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Original Research

Optimizing Targeting of Pinyon-Juniper Management for Sagebrush Birds of Conservation Concern While Avoiding Imperiled Pinyon Jay[☆]

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A B S T R A C T

Contemporary restoration and management of sagebrush-dominated (*Artemisia* spp.) ecosystems across the intermountain west of the United States increasingly involves the removal of expanding conifer, particularly juniper (*Juniperus* spp.) and pinyon pine (*Pinus edulis*, *P. monophylla*). The impetus behind much of this management has been the demonstrated population benefits of sagebrush restoration via conifer removal to greater sage-grouse *(Centrocercus urophasianus)*, a species of conservation concern. One of the challenges with scaling up from a focal-species approach to a community-level perspective, however, is balancing the habitat requirements of different species, some of which may overlap with sage-grouse and others which may have competing habitat needs. Here, we use a systematic conservation planning approach to compute spatial optimizations that prioritize areas for conifer removal across the sage-grouse range while incorporating woodland and sagebrush songbirds into decision making. Three of the songbirds considered here, Brewer's sparrow *(Spizella breweri)*, green-tailed towhee *(Pipilo chlorurus)*, and sage thrasher *(Poocetes gramineus)*, are sagebrush-obligates, while another is a woodland-obligate, the pinyon jay *(Gymnorhinus cyanocephalus)*. We find that the inclusion of sagebrush-obligates expands the model-selected area of consideration for conifer management, likely because habitat overlap between sagebrush-obligates is imperfect. The inclusion of pinyon jay, a woodland-obligate, resulted in substantial shifts in the distribution of model-selected priority areas for conifer removal, particularly away from pinyon jay strongholds in Nevada and east-central California. Finally, we compared the conifer optimizations created here with estimates of ongoing conifer removal efforts across the intermountain west and find that a small proportion (13−18%) of management efforts had occurred on areas predicted as being important for pinyon jay, suggesting that much of the ongoing work is already successfully avoiding critical pinyon jay habitat areas.

Introduction

Conifer expansion into sagebrush-dominated (*Artemisia* spp.) ecosystems is an ongoing phenomenon that has garnered attention in recent years (Miller et al. 2008; Miller et al. 2011; Chambers et al. 2017; Miller et al. 2019). The extent of native juniper (*Juniperus* spp.) and pinyon pine (*Pinus edulis, P. monophylla*) woodlands in western North America has increased substantially since 1860, with cover increases ranging between 125% and 625% depending on the region (Miller et al. 2008). Much like other instances of woodland expansion into grass- and shrub-dominated systems

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from around the world (see Nackley et al. 2017), pinyon-juniper expansion into sagebrush systems is a concern due to the associated changes in plant diversity (Miller et al. 2000; Bates 2005), ecosystem resistance and resilience (Chambers et al., 2007; Chambers et al. 2014; Miller et al. 2014), and impacts on native wildlife (Rickart et al. 2008; Baruch-Mordo et al. 2013; Severson 2016). The ongoing impact of pinyon-juniper expansion on these different aspects of sagebrush ecosystems has elicited a strong interest in restoration and management efforts focused on reducing and removing expanding pinyon-juniper woodlands across the US Intermountain West (Miller et al. 2017; Maestas et al. 2021).

Much of the pinyon-juniper management being conducted in sagebrush ecosystems has been driven by conservation interest in the greater sage-grouse (*Centrocercus urophasianus,* hereafter "sage-grouse"), largely because this imperiled species was a candidate for listing under the US Endangered Species Act (USFWS 2015). Recent management activities have largely focused on removing pinyon-juniper from sites with relatively low tree canopy cover, in response to research conducted by Baruch-Mordo et al. (2013), which found the sage-grouse to be sensitive to even low levels of conifer cover (~3–4%) on breeding sites. This revelation has spurred both management activities and motivated numerous studies assessing pinyon-juniper removal as an integral component of sage-grouse habitat improvement (e.g., Severson et al. 2017a, 2017b; Olsen et al. 2021). Much of this recent work reinforces the efficacy of pinyon-juniper removal as a tool for sage-grouse conservation via a number of different metrics, including increasing nesting habitat availability, space-use, bird abundance, and population growth (Olsen et al. 2021; Sandford et al. 2017; Severson et al. 2017a, 2017b).

