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Quantifying Pinyon-Juniper Reduction within North America's Sagebrush Ecosystem☆

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ABSTRACT

One of the primary conservation threats surrounding sagebrush (*Artemisia* spp.) ecosystems in the Intermountain West of the United States is the expansion and infilling of pinyon pine *(Pinus edulis, P. monophylla)* and juniper (*Juniperus* spp.) woodlands. Woodland expansion into sagebrush ecosystems has demonstrated impacts on sagebrush-associated flora and fauna, particularly the greater sage-grouse *(Centrocercus urophasianus)*. These impacts have prompted government agencies, land managers, and landowners to ramp up pinyon-juniper removal efforts to maintain and restore sagebrush ecosystems. Accurately quantifying and analyzing management activities over time across broad spatial extents still poses a major challenge. Such information is vital to broad-scale planning and coordination of management efforts. To address this problem and aid future management planning, we applied a remote sensing change detection approach to map reductions in pinyon-juniper cover across the sage-grouse range and developed a method for rapidly updating maps of canopy cover. We found total conifer reduction over the past several yr (2011–2013 to 2015–2017) amounted to 1.6% of the area supporting tree cover within our study area, which is likely just keeping pace with estimates of expansion. Two-thirds of conifer reduction was attributed to active management (1.04% of the treed area) while wildfire accounted for one-third of all estimated conifer reduction in the region (0.56% of the treed area). Our results also illustrate the breadth of this management effort—crossing ownership, agency, and state boundaries. We conclude by identifying some key priorities that should be considered in future conifer management efforts based on our comprehensive assessment.

Introduction

In recent decades, heightened attention has been directed toward the ongoing expansion of conifer woodlands into predominantly treeless ecosystems across the western United States. Of particular concern is the expansion of native juniper (*Juniperus* spp.) and pinyon pine *(Pinus edulis, P. monophylla)* woodlands (hereafter, pinyon-juniper) into sagebrush ecosystems across the US Intermountain West. The extent of these woodlands is estimated to have increased between 125% and 625% since European settlement in the late 19th century (Miller et al. 2008). This trend of pinyon-juniper woodland expansion has been attributed to a number of factors including altered fire regimes, historic overgrazing, and shifting climate conditions, and the relative impact of these factors is still being debated (Miller and Station 2005; Van Auken 2009; Miller et al. 2011; Miller et al. in press). Ninety percent of pinyon-juniper woodland expansion has occurred at the expense of sagebrush ecosystems (Miller et al. 2011). Miller et al. (2008)

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estimated that 75% of impacted sagebrush sites will type-convert from shrublands (with < 10% pinyon-juniper canopy cover) to pinyon-juniper woodland (> 30% tree canopy) in the next 30–50 yr. However, these estimates do not account for recent information regarding the impacts of drought and climate change on pinyon-juniper woodlands (e.g., Friggens et al. 2012; Bradford et al. 2017; Snyder et al. 2019; Hartsell et al. 2020).

Ongoing pinyon-juniper expansion at the expense of other ecosystems is an example of a broader contemporary ecological trend. Recent literature contains several notable examples of woodlands encroaching into grassland and shrubland biomes across multiple continents (Ratajczak et al. 2012; Veldman et al. 2015; Stevens et al. 2017). Much of this woodland expansion has been driven by anthropogenic activity, which affects both top-down processes, such as altered fire regimes and grazing (Roques et al. 2001; Briggs et al. 2005; Staver et al. 2011; Peng et al. 2013), and bottom-up processes, such as changes in the distribution of resources via anthropogenically facilitated local and global environmental change (D'Odorico et al. 2010; Wigley et al. 2010; Nackley et al. 2017). While this woodland expansion is tempered in some regions by drought-induced tree mortality (Breshears et al. 2005; Flake and Wesiberg 2019), many systems, such as pinyon-juniper woodlands, are still experiencing net expansion and infill (Miller et al. 2008; Sankey and Germino 2008). These woodland expansions have been demonstrated to result in changes in plant diversity (Ratajczak et al. 2012), ecosystem structure and function (Parr et al. 2014), ecosystem services (Kim et al. 2016), and overall biodiversity (Murphy et al. 2016; Newbold et al. 2016). There has been a growing concern regarding the impact of pinyon-juniper woodland expansion in particular because the sagebrush-dominated ecosystems into which the woodlands are expanding have been associated with > 350 species of flora and fauna of conservation concern (Wisdom et al. 2005). One of these species, the greater sage-grouse (*Centrocercus urophasianus,* hereafter sage-grouse), has proven to be a catalyst for broad cooperative action across the Intermountain West of the United States (Miller et al. 2017).

Recently heightened conservation concerns regarding the sage-grouse (Fish and Wildlife Service 2015) have helped spur a partnership of public land managers, private landowners, state and federal agencies, and nongovernmental organizations into cooperative action to restore sagebrush ecosystems affected by pinyon-juniper woodland expansion. Removal of invading pinyon-juniper trees on sites with relatively low tree densities is a primary focus of management activities due in part to research by Baruch-Mordo et al. (2013) demonstrating that the birds abandon their breeding grounds in sagebrush-dominated landscapes when pinyon-juniper canopy cover reaches just 4%. Much of this restoration and management work takes advantage of new actionable science (e.g., Boyd et al. 2017; Chambers et al. 2017; Sandford et al. 2017; Severson et al. 2017a; Severson et al. 2017b; Olson 2019), spurred by the interest in sagebrush ecosystem restoration. While prior management primarily attempted to convert dense pinyon-juniper woodlands back into rangeland through an opportunistic patchwork of treatments, recent work has prioritized management of areas in early phases of pinyon-juniper expansion in strategic locations to remove invading trees from large acreages of sagebrush shrubland (NRCS 2015). Employing the well-known density-impact invasive species curve to guide management (Roberts et al. 2018), managers in the sagebrush ecosystem now focus on addressing tree invasions while densities are low, which can be more cost-effective and successful.

In support of ongoing pinyon-juniper management and sagebrush habitat restoration, Falkowski et al. (2017) created a publicly available conifer cover map (https://map.sagegrouseinitiative.com) derived from aerial remote sensing data. This dataset, which spans 458 000 km^2 at 1-m resolution, has been used by numerous land managers, agencies, and scientists to target pinyon-juniper management, primarily for the benefit of sage-grouse. Recent and ongoing research suggests that targeted pinyon-juniper removal in sagebrush ecosystems has expanded nesting habitat for sage-grouse (Severson et al. 2017a) and resulted in higher survival of females (Severson et al. 2017a), nests (Severson et al. 2017b), and their young (Sandford et al. 2017). These higher survival rates and increases in available nesting habitat are important components of one of the overarching goals of sage-grouse conservation: population growth. Indeed, Olson (2019) found pinyon-juniper removal treatments led to a 12% increase in population growth rate in the Warner Mountains of Oregon. These recent research efforts, as well as the outcomes from ongoing cooperative management efforts to strategically reduce pinyon-juniper expansion, were cited as a few of the reasons obviating the need to list sage-grouse as an endangered species (Fish and Wildlife Service 2015). Similar to other endangered species issues (Lawler et al. 2002), these efforts were catalyzed by sage-grouse conservation but are now expanding into a broader interest in restoring sagebrush ecosystems.

