to include objectives for maintaining ecological integrity, which necessarily includes maintaining biodiversity (Williamson et al. 2020). Forest planning could therefore benefit from information on how biodiversity is likely to change with expected changes in climate and wildfire.

Birds represent a substantial component of biodiversity that is useful to monitor because various species representing different traits and habitat associations are readily detectable without specialized equipment. The Kaibab National Forest (KANF) has leveraged the Integrated Monitoring in Bird Conservation Regions (IMBCR) program administered by Bird Conservancy of the Rockies (Bird Conservancy) to monitor breeding birds over the last decade (2010–2018, 2021–2023). In recognition of ongoing challenges and to provide baseline information for management planning in the face of ongoing environmental change, USFS and KANF partnered with Bird Conservancy to simulate vegetation changes and associated bird responses to climate change and associated changes in wildfire dynamics. We report here major results from this work, present a spatial data repository containing predicted vegetation changes and bird population responses to these changes over a 40-year time horizon, and suggest potential avenues for leveraging this information to further scientific knowledge and inform forest management planning.

Data repository

The primary product of the analysis presented here is a data repository consisting of two components: 1) a folder containing files describing and documenting a predictive model quantifying bird species abundance and distributions and 2) a folder containing raster and summary files with bird population predictions under alternative climate scenarios. Each folder contains a file named "Folder_contents_and_metadata.pdf" providing a detailed and comprehensive catalog of the folder. This report will be housed alongside the data repository and will refer to files and folders contained in the repository. Files and folders in the component 1 will be referred to as "Data_repository/BirdModel/…" and in component 2 as "Data_repository/Results/…." We largely refer directly to the data repository rather than replicating contents in the data repository in the form of figures and tables except for two tables that show major over-arching results arising from our analysis.

Methods

Vegetation simulation with climate change

We used a state and transition modeling framework to simulate changes in vegetation structure and composition over a 40-year time horizon starting in 2017 under alternative climate scenarios using a business-as-usual management strategy. This work builds off of previous an existing set of models developed by Region 3 for each classified vegetation type and structure category across NM and AZ and was adapted specifically for the Kaibab National Forest. We represented vegetation conditions using the distribution of ecological response units (ERUs), which describe vegetation classes defined by tree species dominating the canopy, along with additional attributes describing fine-scale vegetation structure (e.g., average stand tree size, canopy cover, shrub cover). We represented transitions as able to modify vegetation structure, for example a harvest event would reduce tree size and canopy cover.

To make the model climate informed, we relied on projections of future vegetation types produced by the dynamic global vegetation model known as MC2 (Kim XXXX). This was done in the methods outlined by Kutschera et al. (2023), where we compared future MC2 vegetation types against a spatial overlay of ERU and MC2 vegetation types under historical conditions to create a set of transitions to inform climate driven changes in vegetation type location.

We selected five climate scenarios representing a subset of available general circulation models (GCMs) varying in predicted climate for KANF: 1) a warm wet scenario (canesm), 2) a warm dry scenario (ipsl), 3) a warm scenario with average moisture (mirocesm), 4) a cool scenario with average moisture (inm), and 5) an average temperature and precipitation scenario (ccsm; Figure 1). Simulations tracked vegetation conditions at a 300m resolution, so simulated vegetation values had to be scaled up to a 1km resolution to develop covariates used to inform the predictive model of bird species abundance and distribution (see below). In addition to the 5 climate scenarios, we simulated 6 reference scenarios, 5 representing predicted fire dynamics but no climate change (hereafter fire reference scenarios) and the sixth representing no change in climate or wildfire dynamics (hereafter baseline reference scenario). We ran 5 replicate simulations for each scenario (hereafter iterations). A sixth replicate was inadvertently implemented and is included in the data repository for each climate and the baseline reference scenario, but calculations comparing scenarios reported here only include iterations 1–5.