Several broad-scale spatial datasets and decision-support tools have been developed in tandem with the growth in sage-grouse and pinyon-juniper management activities and research. One of the most fundamental of these is a high-resolution (1-m^2) conifer cover map (Falkowski et al. 2017), which provides a synoptic view of pinyon-juniper across the 458 000 km^2 sage-grouse range. This dataset has been used by land managers and stakeholders as a planning tool and, in conjunction with other data, has informed a number of research efforts, including assessments of the impact of conifer expansion on sage-grouse nesting site selection (Severson et al. 2017a) and developing frameworks for considering local-scale conifer cuts in a landscape context (Reinhardt et al. 2017). Broad-scale datasets and analyses such as this have also proven essential for evaluating ongoing conifer management efforts (Reinhardt et al. 2020). Recently developed tools such as the Rangeland Analysis Platform (Jones et al. 2018; Allred et al. 2021) expand the spatial toolset even further and make data available to managers and scientists by incorporating a wide range of vegetative cover types across large timescales.

The expansion of these large-scale spatial analyses and tools to include other species and community components is encouraging because while the sage-grouse has been much of the impetus behind conifer removal efforts in sagebrush systems, several other species have been shown to benefit from conifer management (Maestas et al. 2021). Removal of conifers from sagebrush systems results in more herbaceous plant cover and biomass (Bates et al. 2017; Bates et al. 2019; Fick et al. 2022), increases in Brewer's sparrow *(Spizella breweri),* green-tailed towhee *(Pipilo chlorurus),* and vesper sparrow *(Poocetes gramineus)* populations (Crow and Van Riper 2010; Donnelly et al. 2017; Holmes et al. 2017), enhanced mule deer *(Odocoileus hemionus)* fawn overwintering survival (Bergman et al. 2014a), and possibly mule deer size and condition (Bender et al. 2013; Bergman et al. 2014b).

While sage-grouse—acting as a focal-species driver of sagebrush ecosystem restoration—has been beneficial for a number of species, it is also important to consider the possible nontarget negative impacts of what has effectively been an umbrella species approach to management (Rowland et al. 2006; Zeller et al. 2021). Indeed, there has been an ongoing debate regarding whether pinyon-juniper removal efforts in support of sage-steppe improvement projects is resulting in substantial loss of pinyon-juniper woodlands and negatively impacting woodland-associated species (Boone et al. 2018; Coe et al. 2018; Clark et al. 2019; Maestas et al. 2019; Zeller et al. 2021). A recent review (Bombaci and Pejchar 2016) found little overall negative impact of conifer removal on woodland associate species, but data were lacking for some taxa, particularly invertebrates. One species of particular concern with regard to conifer removal is the pinyon jay *(Gymnorhinus cyanocephalus).* Pinyon jay populations have demonstrated significant long-term rangewide population declines (Sauer et al. 2017) and is a species of high conservation concern (Boone et al. 2018). Given pinyon jay reliance on pinyon pine woodlands, there has been some concern that sagebrush management efforts incorporating conifer removal may adversely affect the species. Despite these concerns, however, there has been relatively little work has been done to examine potential mechanisms behind the pinyon jay's population decline or effects of woodland management relative to drought or other ecosystem stressors (Boone et al. 2018).

Given the potential multispecies implications of conifer removal, it is important for management planning tools and datasets to incorporate species with potentially overlapping and competing habitat requirements, beyond sage-grouse alone. Here, we use a systematic conservation planning approach implemented as a spatial optimization scenario to target conifer removal in a way that balances the habitat requirements of multiple bird species. Specifically, we set out to optimize areas for conifer removal based on habitat requirements of the greater sage-grouse, three sagebrush-obligate songbirds: the Brewer's sparrow, sage thrasher *(Oreoscoptes montanus),* and green-tailed towhee, and the woodland-obligate pinyon jay. Each of the sagebrush-obligate songbirds and the pinyon jay were selected because they demonstrate long-term population declines based on North America Breeding Bird Survey data (Sauer et al. 2017; Tack et al. *in review*).

Our objectives in this work were to 1) assess the relative effect of incorporating different types of species habitat requirements on optimal locations for conifer removal across the sage-grouse range, 2) evaluate in detail the effect of incorporating pinyon jay—a woodland obligate with potentially competing habitat requirements—on conifer removal optimization, and 3) determine how recent conifer removal efforts align with the different optimizations, particularly as it relates to areas potentially important to pinyon jay.

Methods

Study area

We considered the same region of the intermountain west for which canopy cover was mapped by Falkowski et al. (2017), including parts of Oregon, Idaho, Montana, California, Nevada, Utah, Wyoming, and Colorado. This region overlaps with Western Association of Fish and Wildlife Agencies Sage-Grouse Management Zones III, IV, V, and VII, covering approximately 458 000 km^2, 134 000 km^2 of which has at least some conifer cover (i.e., > 0%). A substantial portion (250 971 km^2) of the study area falls within US Fish and Wildlife Service Priority Areas for Conservation for sage-grouse (US Fish and Wildlife Service 2013).