Ongoing pinyon-juniper management and sagebrush restoration efforts in the US Intermountain West highlight the importance of broad, cross-ownership cooperation and clear conservation objectives. Landscape-scale cross-ownership efforts, such as pinyon-juniper management, often face a number of entrenched disincentives hindering progress. These disincentives can include factors such as high short-term costs, uncertainty about future policy, incompatibility of organizational mandates, and differing stakeholder objectives (Kiss 2008; Jacobson and Robertson 2012; North et al. 2015). Outlining clearly defined objectives for cooperative management provides one means of overcoming these disincentives and enables land managers, policymakers, and scientists to play a role in both coordinating efforts and co-producing actionable science (*sensu* Beier et al. 2017; Naugle et al. 2019) that can be applied across ownership boundaries (Lemos et al. 2018).

One of the major challenges in the realm of pinyon-juniper management and sagebrush habitat restoration is quantifying ongoing conifer removal efforts. Despite early and ongoing cooperative efforts in managing pinyon-juniper expansion, a quantitative spatial assessment of pinyon-juniper management is still lacking. An overall approach for tracking these management efforts has proven incredibly difficult with currently available data, as management occurs across ownerships (federal, state, county, private) and the associated prescriptions and details are not always recorded in a temporally or spatially explicit manner. However, advances in remote sensing have enabled tracking of changes in forest cover at a global scale (Hansen et al. 2013) and may also prove useful for tracking changes in sparse woodlands over broad extents. Such tools may also allow for quantifying the relative changes in pinyon-juniper woodlands attributable to management versus wildfire. The ability to quantify and analyze pinyon-juniper management over time at broad scales is an important component for evaluating the overall distribution of effort, identifying potential gaps or opportunities for management, and comparing the extent of reduction efforts across different conservation considerations. Spatiotemporal tracking of pinyon-juniper management may also aid efforts to evaluate their ecological consequences including changes in the distribution and viability of sagebrush-obligates, as well as potential unintended effects such as facilitation of invasive exotics.

In this paper, we use remote sensing to update maps of tree canopy cover within the range of sage-grouse and quantify patterns in pinyon-juniper woodland reduction to aid future management. We developed an approach to rapidly update maps of canopy cover by incorporating temporally segmented Landsat time-series (Kennedy et al. 2010) and samples of high-resolution cover maps derived from aerial imagery (Falkowski et al. 2017) in a random forest regression model, which can be applied across broad extents. To quantify and map patches of cover reduction in the sage-grouse range, we apply a remote sensing change detection approach, which has proven invaluable for mapping forest disturbances across the United States (Kennedy et al. 2007; 2010; Cohen et al. 2018). Our objectives were to 1) assess the extent and magnitude of pinyon-juniper reduction within the sage-grouse range where conifer expansion is considered a threat, 2) illustrate the current and potential distribution of effort of pinyon-juniper management across ownerships and agencies, 3) quantify the contribution of wildfire in pinyon-juniper reduction, 4) produce updated maps of canopy cover, and 5) use these maps and analyses to inform future sagebrush ecosystem restoration.

Methods

This study uses advances in remote sensing and cloud computing to create tools for aiding and assessing control of pinyon-juniper expansion across the entire sage-grouse range. Building on the work of Falkowski et al. (2017), we developed a method to rapidly map canopy cover through random forest regression modeling of accurate cover estimates derived from National Agriculture Imagery Program (NAIP) imagery with temporally segmented Landsat time-series produced with the LandTrendr algorithm as shown in Figure S1, available online at https://doi.org/10.1016/j.rama.2020.01.002. To map patches of pinyon-juniper reduction, we apply a change detection approach developed by Cohen et al. (2018) since simply differencing the estimates of cover at two points in time would be subject to compound errors from each map. This approach uses metrics of spectral change derived from the temporally segmented Landsat time-series as predictor variables, which we incorporated in a random forest model to detect significant reductions in pinyon-juniper cover as identified from NAIP imagery (Fig. S2, available online at https://doi.org/10.1016/j.rama.2020.01.002). Details of the canopy cover and cover reduction modeling are given below and in Appendix 1. We then used the map of pinyon-juniper reduction produced from this model to quantify the areas of reduction in several categories and areas of interest.

Study Area

We updated maps of conifer canopy cover to 2015–2017 for the same region of the Intermountain West originally mapped by Falkowski et al (2017) for 2011–2013 (see Appendix 1), which covers 458 000 km^2 in total and contains 134 000 km^2 with some tree cover. This same area was used to evaluate reductions in pinyon-juniper cover over the same time period (2011–2013 to 2015–2017, Table 1). Our evaluation area overlays Western Association of Fish and Wildlife Agencies Sage-Grouse Management Zones III, IV, V, and VII (Falkowski et al. 2017) with over half (250 971 km^2) designated as Priority Areas for Conservation (PACs) for sage-grouse (US Fish and Wildlife Service 2013). PACs are key habitat areas that are essential for the long-term viability of sage-grouse and where anthropogenic impacts are minimized (US Fish and Wildlife Service 2013). The study area is managed by a variety of entities including the US Bureau of Land Management (BLM; 269 388 km^2), private landowners (114 551 km^2), other federal agencies (54 886 km^2), and state and local governments (18 869 km^2).

Table 1
Years of imagery used for mapping of tree canopy cover and pinyon-juniper reduction by state.

State	Yr 1	Yr 2
California	2012	2016
Colorado	2013	2017
Idaho	2013	2017
Montana	2013	2015
Oregon	2011	2016
Nevada	2013	2017
Utah	2011	2016
Wyoming	2012	2017

The mapped area largely overlaps the Great Basin and extends into the Columbia and Colorado Plateaus, where climate is predominantly cold and semiarid (Kottek et al. 2006). Winters (December–February) have minimum temperatures ranging from −19.5°C to −1.8°C, maximum temperatures ranging from −6.2°C to 11.5°C, and an average precipitation between 13 and 532 mm (Daly et al. 2008). Summers (June–August) have minimum temperatures from −1.2°C to 17.1°C, maximum temperatures from 11.3°C to 37.3°C, and an average precipitation of 16–212 mm (Daly et al. 2008). Both human-caused and natural disturbances played a significant role in reshaping our study area over the past decade. The primary drivers of changes in pinyon-juniper cover include intentional reduction efforts (US Fish and Wildlife Service et al. 2018) and wildfires (Kolden et al. 2012; Sparks et al. 2015). Drought-induced mortality has also contributed to reductions in pinyon-juniper cover (Breshears et al. 2005) and remains an important change-agent in these ecosystems (Buotte et al. 2019). Significant pinyon-juniper mortality has been recorded in portions of our study area, particularly on warmer and drier sites (Greenwood and Weisberg 2008; Redmond et al. 2017; Flake and Weisberg 2018, 2019).

