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Mapping Tree Canopy Cover in Support of Proactive Prairie Grouse Conservation in Western North America☆

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ABSTRACT

Invasive woody plant expansion is a primary threat driving fragmentation and loss of sagebrush (*Artemisia* spp.) and prairie habitats across the central and western United States. Expansion of native woody plants, including conifer (primarily *Juniperus* spp.) and mesquite (*Prosopis* spp.), over the past century is primarily attributable to wildfire suppression, historic periods of intensive livestock grazing, and changes in climate. To guide successful conservation programs aimed at reducing top-down stressors, we mapped invasive woody plants at regional scales to evaluate landscape level impacts, target restoration actions, and monitor restoration outcomes. Our overarching goal was to produce seamless regional products across sociopolitical boundaries with resolution fine enough to depict the spatial extent and degree of woody plant invasion relevant to greater sage-grouse *(Centrocercus urophasianus)* and lesser prairie-chicken *(Tympanuchus pallidicinctus)* conservation efforts. We mapped tree canopy cover at 1-m spatial resolution across an 11-state region (508 265 km^2). Greater than 90% of occupied lesser prairie-chicken habitat was largely treeless for conifers (<1% canopy cover), whereas > 67% was treeless for mesquite. Conifers in the higher canopy cover classes (16 − 50% and >50% canopy cover) were scarce (<2% and 1% canopy cover), as was mesquite (<5% and 1% canopy cover). Occupied habitat by sage-grouse was more variable but also had a relatively large proportion of treeless areas ($\bar{x}$ = 71, SE = 5%). Low to moderate levels of conifer cover (1 − 20%) were fewer ($\bar{x}$ = 23, SE = 5%) as were areas in the highest cover class (>50%; $\bar{x}$ = 6, SE = 2%). Mapping indicated that a high proportion of invading woody plants are at a low to intermediate level. Canopy cover maps for conifer and mesquite resulting from this study provide the first and most geographically complete, high-resolution assessment of woody plant cover as a top-down threat to western sage-steppe and prairie ecosystems.

Introduction

In the western United States and southern Great Plains, the expansion of invasive woody plants into predominantly treeless landscapes has structurally altered these ecosystems and reduced habitat availability for many wildlife species (Brown and Archer, 1999; Engle et al., 2008; Miller et al., 2011). Expansion of native woody plants, including conifer (primarily *Juniperus* spp.) and mesquite (*Prosopis* spp.), over ca. 130 years is primarily attributable to wildfire suppression, historic periods of intensive livestock grazing, and changes in climate (Brown and Archer, 1989; Miller and Wigand, 1994; Miller and Rose, 1999;

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Waichler et al., 2001; Miller et al., 2005; Van Auken, 2009). Woody encroachment increases surface water runoff and erosion by shading out the native abundance and diversity of herbaceous cover (Buckhouse and Gaither, 1982; Gaither and Buckhouse, 1983; Miller et al., 2011). With increased runoff and rainfall interception, encroachment can lower the water table, thus reducing water availability in the system, benefitting more deeply rooted species such as mesquite (Baker, 1984; Heitschmidt et al., 1988; Wilcox, 2002; Thorp et al., 2013; Ansley et al., 2014). Woody encroachment — related habitat changes in turn can have negative consequences on prairie grouse by altering food availability and predator dynamics, among others.

Indeed, impacts to wildlife populations from woody encroachment — related changes in ecosystem dynamics are well known. In the southern Great Plains the invasion of eastern redcedar *(Juniper virginiana)* and mesquite into prairie ecosystems has been linked to population declines in the lesser prairie-chicken (*Tympanuchus pallidicinctus,* hereafter prairie-chicken[s]) (Fuhlendorf et al., 2002; Hunt and Best, 2010) and other grassland nesting birds (Coppedge et al., 2001; Grant et al., 2004). Similarly, woody species encroachment has been demonstrated to impact site occupancy of greater prairie-chicken (*Tympanuchus cupido;* McNew et al., 2012). In a recent study, prairie-chicken space use was constrained by the distribution and density of invasive mesquite trees (Boggie et al., 2017-this issue) and redcedar (Lautenbach et al., 2017-this issue). In sage-steppe ecosystems of the Great Basin, numerous studies have documented impacts from conifer encroachment to greater sage-grouse (*Centrocercus urophasianus,* hereafter sage-grouse; Doherty et al., 2008; Atamian et al., 2010; Doherty et al., 2010; Casazza et al., 2011; Baruch-Mordo et al., 2013; Knick et al., 2013a, 2013b) and other sagebrush obligates (Noson et al., 2006; Larrucea and Brussard, 2008; Woods et al., 2013; Holmes et al., 2017-this issue).