The study area is dominated by sagebrush ecosystems, pinyon pine and juniper woodlands, and agricultural land (Miller et al. 2008; Homer et al. 2015). The area of interest encompasses a large portion of the intermountain west where climate conditions tend to be cold and dry (Kottek et al. 2006). Summer (June-August) temperatures generally range from a maximum of

11.3°C to 37.3°C to minimums of −1.2°C to 17.1°C, while winter (December−February) temperatures range from a maximum of −6.2°C to 11.5°C with a minimum of −19.5°C to −1.8°C (Daly et al. 2008). Summer precipitation averages between 16 and 212 mm, while winter averages between 13 and 532 mm (Daly et al. 2008).

Data

A series of geospatial datasets were required to conduct the optimization analyses. To identify where pinyon-juniper woodlands were located on the landscape in our study area, we used the high-resolution conifer cover prediction map created by Falkowski et al. (2017). This dataset maps conifer at a 1-m spatial resolution and was created using a spatial wavelet analysis approach (Falkowski et al. 2006) on National Agricultural Imagery Program aerial imagery. Areas important to sage-grouse were identified using a sage-grouse distribution model created by Doherty et al. (2016) using a random forest modeling approach in conjunction with numerous environmental considerations including sagebrush cover, perennial and intermittent water availability, climate factors, and topography. Habitat suitability models for each of the songbirds included in this analysis (Brewer's sparrow, green-tailed towhee, sage thrasher, and pinyon jay) were obtained from the US Fish & Wildlife Service (Tack et al. *in review*). Each model was created using a random forest modeling approach in conjunction with environmental data and North American Breeding Bird Survey data (Sauer et al. 2017). All spatial data were aggregated by computing zonal statistics across a hexagonal grid with 16.24 km^2 grid cells (2.5 km on a side). The relatively coarse scale of data aggregation reflects our interest in broad landscape-level patterns rather than fine-scale details.

Analysis

We used an integer linear programming (ILP) approach (Beyer et al. 2016; Hanson et al. 2019) to compute the optimization of areas for pinyon-juniper removal across six different sage-grouse and songbird data combinations (Table 1). Brewer's sparrow was considered in a scenario configuration alongside sage-grouse on its own and in the "all sagebrush-obligate songbirds" group as it is the sagebrush-obligate with the largest population declines among those included in this study (Tack et al. *in review*). The ILP optimization was computed using the *prioritizr* package in R (Hanson et al. 2019) and leveraged the *Gurobi* solver (Gurobi Optimization 2017). Optimizations were run using a minimum set objective that seeks to select a combination of grid cells which minimizes a "cost" parameter while meeting goals for "conservation features" (Beyer et al. 2016; Hanson et al. 2019). The spatial unit of data aggregation was a hexagonal grid, where each hexagon was approximately 16.24 km^2. Sage-grouse along with the sagebrush obligate songbirds were the conservation features. Cost was a function of canopy cover for optimization scenarios not including pinyon jay, and canopy cover + pinyon jay habitat suitability for optimizations that included the species, such that grid cells with high canopy cover and high pinyon jay habitat suitability represented high-cost areas. This will result in the optimization preferentially selecting areas of lower canopy cover and lower pinyon jay habitat suitability, which is our goal. Grid cells that contained no conifer cover were excluded from analyses as they contained no conifer to prioritize for removal. We set proportional targets of 0.3 for each conservation feature, in line with the International Union for Conservation of Nature stated goal of 30% area-based conservation targets (Woodley et al. 2019) and previous assessments of minimum set objectives (Rodrigues et al. 2000; Ardron et al. 2010), and we used a boundary penalty of 0.001 to discourage heavily fragmented solutions (Ardron et al. 2010).

We generated a portfolio of the top 100 solutions for each optimization scenario; increasing the portfolio beyond 100 in preliminary runs had no significant impact on overall results or trends. Selection frequency (sf), which is the proportion of solutions in which a particular grid cell was selected as a priority for conifer management, was used as an indicator of relative importance (Carwardine et al. 2007; Ardron et al. 2010). Spatially explicit selection frequency was computed for all optimizations, and the distributions were summarized using kernel density plots. Kolmogorov-Smirnov tests were used alongside linear models to evaluate the potential impacts both between and within states of adding pinyon jay as a consideration to each of the three sagebrush obligate combinations. Optimization results were compared between states using density plots of the values and within states using linear models. Statistical analyses of the optimization scenarios were conducted using R (R Core Team, 2019).

Differences between conifer optimizations that included and excluded pinyon jay were computed using zonal subtraction. These differences in priority as a result of the inclusion of pinyon jay were compared with estimates of recent conifer removal efforts attributable to management as predicted by Reinhardt et al. (2020). Areas of conifer removal were sorted into categories on the basis of whether they overlapped areas where the inclusion of pinyon jay caused a loss in selection frequency (i.e., areas that may be particularly important to pinyon jay), a gain in selection frequency (i.e., areas that may be less important to pinyon jay but important to the other species in the optimization), or areas of little to no change (Δsf < ±0.5 standard deviation).