Data

Mapping the change in pinyon-juniper cover was performed by leveraging several remotely sensed and geospatial datasets that represent or are sensitive to pinyon-juniper cover. These datasets include the aforementioned initial range-wide cover map generated by Falkowski et al. (2017), Landsat imagery, and topographic indices from the National Elevation Dataset (NED). All geospatial data analysis and modeling were performed in Google Earth Engine, a cloud-based computing platform developed specifically for rapidly analyzing large volumes of satellite imagery and geospatial datasets. We obtained samples used for modeling of canopy cover and cover reduction from stratified random sampling of the initial cover map produced by Falkowski et al. (2017) in strata of 5% cover (e.g., 0, 1–4%, 5–9%, 10–14%) since areas of low cover were far more common than high cover. Falkowski et al.'s (2017) map was produced by applying spatial wavelet analysis to NAIP imagery to map individual tree crowns, which we then aggregated to map percent canopy cover within 30-m pixels. Each sample was compared with NAIP imagery and labeled for its apparent accuracy in capturing tree crowns and whether a change had occurred within the time period of interest (see Table 1). Samples with no apparent change and which accurately represented canopy cover were included in modeling of cover in the second time period ($n = 2\ 685$). Samples with an identified change were included in classification of cover reduction between Time 1 and Time 2 through the change detection approach described later ($n = 6\ 723$). Additional details of the sampling procedure are given in Appendix 1.

Image Preparation

Predictor variables used in models of canopy cover and cover reduction were derived from the Landsat Tier 1 Surface Reflectance products. The image analysis process included cloud masking, the calculation of spectral indices, and temporal aggregation followed by temporal segmentation of the annual time series with the

LandTrendr algorithm in Google Earth Engine (Kennedy et al. 2010, 2018). We selected Landsat images between 1 May and 30 September 2009–2017 to encompass the period of interest across the study area, with an additional 2-yr buffer to aid LandTrendr segmentation. Images with > 50% cloud cover were excluded, and remaining clouds and snow were masked in each Landsat image using the included quality assessment band, which is based on the CF-mask algorithm (Foga et al. 2017). Landsat-8 images were harmonized to Landsat-7 to improve continuity between sensors (Roy et al. 2016) before calculating several spectral indices for each image, which included the normalized difference vegetation index, normalized burn ratio, normalized difference moisture index, and tasseled-cap brightness, greenness, wetness (Crist 1985; Huang et al. 2002) and angle (Powell et al. 2010). We temporally aggregated images by calculating the annual median value of each band for each pixel. Each band of the annual composite was then temporally segmented using the LandTrendr algorithm with the following settings: maximum number of segments = 4, spike threshold = 0.9, vertex count overshoot = 3, prevent 1 yr recover = false, recovery threshold = 0.5, *P* value threshold = 0.05, best model proportion = 0.25, minimum observations needed = 6. These parameters were selected by visualizing the apparent fit of the temporal segmentation to the original data values for several sample locations with different disturbance histories. Segments were then temporally clipped to time period of interest depending on the NAIP collection years for each state (see Table 1) because our training and validation data were based on NAIP imagery.

Different variables were derived from the LandTrendr segmentation and included with topographic variables for modeling of pinyon-juniper cover and the occurrence of cover reduction. For regression modeling of canopy cover we extracted LandTrendr fitted spectral values for each respective time period depending on year of NAIP collection in each state (see Table 1). For classification of pinyon-juniper reduction, we included several metrics derived from the LandTrendr segments of each band that had the greatest disturbance (i.e., greatest change from start to end of the segment), fastest disturbance (i.e., greatest slope), and greatest decrease across segments from the initial value. These metrics included start and end values, change, percent change, slope, and duration for these three temporal segments, which could be the same segment in some cases. Elevation, slope, cosine and sine of aspect, and combined slope and aspect (Stage 1976) were derived from the NED and included as predictors in the models of canopy cover and cover reduction as well.

Mapping Pinyon-Juniper Reduction Attributable to Wildfire and Management

We mapped patches of reduction in pinyon-juniper cover through random forest classification and attributed the reductions to one of two categories: 1) wildfire or 2) management. Samples used to model and produce an updated map of canopy cover, as described in Appendix 1, were also included in modeling the probability of cover reduction (n = 6 487) after splitting into training (70%) and validation (30%) datasets. Because there were far fewer samples with observed cover reduction, we addressed class imbalance in the training dataset through up-sampling the minority class to match the number of samples in the majority class. This up-sampling was performed with the SMOTE algorithm (Chawla et al. 2002), which generates synthetic replicates along the vector between each sample of the minority class and its k-nearest neighbors in feature space. Predictor variables in the random forest model (Breiman 2001) included the previously described LandTrendr disturbance metrics for all spectral bands and indices, which has proven more effective than using a single spectral index (Cohen et al. 2018), along with topographic indices. We did not assess variable importance values from the random forest model of cover reduction, or canopy cover, since this information is not provided by the Google Earth Engine implementation of random forest and because we were primarily interested in prediction ability rather than interpreting the models. The threshold of pinyon-juniper reduction probability yielding the highest F1-score (i.e., harmonic average of precision and recall) was used to map the occurrence of reduction. To reduce noise in the map, we removed isolated clusters of fewer than 50 pixels and holes smaller than 20 pixels since removal activity often took place over much larger contiguous patches. We visually compared maps produced from a range of patch size thresholds to the two dates of NAIP imagery to identify these size thresholds, which appeared to minimize false positives while maintaining true positives.

Pinyon-juniper reduction was labeled as wildfire if it overlapped fire boundaries from the National Burned Area Boundaries Dataset from the Monitoring Trends in Burn Severity project (USDA Forest Service/US Geological Survey 2017) that occurred in the time period of interest depending on state (see Table 1; 2011–2013 to 2016). Other identified reductions were attributed to management since we limited our analysis to the landscape scales at which management typically occurs through the minimum patch size requirement described earlier. However, it is possible that some reductions could have been caused by other agents of mortality such as pests, disease, or drought (Flake and Weisberg 2018).

Area of predicted pinyon-juniper reduction from management and wildfire was summarized in five different ways: 1) by state, 2) land ownership (USGS 2004), 3) proportion within sage-grouse PACs, 4) initial percent cover from Falkowski et al. (2017), and 5) relative resilience to disturbance and resistance to invasive grasses using a soils-based landscape indicator as defined by Maestas et al. (2016).

Results

Estimation of Canopy Cover

Our random forest models of pinyon-juniper cover yielded pseudo-R^2 values of 0.63 and 0.61 and root mean square errors of 10.44% and 10.74%, for Time 1 and Time 2, respectively. Variability in errors were similar across the range of cover values, except for an apparent negative bias when cover exceeded 60% (Fig. S3, available online at https://doi.org/10.1016/j.rama.2020.01.002). Resulting maps (Fig. S4, available online at https://doi.org/10.1016/j.rama.2020.01.002) depict spatial patterns similar to the initial cover mapping from Falkowski et al. (2017). One apparent difference is a greater estimated cover in some high-elevation areas, which could be due in part to an underestimation of cover in the initial map (Falkowski et al. 2017). This is a known limitation of the spatial wavelet analysis algorithm, which is more likely to omit trees and underestimate cover in high cover and closed canopies (Poznanovic et al. 2014).