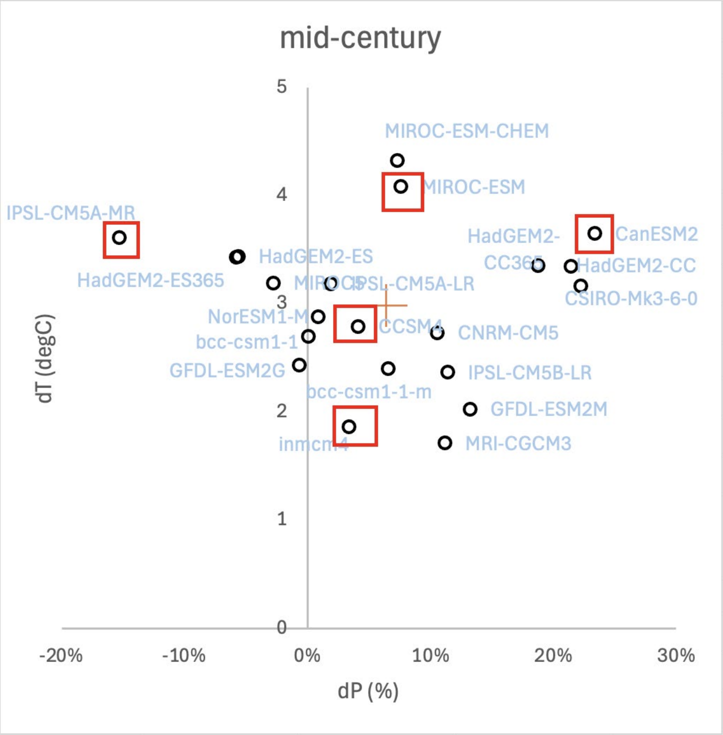

Figure 1. General circulation models plotted as a function of projected temperature change (y-axis) and precipitation (x-axis). Models represented in vegetation simulations for this study are blocked in red.

Bird sampling and data collection

The IMBCR sampling design applies a spatially balanced algorithm (Stevens and Olsen 2004) to select primary sampling units, which are 1km grid cells, from a series of strata representing various mutually exclusive geographic units of management interest (e.g., a national forest; Pavlacky et al. 2017). The KANF dataset represented 360 grid cells selected from 17 strata. The particular strata represented in each year varied and moreover only provided full coverage of KANF in 2010–2016 and 2021–2023 (2017–2018 data only represented treatment units for the 4-Forest Restoration Initiative [4FRI]). Although not all grid cells were surveyed every year, the IMBCR design allows inter-annual variability in sampling intensity while maintaining spatially balanced sampling within each stratum in any given year. We included all available data to provide maximum representation of bird communities across vegetation conditions represented at KANF, which consisted of 640 grid cell × year observations. Our analysis assumes available data represented bird populations across sufficient range of vegetation conditions to allow prediction of species abundance with changes in the distribution of represented conditions with climate change.

Each grid cell sampling unit consisted of a 4×4 array of evenly (250 m) spaced survey points. Surveyors visited points within each sampled grid cell in any given year once per breeding season (May–July) during morning hours to conduct a 6 min count of all birds seen or heard along with the time (min) to detection and the distance to each detected individual (McLaren et al. 2025). In most cases, only a subset of the 16 points in a grid cell could be completed due to logistical constraints or land access issues (mean [SD] effort = 9.6 [5.1] points completed).

Modeling and prediction of bird abundance and distribution

We analyzed bird species abundance and quantified relationships with vegetation conditions using a Bayesian hierarchical community model. The complete model description along with how we derived abundance predictions from the model are provided in Data_repository/BirdModel/Bird_model_and_predictions.pdf. While accounting for two components of detection probability (the frequency at which birds are available for detection over time and the distance from the surveyor), the model estimated abundance for each of the 144 species represented in KANF data in relation to vegetation metrics describing conditions during data collection. The model included 14 metrics as covariates of abundance, including 8 quantifying coverage extent of ERUs within the (surveyed) grid cell and the remaining 6 quantifying aspects of vegetation structure (model covariates listed in the “Covariates” sheet contained in the Data_repository/BirdModel/Tables_reference.xlsx file). The 8 ERUs included as covariates represented 8 of 9 ERUs represented at a substantial number of surveyed points (ERUs listed in the ‘ERU_list_complete’ sheet in Data_repository/BirdModel/Tables_reference.xlsx). We excluded from model covariates one of the nine major ERUs represented in the bird data, ponderosa pine forest, to limit multicollinearity. Ponderosa pine forest therefore represented the reference ERU such that negative relationships with all the other ERUs implied a positive relationship with ponderosa pine forest. Two other ERUs, “Herbaceous (wetland)” and “Water”, were only represented at a single survey point each and were therefore excluded from the predictive model.