Table 1
Six different sage-grouse and songbird data configurations used to generate conifer removal optimizations.

Optimization scenario configuration	Label
Sage-grouse only	SG only
Sage-grouse, Brewer's sparrow	SG + BRSP
Sage-grouse, all sagebrush-obligate songbirds	SG + SBSong
Sage-grouse, pinyon jay	SG only + PIJA
Sage-grouse, Brewer's sparrow, pinyon jay	SG + BRSP + PIJA
Sage-grouse, all sagebrush-obligate songbirds, pinyon jay	SG + SBSong + PIJA

Results

The conifer optimizations selected between 4 676 and 6 999 grid cells (75 938.24 and 113 663.76 km^2) in at least one solution (sf > 0) for the entire study area. The sage-grouse only and sage-grouse + pinyon jay optimizations selected the smallest amount of area and all four optimizations incorporating additional sagebrush obligates selecting > 6 000 cells (97 440 km^2, Table 2).

Adding pinyon jay to any optimization scenario resulted in appreciable changes in selection frequency distribution across states (see Table 2). Because the optimizations were computed using a minimum set objective, reductions in selection frequency in one area would necessarily lead to increases in selection frequency in

Table 2
Number of 16.24 km^2 grid cells selected at least once for each model. Results are summarized rangewide and within four influential states containing the most conifer (see Fig. 1).

	Sagebrush obligates only			Pinyon jay included		
Area	SG only	SG + BRSP	SG + SBSong	SG only	SG + BRSP	SG + SBSong
Rangewide	4 869	6 769	6 999	4 676	6 294	6 678
Idaho	389	855	806	423	909	871
Nevada	2 040	2 345	2 682	1 644	1 663	1 785
Oregon	907	1 021	797	927	1 157	1 031
Utah	923	1 083	1 274	1 105	1 074	1 309

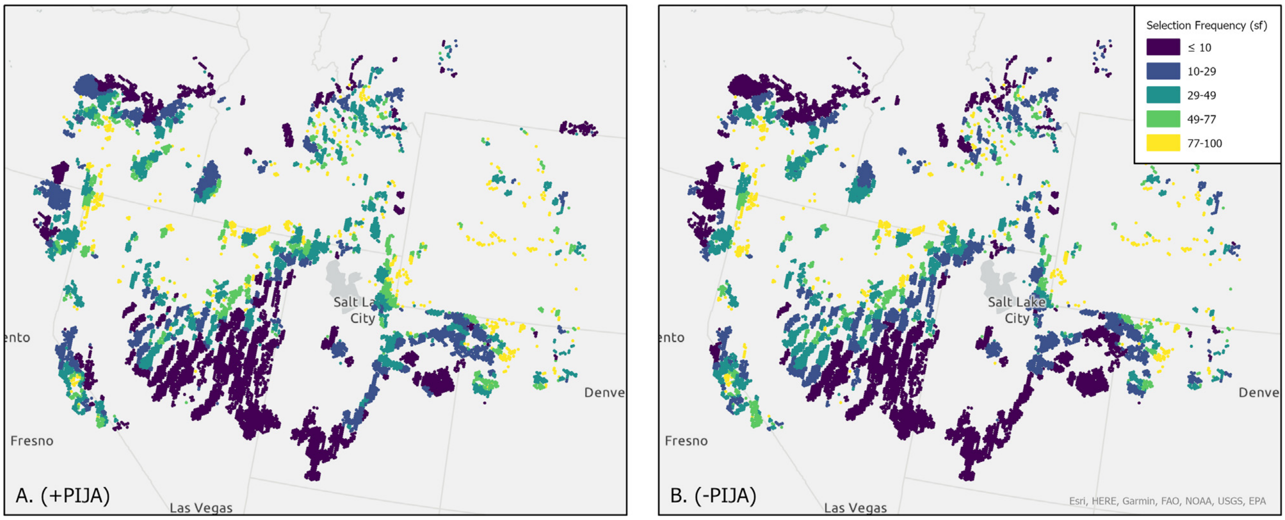

Figure 1. Conifer optimizations for sage-grouse + all sagebrush-obligate songbird combinations. Optimization **A**, with and **B**, without pinyon jay (PIJA). Warmer colors depict higher selection frequency (sf) indicating the most optimal places for conifer removal. Each map grid cell is a 16.24 km^2 hexagon, 2.5 km on a side. Areas where sf = 0 were not colored, as were areas with no conifer cover because there was no conifer to prioritize. Note that when PIJA was included in the optimization (**A**), selection frequency was lower in many parts of Nevada and Utah.

other areas. Broadly, the inclusion of pinyon jay resulted in a reduction of area selected in Nevada and an increase in area selected in Oregon, Idaho, and, to a lesser extent, Utah and other areas of Nevada (see Table 2, Fig. 1). The largest change was found in the sage-grouse + all sagebrush obligate songbird optimization, where adding pinyon jay resulted in a decrease of approximately 900 grid cells in Nevada (14 616 km^2; see Table 2, Fig. 1).