Estimation of Pinyon-Juniper Management and Wildfire

The receiver operating characteristic (ROC) curve for probability of pinyon-juniper reduction had an area under the curve (AUC) of 0.97 (Fig. S5, available online at https://doi.org/10.1016/j.rama.2020.01.002). A threshold of 0.62 had the highest F1-score (0.78) and was used to map areas with a predicted reduction (Fig. 1) and assess binary classification accuracy (Table 2), which had a commission rate of 19%, an omission rate of 24%, and an overall accuracy of 96%. Because we are detecting a relatively rare phenomenon, the class imbalance in the validation dataset (119 disturbed and 1 297 undisturbed) should be taken into account when interpreting the overall accuracy and we suggest focusing on omission and

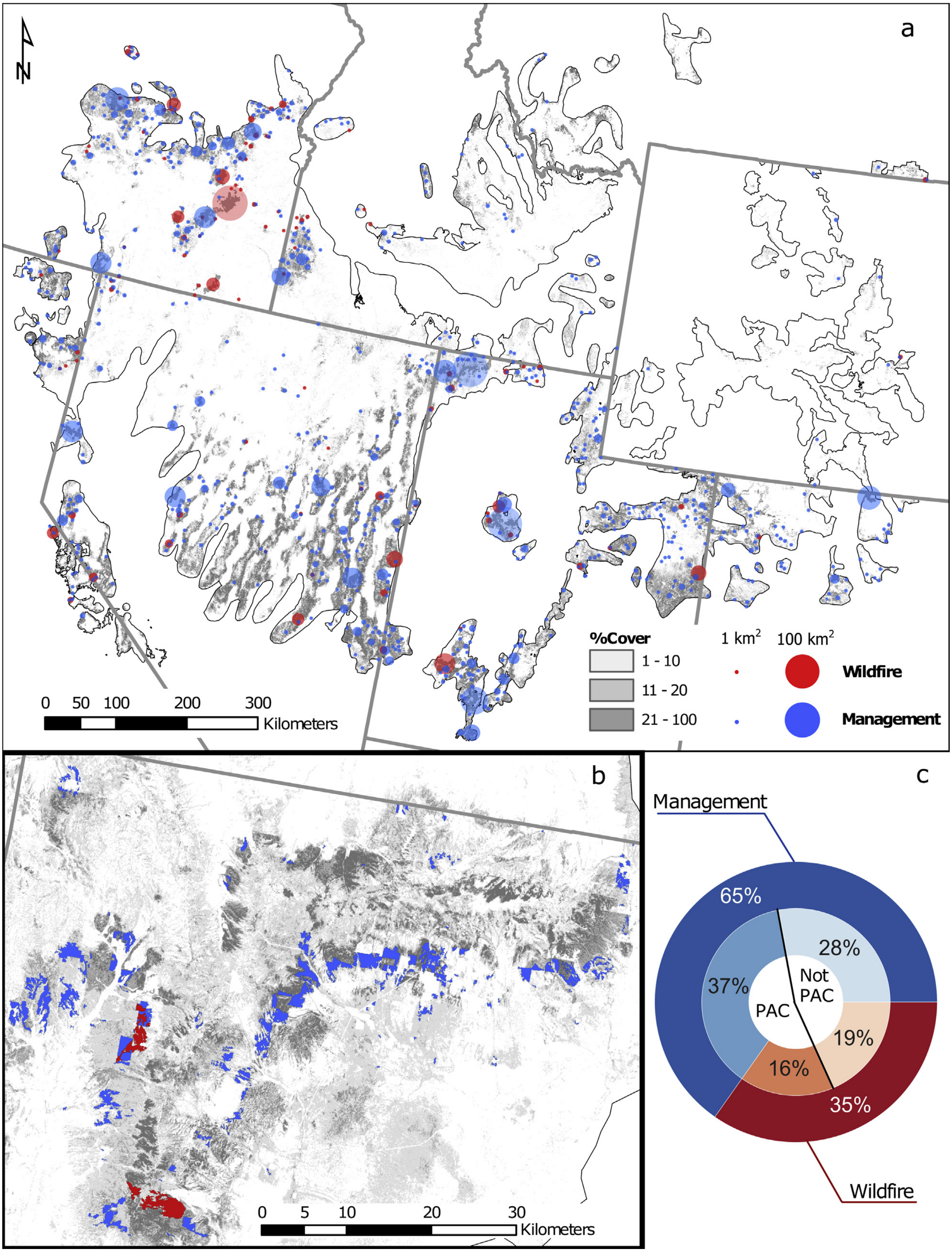

Figure 1. Map of predicted conifer management and wildfire locations (**a**) with inset of northwest Utah (**b**) and pie chart of conifer management and wildfires inside and outside of sage-grouse Priority Areas for Conservation (**c**). Wildfire area reflects predicted treatments overlapping Monitoring Trends in Burn Severity wildfires from 2011 to 2013 to 2016 to match the time period of interest by state in Table 1.

Table 2
Confusion matrix for the random forest model of cover reduction. A threshold of 62% was applied to disturbance probability because it had the highest F1-score (0.78). Omission rate = 24%, Commission rate = 19%, Overall accuracy = 96%.

	$N = 1416$	Observed	
		Disturbed	Undisturbed
Predicted	Disturbed	90	21
	Undisturbed	29	1276

commission rates and F-1 score instead. We also generated a model of pinyon-juniper reduction, which was constrained to restoration treatments and high-severity wildfire by selecting samples that had at least 10% initial cover and experienced at least a 90% loss in canopy cover. This model yielded a higher AUC (0.99), and when using a threshold of 0.50 the model had a commission rate of 13%, an omission rate of 14%, an overall accuracy of 99%, and F1-score of 0.86. The map of predicted pinyon-juniper reduction produced from the model using all samples (see Fig. 1a and 1b) correctly captured the area of many actual management treatments and wildfires (Fig. S6a and S6b, available online at https://doi.org/10.1016/j.rama.2020.01.002). False positives were most prevalent in areas dominated by shrubs (see Fig. S6c and S6d), and false negatives mostly occurred in areas of low initial cover (see Fig. S6e and S6f).