Prediction of bird abundance relied on species relationships with vegetation conditions estimated by the fitted community model. Each species is represented by a regression sub-model predicting abundance for the species at a 1km grid cell as a function of vegetation metrics included in the model. We derived values for these metrics from vegetation simulations representing the initial year (same for all scenarios) and year 40 for each iteration ($n = 5$) of each climate scenario. Considering that vegetation simulations were implemented at a 300m resolution, we had to summarize across simulated vegetation metric values to generate 1km resolution values used to fit and apply the bird model. Summarization entailed calculating the mean of values for 300m pixels contained within the 1km pixel. For binary metrics (e.g., ERU membership), scaled up values thereby represented the proportion of the 1km pixel assigned a value of 1. For model fitting, we extracted raw 300m values to survey points based upon where points were located, and then summarized across values extracted to points to generate 1km values for the grid cells where birds were surveyed. For model application, we used the terra::resample function in R (Hijmans 2023) to summarize across 300m pixels intersecting 1km pixels to generate scaled up values. One notable difference between model fitting and model application was that survey point values were weighted equally when generating values for model fitting whereas terra::resample weights summary values by the proportion of each the 300m pixel contained within the 1km pixel (i.e., 300m pixels straddling the 1km pixel boundaries are accordingly weighted less than those fully inside the 1km boundaries). Section 3 in Data_repository/BirdModel/Bird_model_and_predictions.pdf provides additional details on model application to generate predicted bird abundances for initial and simulated landscapes.

Application of the predictive bird abundance model was limited by the range of vegetation conditions represented in the data to which the model was fitted. In particular, we could not apply the model to ERUs outside the 9 ERUs substantially represented in KANF IMBCR data (hereafter "prediction extent") as the model would treat these as the reference ERU, i.e., ponderosa pine forest. At the 300m resolution (i.e., the resolution at which vegetation simulations were implemented), 99.6% of the initial (contemporary) landscape was within the prediction extent. The final (year 40) simulated landscapes for most scenarios were also ≥97% within the prediction extent, but for the ccsm climate scenario, final-year landscapes ranged 73-76% within the prediction extent across iterations due to unexpected expansion of the sand sage ERU. We calculated 1km resolution summary prediction extents by calculating the mean of 300m binary values using the terra::resample function (Hijmans 2023). We then used the 1km prediction extent values to weight abundance predictions as described further below to account for prediction extent.

We operated within a Bayesian paradigm to derive estimates of abundance change through time for each scenario and differences in abundance between climate and corresponding reference scenarios for each species. The Bayesian model object fitted to available data contains MCMC samples of the posterior distribution for each model parameter [1]. We can derive estimates of any parameter, p_D, not explicitly part of the core model structure but calculable as a function of core parameters, $p_D = f(\boldsymbol{p_C})$, by applying $f(\boldsymbol{p_C})$ to each MCMC sample and then summarizing across MCMC samples. We summarized the median and 80% credible intervals (CIs) for derived parameters, whereby estimates whose 80% Cis excluded zero were considered statistically supported.

We first generated a raster stack containing derived MCMC samples for abundance predictions for each species during the initial year (same for all scenarios) and the final year for each iteration of each scenario. For each of these raster stacks, the first layer is the prediction extent (named "prediction_extent") and all subsequent layers are predicted abundances for each MCMC sample ignoring prediction extent (named "psamp[sample number]"). Raster stacks for the initial year are

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[1] The saved model object is stored as the Data_repository/BirdModel/mod_KANF file and can be loaded into R using the `R.utils::loadObject` function.