Pinyon jay also had an impact on the overall selection frequency distributions, resulting in significant changes in how often particular areas were selected, given that they were selected at all (Fig. 2). Indeed, while we found coarse overall relationships between the selection frequencies of models with and without pinyon jay (sage-grouse only $r^2 = 0.803$; sage-grouse + Brewer's sparrow $r^2 = 0.884$; sage-grouse + all sagebrush obligates $r^2 = 0.783$), the inclusion of pinyon jay resulted in meaningful changes to the overall shape of the distribution (sage-grouse only $D = 0.059$, $P < 0.001$; sage-grouse + Brewer's sparrow $D = 0.077$, $P < 0.001$; sage-grouse + all sagebrush obligates $D = 0.078$, $P < 0.001$) (see Fig. 2).

In addition to the quantifiable impact of including pinyon jay in the conifer optimizations at the sage-grouse rangewide scale, we also found apparent impacts at the state level, particularly for the four states (see Fig. 1) with the most prioritized conifer in our analyses. While linear relationships were generally apparent between the selection frequencies of optimizations with and without pinyon jay (ranging from $r^2 = 0.693$ to $r^2 = 0.952$; Table 3), the inclusion of the pinyon-juniper woodland obligate species had an impact on the overall shape of the selection frequency distributions across each state in all instances except the sage-grouse + all sagebrush obligate optimization for Idaho ($D = 0.087$, $P = 0.092$) (see Table 3, Fig. 3).

A comparison of areas experiencing selection frequency loss or gain as a result of the inclusion of pinyon jay to the conifer optimizations (Fig. 4) with areas of predicted conifer removal occurring between 2011 and 2013 and 2015 and 2017 (Reinhardt et al. 2020) (see Fig. 4) indicated that a majority of estimated management efforts have occurred in areas experiencing an increase in selection frequency as a result of the inclusion of pinyon jay (sage-grouse only: 259.5 km^2, 19.4% of estimated management efforts; sage-grouse + Brewer's sparrow: 331.5 km^2, 24.8%; sage-grouse + all sagebrush obligates: 293.3 km^2, 22%) or in areas experiencing little to no change in selection frequency ($\Delta sf < \pm 0.5$ SD) (sage-grouse only: 876.15 km^2, 65.6% of estimated management efforts; sage-grouse + Brewer's sparrow: 828.2 km^2, 62%;

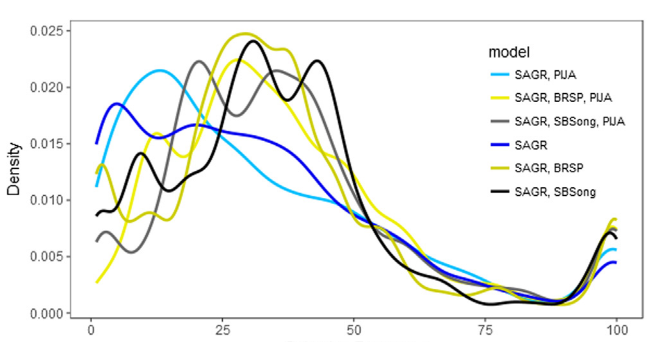

Figure 2. Distributions of selection frequencies for kernel density plots across the study area (see Fig. 1). Color pairings for six bird groupings depict models with (lighter) and without pinyon jay (darker).

Table 3
Impact of adding pinyon jay (PIJA) into optimizations, as measured by differences in distributions of selection frequencies (sf) across the range of sage-grouse and within Nevada, Oregon, Utah, and Idaho. Differences in sf distributions were assessed via the Kolmogorov-Smirnov test (*D* statistic).