Management and Wildfire Outcomes

Total pinyon-juniper reduction was an estimated 2 207 km^2, with 65% attributable to management (1 441 km^2) and another 35% to wildfire (766 km^2; see Fig. 1c). Only 1.6% of areas supporting ≥ 1% cover (0.9–3.0% by ownership; Fig. 2) were reduced by management and wildfire combined. Approximately 87% of reductions occurred in the three Great Basin states of Utah (691 km^2), Oregon (666 km^2), and Nevada (555 km^2; see Fig. 2). Utah represents 10% of the study area but contained one-third of pinyon-juniper reduction (see Fig. 2). Most management occurred on lands administered by the Bureau of Land Management (BLM, 829 km^2; Fig. 3); their percent of total reduction (58%) is proportional to the amount of land they manage in the study area (59% of surface area). After BLM, most reductions were implemented by private landowners (391 km^2), other federal agencies (142 km^2), and state and local governments (79 km^2) (see Fig. 3).

Half (53%) of pinyon-juniper reductions were inside sage-grouse PACs. Of states with greatest reductions (Utah, Oregon, and Nevada), Utah had the highest proportion of reduction and burned area inside its PACs (see Fig. 2). Some regions, such as Central Utah, exhibited pinyon-juniper reductions across land ownership boundaries (Fig. 4a and 4b); in others, management was completed primarily by a single entity despite multiple ownerships within the watershed (see Fig. 4c).

Reductions on private lands and across ownerships in Colorado and Oregon were targeted to early (1–10% cover) and mid (11–20%) pinyon-juniper seral stages (Fig. 5). Other ownerships and states included more dense stands (21–35%; see Fig. 5) in their management.

As a whole, reductions were equitably distributed across landscapes with low (39%), moderate (35%), and high (26%) resilience to disturbance and resistance to invasive grasses (Fig. 6). However, individual states presented a dichotomy wherein some reductions

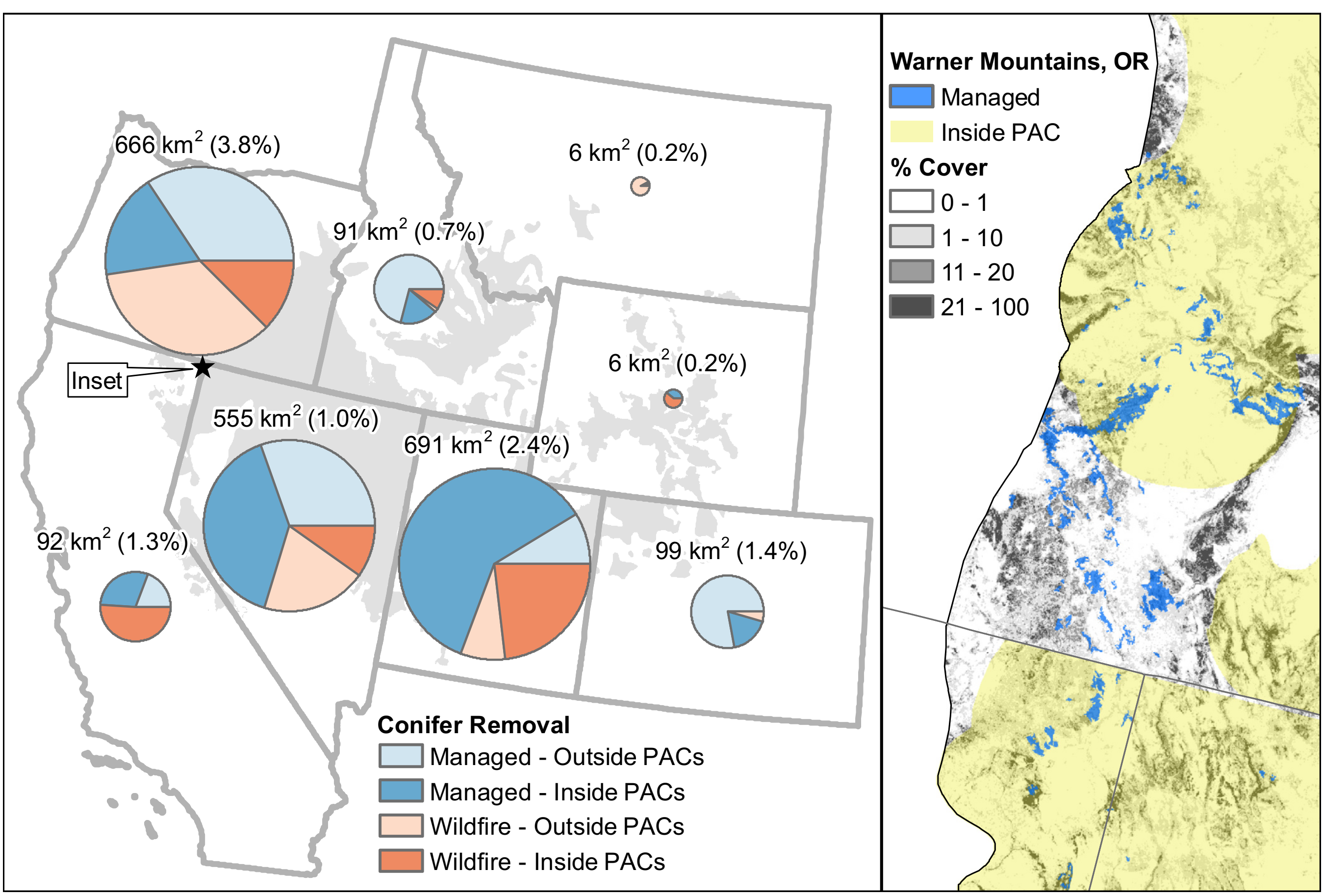

Figure 2. Area of predicted cover reduction by state and their classification as wildfire or management inside or outside of sage-grouse Priority Areas for Conservation.

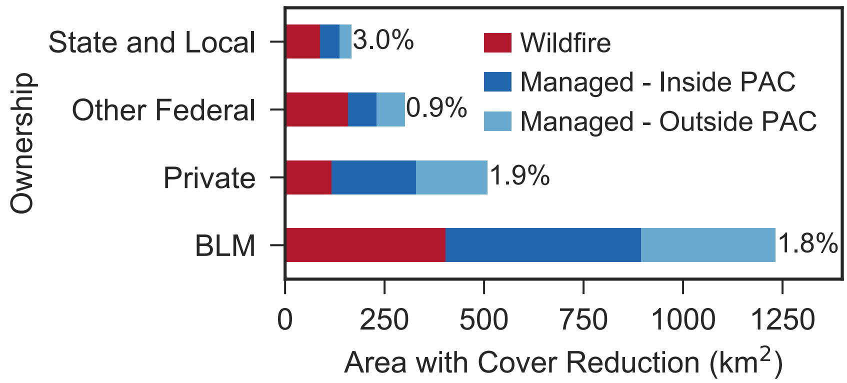

Figure 3. Area of predicted cover reduction by land ownership and their classification as wildfire or management inside and outside of Priority Areas for Conservation. At end of bars is percent of area of conifer reduction for each ownership.

were situated in landscapes considered more resilient and resistant (Montana, Idaho, Colorado, Oregon) while others were less so (Utah, California, Wyoming, Nevada; see Fig. 6). For the three most active states, pinyon-juniper reduction in landscapes least resilient and resistant was a function of its availability (Nevada 61% of reduction in low resilience vs. 54% of landscapes with low resilience and tree cover > 0%, Utah 49% vs. 32%, Oregon 16% vs. 19%).