Broad-scale mapping of invasive woody species is urgently needed to inform proactive management to restore habitats impacted by woody encroachment already under way through partnership efforts, such as the National Resource Conservation Service (NRCS)-led Sage-Grouse Initiative (SGI; NRCS, 2015a) and Lesser Prairie-chicken Initiative (LPCI; LPCI, 2015). To date, SGI has invested $760 million in sage-grouse conservation, including the mechanical removal of early successional conifer to restore 182 610 ha (451 239 ac) of sage-steppe habitats in and around sage-grouse population strongholds (NRCS, 2015a). Similarly, LPCI has invested $1.06 million in prairie-chicken habitat conservation and, with partners, has leveraged 67 723 ha (166 112 ac) of prairie restoration through redcedar and mesquite removal.

Regional mapping of woody invasion using remotely sensed data to inform species and ecosystem conservation has become increasingly feasible and desired, yet efficacy depends on the scale of the object of interest (e.g., individual or stand of wood plants), sensor-specific resolutions, and spatial extent of the mapping area of interest (Coops et al., 2007; Falkowski et al., 2009). Remote sensing systems that acquire images with large spatial extents will have a lower spatial resolution and will ultimately measure less spatial detail as compared with images acquired by higher spatial resolution sensors that provide detailed depictions of ecosystem characteristics across small spatial extents. The emergence of object-based image analysis (OBIA) techniques and very high spatial resolution (VHSR) data (spatial resolution < 2 m) has resulted in increased accuracy and precision of woody plant mapping. OBIA methods extract objects of interest from digital imagery by first grouping together neighboring pixels with similar spectral and spatial properties and then classifying these pixel groups into objects of interest (e.g., trees). When using VHSR data for mapping woody plants, OBIA outputs are typically polygons delineating specified objects of interest (e.g., woody plants or patches of woody plants; Poznanovic et al., 2014).

Among the various OBIA methods available, spatial wavelet analysis (SWA) is the most efficient method because it requires the least user input and the least amount of processing time to characterize tree and shrub cover, while preserving relatively high accuracies (Poznanovic et al., 2014). In SWA, individual trees are identified by both reflectance and shape, marked with spatial coordinates (x, y), assigned with an image-derived tree crown diameter value, and converted to points and circular buffers indicating tree location and crown area (Falkowski et al., 2006; Smith et al., 2008; Poznanovic et al., 2014). The detailed output provided by SWA can be used to calculate useful metrics including canopy cover, tree density, canopy configuration, and crown diameter distributions, many of which have been identified as important drivers of sage-grouse lek activity (Baruch-Mordo et al., 2013) and prairie-chicken space use (Lautenbach et al., *this issue*; Boggie et al., *this issue*).

In this paper we present the results of a project focused on mapping invasive woody plants at regional scales. These maps are ultimately used to evaluate the threat of invasive woody plants on prairie grouse, aid in spatial targeting of restorative actions, and support the quantification and tracking of restoration progress and outcomes. Our overarching goal is to produce seamless regional products across political and administrative boundaries with a resolution fine enough to allow a nuanced depiction of the spatial extent and degree of woody plant invasion. Toward this end, our mapping framework meets five criteria to ensure its utility:

1. Accurate mapping of woody plant abundance at low canopy values because both grouse species avoid otherwise suitable habitats at < 5% tree canopy cover (e.g., Fuhlendorf et al., 2002; Baruch-Mordo et al., 2013; Knick et al., 2013a, 2013b)
2. Adequate tree-level detail (e.g., tree location and crown diameter) to provide the most flexibility for estimating multiple woody plant metrics such as canopy cover, tree density, spatial canopy configuration, and crown size distributions that could be leveraged in proactive conservation (Baruch-Mordo et al., 2013)
3. High level of consistency in derived woody plant metrics through the leveraging of freely available VHSR data that are collected in a uniform manner
4. Automated processing techniques that directly derive encroachment information from the VHSR data, avoiding methods that require empirical data for parameterization or calibration (e.g., image classification or spectral mixture analysis)
5. High level of automation (through OBIA) given the vast size of the mapping extent, which is balanced and blended with manual image interpretation to maintain consistency and accuracy

Methods

Study Areas

Conifer and mesquite mapping were conducted across two different geographic areas, both corresponding to sage-grouse and prairie-chicken distributions. The sage-grouse mapping area (referred to as SGI mapping extent hereafter) included 414 803 km^2 of occupied habitat within the Western Association of Fish and Wildlife Agencies (WAFWA) Sage-Grouse Management Zones III — V and VII. Mapped areas include priority areas of conservation (PACs) and all surrounding occupied non-PAC habitats regardless of ownership. The prairie-chicken mapping area (referred to as LPCI mapping extent hereafter) included 107 242 km^2 of occupied habitat within four WAFWA ecoregions and included focal areas, connectivity zones (FACZs), and all surrounding modeled habitats (Van Pelt et al., 2013); (Figs. 1 and 2).