Scope	Model set	*D*	*P*	r^2
Rangewide	SG only	0.059	< 0.001	0.803
	SG + BRSP	0.077	< 0.001	0.884
	SG + SBSong	0.078	< 0.001	0.783
NV	SG only	0.118	< 0.001	0.871
	SG + BRSP	0.760	< 0.001	0.768
	SG + SBSong	0.096	< 0.001	0.795
OR	SG only	0.117	< 0.001	0.952
	SG + BRSP	0.070	0.009	0.892
	SG + SBSong	0.128	< 0.001	0.871
UT	SG only	0.167	< 0.001	0.827
	SG + BRSP	0.219	< 0.001	0.838
	SG + SBSong	0.277	< 0.001	0.800
ID	SG only	0.087	0.092	0.770
	SG + BRSP	0.099	< 0.001	0.693
	SG + SBSong	0.096	< 0.001	0.731

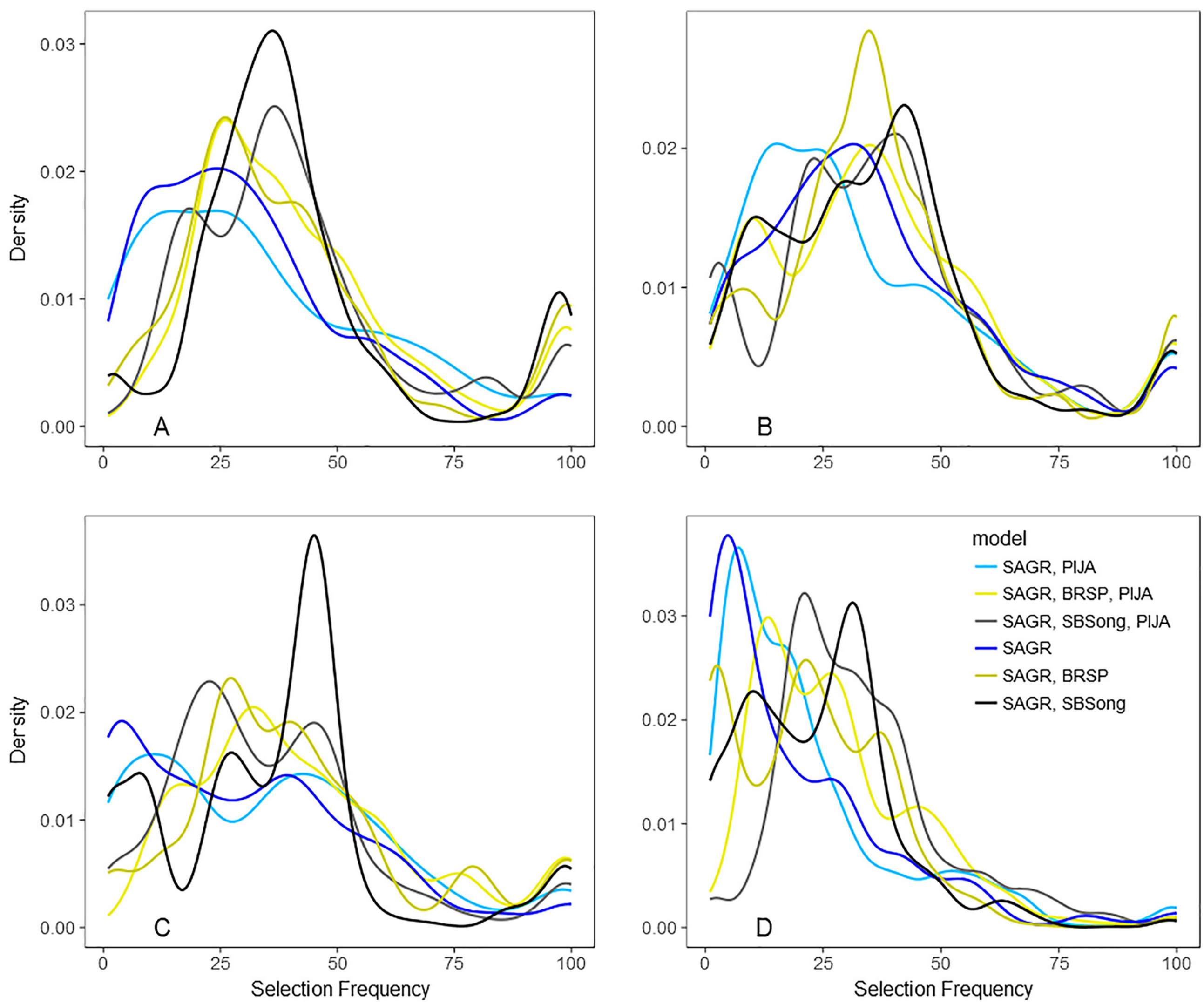

Figure 3. Variability in selection frequencies among **A**, Nevada, **B**, Oregon, **C**, Utah, and **D**, Idaho. Color pairings depict models with (lighter) and without pinyon jay (darker).

sage-grouse + all sagebrush obligates: 798.52 km^2, 59.8%). Relatively fewer estimated conifer removal efforts occurred on areas demonstrating a loss in selection frequency as a result of the incorporation of pinyon jay (sage-grouse only: 199.9 km^2, 14.9% of estimated management efforts; sage-grouse + Brewer's sparrow: 175.8 km^2, 13.2%; sage-grouse + all sagebrush obligates: 243.7 km^2, 18.2%).