named “Initial_[SPP]” (SPP is the 4-letter species code listed in the ‘Species_list’ sheet in Data_repository/BirdModel/Tables_reference.xlsx), raster stacks for the final year are named “[Scenario]_iteration[iteration number]_ts40_[SPP].tif”, and both are stored in the Data_repository/Results/spp_predN_stacks folder. We then derived a series of raster file sets and tabulated population estimates that summarize across simulated landscapes that together quantify projected changes in species abundance over time (hereafter abundance changes) and differences in species abundance between climate and reference scenarios (hereafter abundance differences). These files and tables are listed along with details on their calculations in Data_repository/Results/Folder_contents_and_metadata (both PDF and HTML versions available). For raster files reporting posterior median estimates of abundance changes and abundance differences, we zeroed out any pixel values that were entirely outside the prediction extent (i.e., 1km prediction extent value = 0). For landscape-wide population changes and differences, we multiplied pixel level abundance estimates by 1km prediction extent values before summarizing across landscapes. Here, we report two over-arching summaries of abundance changes and differences: 1) the number of species with statistically supported increases and decreases through time for each scenario and 2) the number of species with supported positive and negative differences in abundance between climate and corresponding reference scenarios.

Results and Discussion

We clearly projected negative consequences of climate change for bird populations for KANF. The number of species for which we projected statistically clear declines substantially exceeded the number of species with supported increases under all climate scenarios, whereas these two quantities were similar for all reference scenarios (Table 1). Moreover when contrasting abundance in the final simulation year, the number of species with clearly less abundance in the climate change scenario far exceeded the number of species with greater abundance (Table 2). When contrasting climate versus reference scenarios, 73 species exhibited statistically lower climate change abundance in at least one contrast and never greater climate change abundance in any contrasts. By comparison, only 17 species exhibited only greater climate change abundances and 13 species exhibited a mix of greater or lesser climate change abundances across contrasts (Data_repository/Results/Species_scenario_differences.csv). Considering the similarity in abundance changes regardless of whether climate-related wildfire dynamics were retained in reference scenarios, these projections appear to arise from direct climate change effects on vegetation rather than indirect effects on wildfire.

Table 1. The number of bird species with statistically clear increases and decreases in abundance (i.e., 80% credible intervals for abundance change over time above and below zero, respectively) from year 0 to 40 for the Kaibab National Forest when applying a predictive model to simulated vegetation change under alternative climate scenarios (canesm, ccsm, inm, ipsl, and mirocesm) and corresponding reference scenarios that either maintained expected changes in wildfire or eliminated both climate and wildfire change.

Scenario	*n* Species	
	increases	decreases
canesm	17	53
ccsm	22	46
inm	1	65
ipsl	4	71
mirocesm	20	52
canesm fire, no climate change	33	31
ccsm fire, no climate change	33	31
inm fire, no climate change	34	32
ipsl fire, no climate change	33	31
mirocesm fire, no climate change	33	31
no climate or fire change	33	32

Table 2. The number of bird species with statistically clearly greater and lesser abundance when contrasting climate versus reference scenarios (i.e., 80% credible intervals for climate minus reference abundance was above and below zero, respectively) in year 40 for the Kaibab National Forest when applying a predictive model to simulated vegetation change under alternative climate scenarios (canesm, ccsm, inm, ipsl, and mirocesm).

Scenario		*n* Species	
Climate	Reference	greater	lesser
canesm	Fire	12	60
	Baseline	11	61
ccsm	Fire	19	49
	Baseline	18	48
inm	Fire	1	71
	Baseline	1	66
ipsl	Fire	4	77
	Baseline	4	74
mirocesm	Fire	13	51
	Baseline	11	51

Study limitations and future directions

The work described here projects clear negative impacts of climate change on bird populations within the Kaibab National Forest over the next 40 years, but these results are largely preliminary especially when considering certain study limitations. We suggest several ways the data repository accompanying this report could be leveraged to meaningfully contribute to scientific knowledge and inform forest management.