Discussion

We provide the first comprehensive assessment of pinyon-juniper reduction within the sage-grouse range of North America's sagebrush ecosystem, painting a picture of how each piece of the cooperative pinyon-juniper management effort fits into a broader restoration story. The overall amount of reduction is low (1.6% of 134 000 km^2, which supports trees) given the concerted effort to combat expansion in recent years. This provides important context for debates about whether current sagebrush ecosystem improvement efforts are resulting in wholesale loss of pinyon-juniper woodlands required by woodland-associated species (Boone et al. 2018; Maestas et al. 2019). Indeed, current efforts may just be keeping up with estimated expansion rates (e.g., ~0.4–1.5% per yr; Sankey and Germino 2008). Similar to the quandaries of other systems experiencing woody plant encroachment (Hobbs et al. 2014), logistical constraints lead to a patchwork of restoration in targeted areas (see Fig. 1) while woodland expansion and infill continue across a broad region despite a renewed interest in management (Miller et al. 2008; Miller et al. 2017).

Despite aggressive suppression efforts, wildfire still accounts for a third of estimated pinyon-juniper reduction (766 km^2; see Fig. 1).

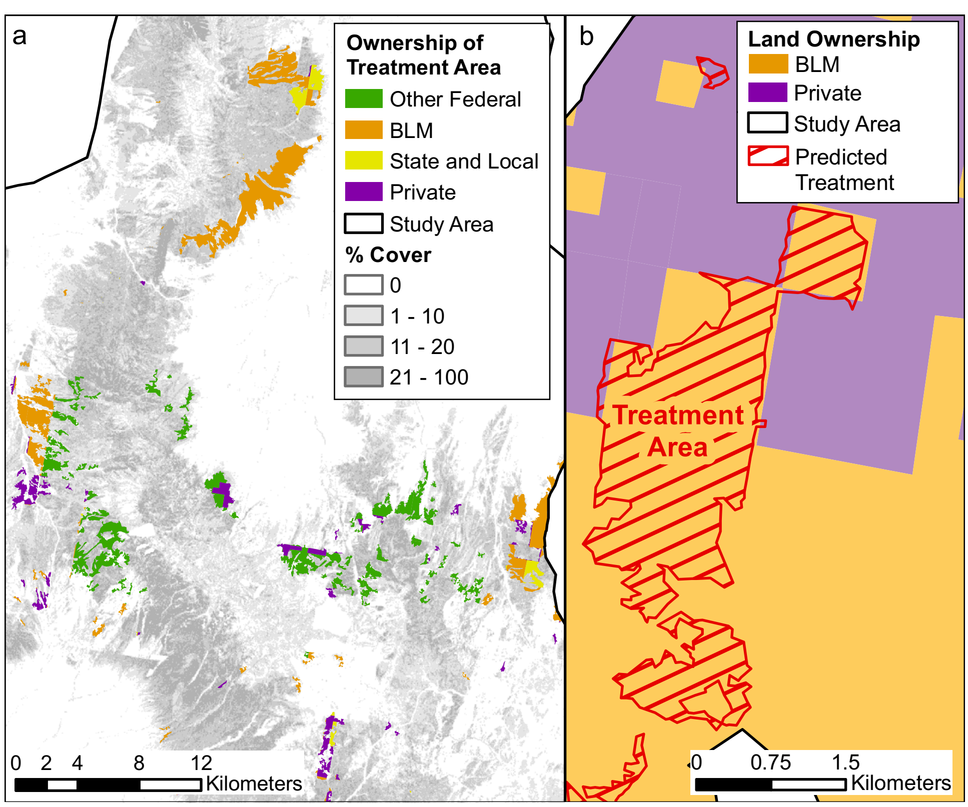

Figure 4. Areas of conifer management often encompassed multiple land ownerships as illustrated in central Utah (**a**). In other landscapes whole-watershed restoration is incomplete as management has been implemented by only one entity (e.g., Bureau of Land Management [orange shading]; **b**).

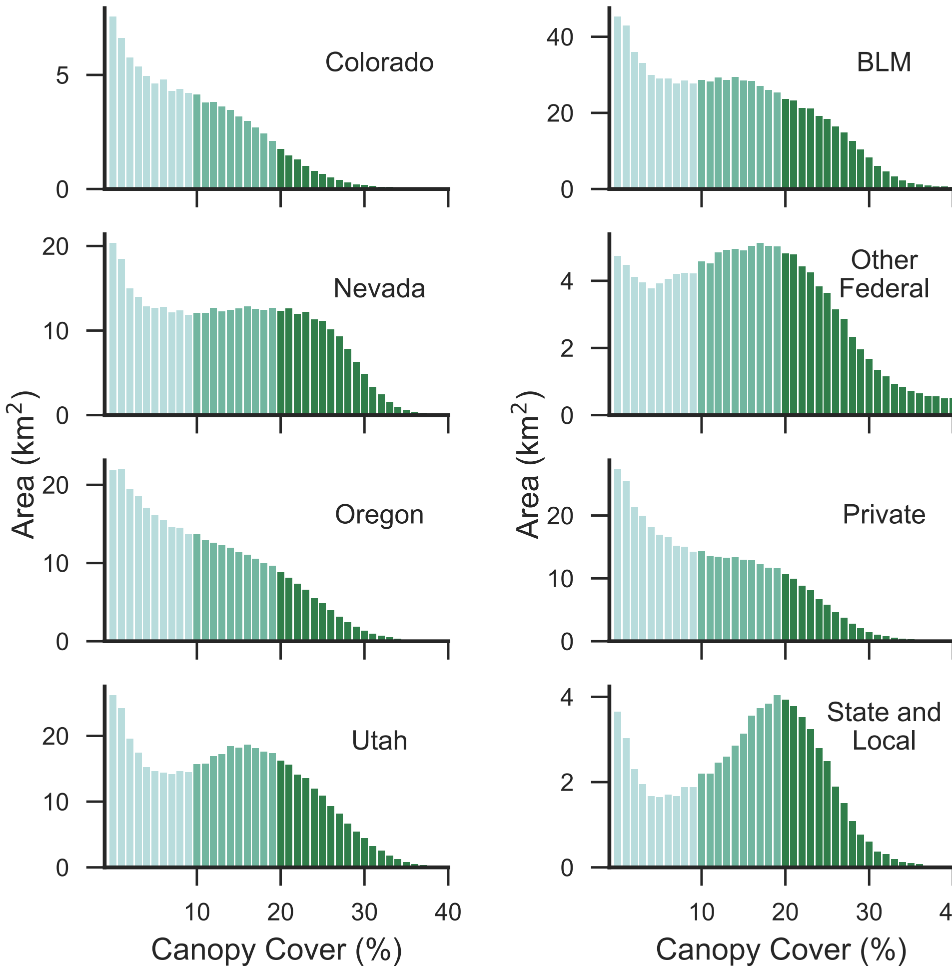

Figure 5. Area of predicted management by canopy cover for the four states with the greatest reduction area and for all ownership classes. Bar shades represent 10% cover intervals.