Discussion

Here, we provide a set of spatial optimizations of areas for conifer removal across the sage-grouse range, which balances the habitat requirements of multiple species, some of which share habitat overlap with the sage-grouse and one which demonstrates competing habitat requirements. Total area considered (i.e., selected at least once) in the optimizations ranged from 79 072 km^2 in the sage-grouse–only scenario to > 100 000 km^2 in the sage-grouse + all sagebrush-obligates scenario. Indeed, adding sagebrush-obligate songbirds to the optimization scenarios resulted in an across-the-board increase in areas selected for conifer management by the algorithm (Table 2). While a substantial change, this is an unsurprising result because while the sagebrush obligate songbirds likely share many important habitat characteristics with sage-grouse, they are unlikely to demonstrate perfect overlap (see e.g., Rowland et al. 2006). Adding additional sagebrush obligates to the optimization scenario was therefore likely to expand the area selected for conifer removal.

The incorporation of pinyon jay resulted in substantial changes to overall optimization results, changing the distribution of priority areas overall (see Fig. 2) and between states (see Table 2, Fig. 1). This shift in priority reflects the competing habitat requirements of pinyon jay and the sagebrush obligate species. Areas most important to pinyon jay, comprising most of the species' range, were largely located in Nevada and Utah. It was in this region where the largest apparent impact of incorporating pinyon jay on the conifer removal optimizations was apparent (see Fig. 4), with several large areas demonstrating a loss in priority when pinyon jay was incorporated into the optimization scenario. There were corresponding gains in priority in many areas not associated with pinyon jay, particularly in Oregon, Idaho, and other parts of Utah and Nevada (see Figs. 1 and 4). Care should be taken when considering these "gains" in priority, however, as this shift is—in part—the result of potential priority areas in pinyon jay strongholds becoming more "costly," and so the optimization, using a minimum set objective, instead selects other areas for conifer management. The gain in selection frequency here is therefore a result of these areas simply being less costly than areas that contain pinyon jay strongholds.

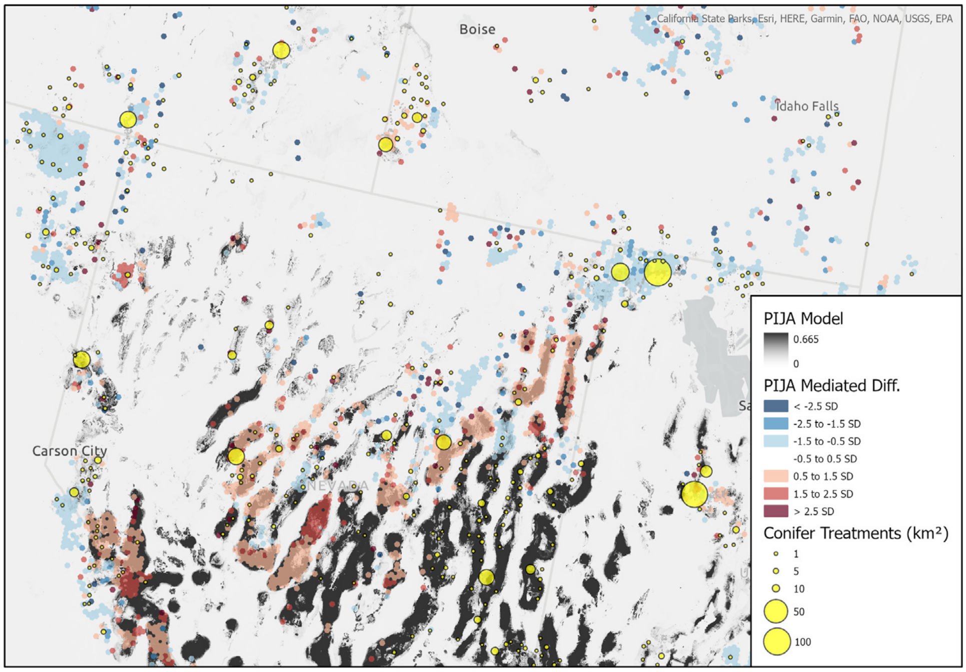

Figure 4. Difference in selection frequencies (sf) between sage-grouse + all sagebrush-obligate songbird models with and without pinyon jay. Blue shading depicts increasing sf with pinyon jays, and red shading illustrates decreasing sf with the inclusion of pinyon jay. Grayscale represents pinyon jay habitat suitability from Tack et al. (2022). *Yellow circles* represent conifer removal treatments as predicted by Reinhardt et al. (2020), with larger circles representing larger treatments. Most (81.8%) treatments are outside of pinyon jay strongholds, suggesting that ongoing management largely avoids pinyon jay habitat.