The first step to understanding projections reported here would be to examine which species are projected to increase and decline with climate change, and identify the vegetation drivers underlying these projections. Population changes projected here are all derived from estimated abundance relationships with vegetation conditions informed by contemporary data, and projected changes in these conditions with changing climate. The most prominent projected changes in vegetation conditions apparent in landscape-side summaries are declining extent of ponderosa pine forest and expansion of pinyon-juniper woodland (Data_repository/Results/Scenario_veg_changes.csv). Species relationships with covariates quantifying the extent of these ERUs were consistent with current knowledge on species ecology. Ponderosa pine forest associates, like Grace's Warbler, exhibited a positive relationship with this ERU (i.e., negative relationships with all other ERUs since ponderosa pine forest was the reference ERU), whereas pinyon-juniper associates, like Pinyon Jay, related positive with the pinyon-juniper woodland. Some ponderosa pine forest associates, such as Williamson's Sapsucker and Pine Siskin, are associated to decline in population with climate change as expected given the projected trajectory of this ERU. Nevertheless, other population projections are on the surface counter-intuitive (e.g., Pinyon Jay decline despite increasing prevalence of pinyon-juniper woodland). Thorough analysis is therefore necessary to identify which vegetation changes are primarily driving population changes observed for each species (e.g., holding each attribute constant and evaluating how much doing so affects population projections).

A number of study limitations are worth considering and suggest avenues for leveraging this data repository to gain knowledge and inform management. We did not implement any model checking, so evaluating model fit and predictive performance using cross-validation would be prudent (Wenger and Olden 2012, Conn et al. 2018). Additionally, the applicability of any model informed with data is largely limited to the range of conditions represented in the data to which the model was trained. For some continuous vegetation metrics such as canopy cover, cautious application of estimated relationships somewhat outside the range of values represented in available data may be reasonable. Application in ERUs outside those represented in the data, however, is impossible except to ERUs that we can assume are close enough to be lumped with sampled ERUs. We did lump some ERUs outside the bird sample with those inside the sample to broaden the prediction extent (see Data_repository/Results/ERUs_KANF.csv).

With the vegetation modeling, there were a number of limitations in the methods, particularly related to creating the climate informed model. The MC2 vegetation types are much coarser than the ERUs, meaning that in developing the crosswalk based on spatial overlays, multiple ERUS could be contained within one MC2 vegetation type. This could lead to rare or niche specific ERUs being spread across the wider landscape without keeping to the original ecological context of the ERU. Such an example is with the sand sage ERU, which unexpectedly spread into initially forested areas within the ccsm climate simulation resulting in substantial restriction of model applicability to this scenario. Consequently, more time and effort could be taken to evaluate each possible MC2 / ERU transition and prevent or limit unlikely transitions. Another issue is that the ecological realities of vegetation type change are more complex than a single probability. One commonality across most of the future climate projections, where pinyon-juniper woodlands are expected to replace ponderosa pine forests, is one that has been observed before (Allen and Breshears 1998). The reasons for it are much more complex, likely resulting from a failure of regeneration by the ponderosa pine combined with some mortality agent (e.g., drought, insect, or fire) for the ponderosa that would allow for the more shade intolerant pinyon-juniper woodland to be able to occupy that area (Minott and Kolb 2020). Moreover, changes within no-analog ERUs could arise or tree species composition could change within ERUs (e.g., loss of pinyon pine from pinyon-juniper woodland), compromising model applicability for prediction in unanticipated ways. Data outside KANF boundaries in the surrounding landscape or data capable of representing or accounting for no-analog vegetation conditions could improve the bird population projections.

The data repository presented here will be most valuable to the KANF if leveraged to inform specific and well-articulated management objectives. The KANF has identified Grace's Warbler, Western Bluebird, and Ruby-crowned Kinglet as focal species for monitoring under the forest plan. These three species vary in their projected responses to climate change among each other and particular scenarios. Evaluating the vegetation drivers of projected population changes for these species could yield valuable knowledge and insight for meeting management objectives targeting these species. More broadly, broader objectives concerning biodiversity as a whole may benefit from evaluating climate change projections for metrics of diversity (Roswell et al. 2021). Raw species-level MCMC predictions (Data_repository/Results/spp_predN_stacks) could be readily synthesized to project a wide range of diversity metrics under alternative scenarios. Moreover, diversity metrics for various species groups or assemblages could help synthesize and tailor climate projections to inform particular objectives (e.g., Latif et al. 2020, 2023).

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