Boyd et al. (2017) suggest integration of fire into regional management is likely necessary to maintain sagebrush habitat through space and time. Recent research suggests that fire contrasts with cutting-based pinyon-juniper treatments in terms of outcome; Davies et al. (2019) found that fire was more effective than cutting treatments at maintaining and conserving sagebrush ecosystems encroached by juniper in the long term. Burning destroys the bulk of juniper seeds and seedlings where cutting treatments do not

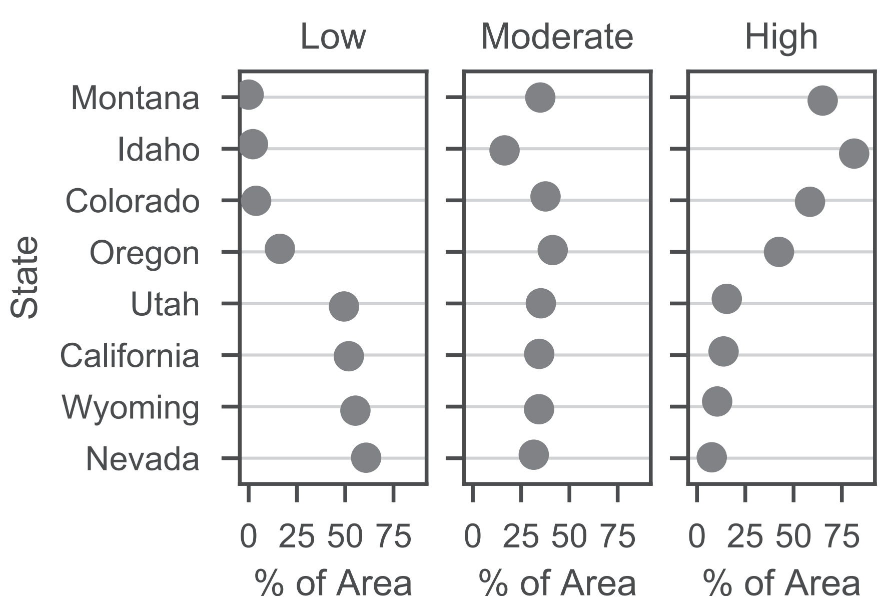

Figure 6. Percent of predicted management occurring within each resistance and resilience class (Maestas et al. 2016) by state.

(Miller et al. 2005), offering an additional angle of effectiveness as a management tool. There is concern, however, that wildfire and prescribed burning may carry a higher risk of invasion by exotic annual grasses, especially cheatgrass *(Bromus tectorum)* (see Miller et al. 2013; Roundy et al. 2014; Boyd et al. 2017; Williams et al. 2017). But recent work by Davies et al. (2019) found no difference in exotic annual grass cover between cutting and burning treatments, instead finding that much of the variation in exotic grass was explained by environmental variables, perennial grass abundance, and site resistance and resilience (Chambers et al. 2014a; Chambers et al. 2014b; Maestas et al. 2016). Areas less resistant to invasion by exotic annual grasses make up 30% of the burned area in this study, making awareness of such information important for management planning. Impacts on sagebrush cover is another important consideration with regards to treatment choice. Some pinyon-juniper treatment approaches, such as hand-felling, maintain sagebrush, whereas fire does not, but the benefits of hand-felling trees may only last a few decades because conifer seedlings are not controlled and seed banks remain intact (see Davies et al. 2019). Fire has a much longer treatment life and would be beneficial for long-term maintenance of sagebrush when applied to cooler sites with low tree density at the correct timing to reduce the risk of invasion by annual exotics (Chambers et al. 2014; Boyd et al. 2017; Davies et al. 2019). While the extensive wildfires we observed do reduce woodland expansion, it is uncertain whether these areas will ultimately recover to sagebrush ecosystems and benefit sagebrush obligates (Coates et al. 2016).

Land tenure insights reveal strong cross-boundary partnerships in some watersheds (see Fig. 4a and 4b) and others where restoration of grouse habitat and ecosystem processes is incomplete (see Fig. 4c). The current mosaic of pinyon-juniper management (see Fig. 1) reflects commitments made by early adopters of contemporary sagebrush restoration objectives whose actions, if replicated in new landscapes, could expand sagebrush ecosystem restoration. States consisting of 87% of mapped reductions (Utah, Oregon, and Nevada) were able to overcome hurdles that have challenged similar woody invasion management attempts in other systems (Head et al. 2015). This may be due in part to leadership, partnership infrastructure, and the presence of a clear and consistent conservation objective, as exemplified by the legislatively appropriated Watershed Restoration Initiative (https://wri.utah.gov/wri/) in Utah. The NRCS-led Sage Grouse Initiative served as a primary catalyst for pinyon-juniper management by providing an incentive-based program for strategic management on private lands (27% of treatments) (NRCS 2015). As the largest single manager of western rangelands, the BLM was also the largest contributor in pinyon-juniper reduction on public lands (73% of treatments).

Successful spatial targeting of pinyon-juniper reductions in priority areas exemplifies the collective ability of conservation partners to restore some landscapes at a scale large enough to benefit imperiled species and maintain ecosystem function. Practitioners steered over half (53%) of treatments into sage-grouse strongholds, with some states and landowners placing a greater focus on PACs than others (see Figs. 2a, 2b, and 3). The benefits of targeting conifer reductions in these priority areas extend beyond the focal sage-grouse. Some research suggests that the sage-grouse may serve as a potential umbrella species for a number of other species in sagebrush-associated communities (Rowland et al. 2006), though some species may benefit from the sage-grouse umbrella more than others (Runge et al. 2019; Timmer et al. 2019). In addition, PACs have been found to be less vulnerable to land use conversion and cheatgrass invasion than the broader landscape (Runge et al. 2019); this may be because sites that support robust sage-grouse populations have remained largely intact (Davies et al. 2006). Additional insights into spatially targeted conifer reductions also inform future monitoring and adaptive management priorities to ensure maintenance of ecosystem functions following restoration. In the three most active states (Utah, Nevada, and Oregon), pinyon-juniper management was implemented across the spectrum of resilience and resistance classes (see Fig. 6), primarily as a function of availability. Treatments in areas with lower resistance and resilience often require follow-up weed treatment and seeding, as well as longer recovery times, to be successful (Miller et al. 2014), which emphasizes the importance of prioritizing monitoring and adaptive management in these areas.