The areas where the inclusion of pinyon jay results in a meaningful loss in priority (see Fig. 4) do not necessarily imply conifer removal should be avoided, but instead these areas represent places where a more nuanced and holistic approach to conifer removal is likely required to balance the needs of sagebrush obligates with pinyon jay. The long-term population decline of the pinyon jay (Sauer et al. 2017; Tack et al. *in review*) coincides with the long-term expansion and infill of native conifer woodlands across the intermountain west (Miller et al. 2008; Fillippelli et al. 2020), suggesting that habitat quantity may not be a driving factor in population decline (Boone et al. 2018). Boone et al. (2018) indicate that factors such as pinyon pine growth and productivity, aspects of habitat quality, landscape structural changes, and climate change may be driving pinyon jay population declines, and some of these factors may be impacted by conifer removal efforts in the areas identified by our analyses. Given current gaps in our knowledge about how pinyon jay responds to conifer management, coupling co-produced science and monitoring (Naugle et al. 2020) with woodland restoration efforts in the Central Basin and Range Ecoregion seems prudent to addressing changing woodland conditions (Filippelli et al. 2020; Shriver et al. 2021) in an adaptive management framework.

Our comparison of the spatially explicit effects of pinyon jay on the optimization scenarios in this study with recent areas of conifer removal as estimated by Reinhardt et al. (2020) revealed that a small proportion (13–18%) of management efforts had occurred on areas we surmise as being important for pinyon jay (see Fig. 4). The large majority of management efforts appear to be occurring in areas we predict as being less important to pinyon jay (i.e., areas where incorporating pinyon jay results in a gain in priority, or little to no change). While these results may be limited by the fact that the analysis of conifer removal was conducted across roughly the same time period as the pinyon jay analyses (2011–2013 to 2015–2017 for the conifer analysis and 2011–2016 for the pinyon jay analysis), this result remains encouraging because it falls in line with other recent work demonstrating similar results (Tack et al. *in review*). Considered together, these results suggest that the ongoing management of encroaching conifer woodlands in sagebrush ecosystems across the intermountain west is largely avoiding areas that may be particularly important for pinyon jay. This result provides additional context for the ongoing debate regarding sage-steppe habitat improvement efforts, and the question as to whether pinyon-juniper removal efforts are resulting in widespread loss of habitat for pinyon-juniper woodland-associated species (Boone et al. 2018; Coe et al. 2018; Clark et al. 2019; Maestas et al. 2019). More broadly, our optimization results suggest an abundance of opportunities for sagebrush habitat restoration in areas outside pinyon jay strongholds (see Figs. 1 and 4).

Optimization results incorporating all species (see Fig. 1) suggest that some of the highest-priority areas remain consistent whether pinyon jay is included in the assessment or not. This includes large parts of central and southeastern Oregon, the northeastern corner of California, northern Utah, and Idaho, particularly southwest Idaho. These high-priority areas also happen to be some of the big “hotspot” regions in terms of quantified ongoing conifer removal efforts (see Fig. 4), suggesting that the broad collaborative effort to restore sagebrush ecosystems and remove encroaching conifer across much of the west has so far successfully targeted some of the best-available areas for conifer removal as indicated by our optimizations.

In addition to the important implications of our analyses with regard to conifer removal priority, sagebrush obligate bird species, and pinyon jay, the optimizations created here have the potential to be useful as decision support tools when considering and planning conifer removal efforts across the western United States. These results, while spatially explicit, are intentionally coarse (16.24 km^2 hexagonal grid) because they seek to analyze large-scale patterns in conifer optimization across the intermountain west while incorporating multiple species with differing habitat requirements. Local-level assessments of ecological site potential and conditions are still required to determine appropriateness of conifer removal treatments and risks (e.g., invasive annual grasses). The systematic conservation planning approach that the optimizations in this study employed, however, are quite adaptable; this approach could be extended or modified to include additional bird species or other taxa or to consider management goals beyond conifer removal. Indeed, we hope that the approach outlined here will provide a useful blueprint for future analyses.

This work builds on previous and ongoing research concerned with sage-grouse conservation, sagebrush ecosystem restoration, and a growing focus on restoration that can realize multispecies benefits. The optimizations conducted here seek to evaluate the potential differences in conifer removal priority for specific areas as a result of the inclusion of species beyond the sage-grouse, including other sagebrush obligates and species with competing habitat requirements in the pinyon jay. Consideration of taxa beyond birds is likely to be important going forward, as sagebrush ecosystem management efforts become increasingly community focused. The continued integration of new spatial datasets into management optimizations will arm managers on the ground with the tools necessary to ensure conservation goals are met for co-occurring species with divergent habitat requirements.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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