Future landscape planning of conifer reductions will also need to account for the growing impact of climate change on pinyon-juniper woodlands and other communities. Climate change has already had a significant impact on ecosystems across the globe in terms of species distributions and community composition, ecosystem function, and resource availability (Walther et al. 2002; Parmesan and Yohe 2003; Parmesan 2006; Rosenzweig et al. 2008; Walther 2010; Grimm et al. 2013), and future projections (IPCC 2014) suggest continued impacts are likely (Grimm et al 2013; Pacifici et al. 2015; Urban 2015; Shukla et al. 2019). In the Intermountain West in particular, there is concern that climate change has increased drought risk (Dai et al. 2012; Diffenbaugh et al. 2015; Swain et al. 2018). Increased temperature and altered precipitation regimes are also predicted to result in shifts in species compositions and community composition, with projections demonstrating potential shifts in the distribution of pinyon-juniper woodlands: contractions are projected for lower elevations and the southern extent of the community's range, while expansion is projected for higher elevations and along the northern portion of the range (Friggens et al. 2012; Rehfeldt et al. 2012; Thorne et al. 2017). While the mapping effort conducted here cannot separate out the effects of drought- or otherwise climate-induced mortality from management, it does document pinyon-juniper reduction as a whole. Coupling comprehensive assessments of pinyon-juniper reductions, as produced here, with detailed climate change projections (e.g., Bradford et al. 2017) and wildfire risk maps (Short et al. 2016; Crist et al. 2017) can help regional prioritization to enhance the resilience and maintenance of both sagebrush shrublands and persistent pinyon-juniper woodlands in the face of changing climate (Floyd and Romme 2012).

Leveraging the Landsat archive and existing cover maps enabled us to produce an updated map of pinyon-juniper cover and quantify pinyon-juniper reduction over the entire sage-grouse range where conifer expansion is considered an ecosystem threat, but several limitations in these remotely sensed products should be considered when interpreting the results. First, the approach described here cannot distinguish between infill within historic pinyon-juniper woodlands and expansion into shrublands. Second, this current map of pinyon-juniper reduction excludes restoration efforts that predate the initial cover map and associated availability of NAIP imagery (see Table 1). Third, the trade-off for mapping pinyon-juniper cover across a 458 000-km^2 area with Landsat is a reduction in accuracy in comparison with methods based on high-resolution imagery (Strand et al. 2008; Davies et al. 2010; Hulet et al. 2014). Overestimation of tree cover at low cover levels (see Fig. S3) was likely due to the influence of other vegetation on the observed spectral signature (Campbell et al. 2012), while underestimation at high cover levels was likely caused by saturation of spectral indices (Lu 2006). Despite reasonable accuracy in mapping pinyon-juniper reduction (see Table 2), landscapes with low initial cover or partial disturbances, such as thinning, posed a technological challenge, as indicated by increased accuracy for restorative sagebrush ecosystem treatments with > 10% cover and > 90% removal. In general, remote sensing efforts to map partial disturbances such as thinning have resulted in significantly lower accuracies (Jin and Sader 2005; Kennedy et al. 2007; Schroeder et al. 2011; Thomas et al. 2011; Wilson and Sader 2002). This limitation suggests our estimates of pinyon-juniper reduction are conservative and likely exclude preventative treatments of early tree invasion, which may have been more prevalent in some states or ownerships (e.g., Schroeder et al. 2011; Thomas et al. 2011). Past conifer woodland mapping studies have focused on quantifying expansion rather than management (Strand et al. 2006; Weisberg et al. 2007; Sankey and Germino 2008; Sankey et al. 2010), with few examples in other types of open woodlands to compare against (Johansen et al. 2015).

Conclusions and Implications

Pinyon-juniper reduction may be just keeping pace with estimated expansion rates (e.g., Sankey and Germino 2008), but the scope of the cooperative management effort is quite broad, especially given the large spatial extent requiring management. Landscape-scale, cross-boundary efforts, such as regional conifer management, are bolstered by establishing clearly defined conservation or restoration objectives and by building a cooperative infrastructure to coordinate multiple entities and stakeholders in both implementation and the production of actionable science. These factors help mitigate some of the disincentives that can hinder broad-scale conservation and natural resource management efforts (Kiss 2008; Jacobson and Robertson 2012; North et al. 2015). One key component of cooperative infrastructure comes in the form of codified policy. In the case of sage-grouse and sagebrush ecosystem restoration, codified policy, as well as the associated regulatory and funding support, have come in large part from Farm Bill legislation, which recognized the early success of cooperative conservation efforts (i.e., NRCS's Working Lands for Wildlife-Sage Grouse Initiative) and provided sustained funding (*H.R.2–Agriculture Improvement Act of 2018,* 2018). This support, along with actionable science, such as the spatial products presented here, paves the way for future restoration to be continually improved and implemented at ecologically meaningful scales.

Future priorities for sagebrush ecosystem conservation should include refinement of pinyon-juniper woodland management plans to include objectives beyond sage-grouse, expansion of cooperative partnerships for continued pinyon-juniper management, improvement of pinyon-juniper woodland change tracking technology, and incorporation of wildfire risk assessments and climate change projections. The map of pinyon-juniper management from this study demonstrates a collective ability to rally behind an initiative to address a known threat to sage-grouse. However, the consequences of pinyon-juniper woodland expansion are evident throughout the West, and an updated strategy and campaign is needed for management in new watersheds with a broader focus on holistic sagebrush ecosystem restoration. Watershed hydrologic function (Pierson et al. 2010, 2013; Kormos et al. 2017) and mule deer (Bergman et al. 2014) benefits associated with pinyon-juniper management are examples of additional management objectives that could be incorporated to include broader audiences. These management efforts also have the potential to expand herbaceous forage production (Bates et al. 2019), increase benefits to sagebrush-obligate songbirds (Donnelly et al. 2017; Holmes et al. 2017), and increase plant diversity (Ratajczak et al. 2012; Bates and Davies 2017; Bates et al. 2017). Expanding the scope of pinyon-juniper management will renew the capacity to reach currently unengaged landowners and managers (Head et al. 2015) whose lands lay outside of sage-grouse priorities.

Here, we present a mapping strategy that can be regularly updated for tracking of pinyon-juniper reduction as new Landsat imagery becomes available, but there is still potential for improvement in map accuracy. Accurate tracking of reduction efforts could be paired with other spatial datasets to quantify the influence of management on sagebrush and woodland ecosystems, biodiversity, and ecosystem services. Some of these spatial datasets are already incorporated into sage-grouse management including the Rangeland Analysis Platform (Jones et al. 2018; https://rangelands.app), which tracks cover of plant functional types, and the Sage Grouse Initiative web application (https://map.sagegrouseinitiative.com/), which provides maps of sagebrush- and woodland-dependent songbird abundance (Donnelly et al. 2017) and maps of mesic resource productivity (Donnelly et al. 2016). Combining this mapping strategy with datasets describing wildfire risk (Crist et al. 2017; Short et al. 2017) and climate change vulnerability (Bradford et al. 2017; Snyder et al. 2019) would enable improved targeting of future treatments. Continually innovating the science, delivery, and evaluation of management outcomes across space and time is vital for maintaining grassland and shrubland ecosystems in the face of woody expansion and environmental change (Ratajczak et al. 2012; Hobbs et al. 2013).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rama.2020.01.002.

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