Remotely Sensed Data

Digital orthophotos from the National Agriculture Imagery Program (NAIP) were leveraged for mapping woody invasive plants across the SGI and LPCI mapping extents. The NAIP program consistently collects aerial imagery across the United States during the growing season on a 3-yr repeat cycle (USDA FSA, 2016). NAIP imagery data are typically four bands (red, green, blue, and near infrared) with a spatial resolution

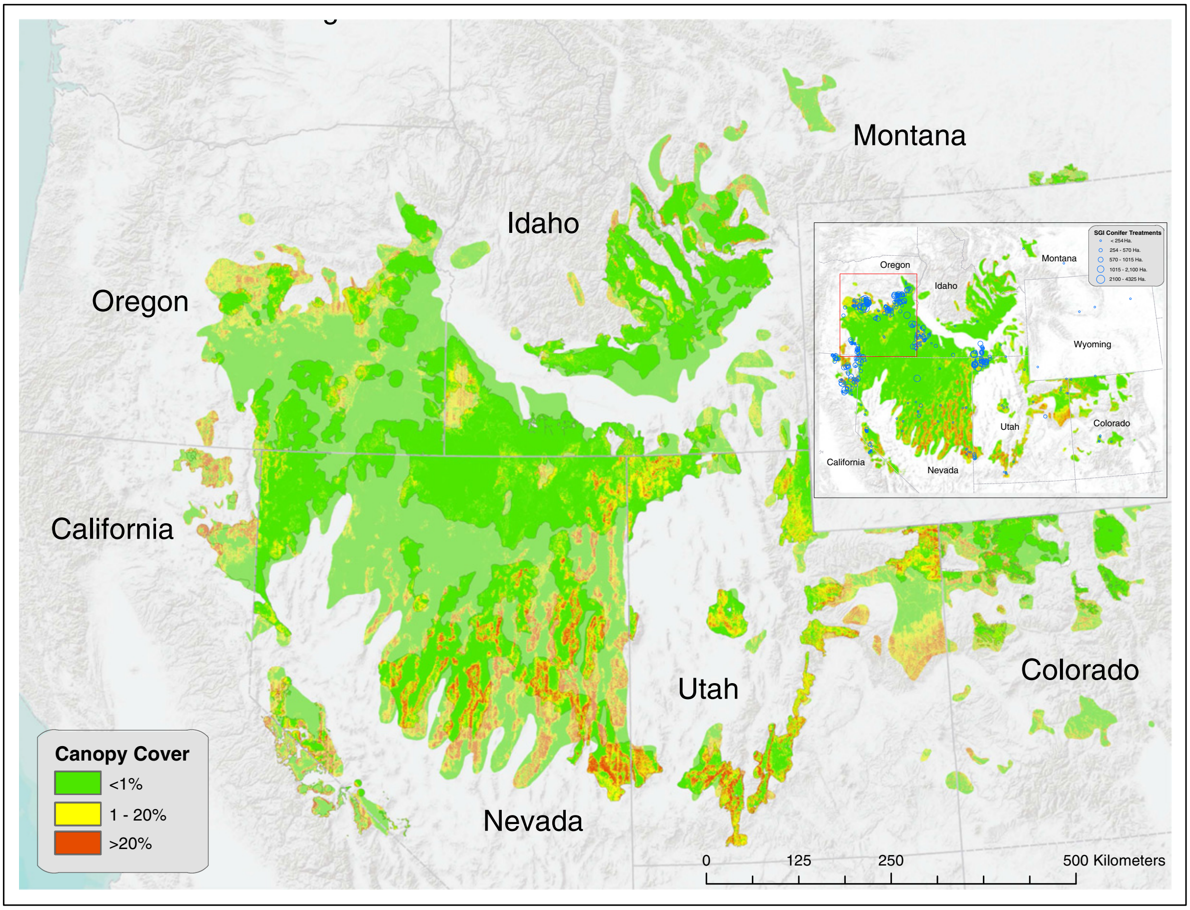

Figure 1. Range canopy cover map for the Sage-Grouse Initiative (SGI) mapping extent. To highlight priority areas of conservation (PACs), non-PAC areas are displayed with a gray transparency. The inset map displays SGI-funded conifer treatments completed in 2010 − 2015 in relation to mapped conifer cover. The size of each blue circle is proportional to size of individual projects. The red bounding box corresponds to the area displayed in Figure 5.

between 0.5 and 1.0 m. For the purpose of our study, we obtained the most recent NAIP data available (from date of project onset) from a variety of sources (Table 1). NAIP data were obtained as digital images tiled on a US Geological Survey (USGS) quarter quadrangle basis. Once obtained, NAIP data were processed to generate several image products suitable for woody invasive mapping. These products included vegetation indices such as the Normalized Difference Vegetation Index (NDVI), which highlights photosynthetically active vegetation, and image derivatives such as the image complement (a digital image inversion). These image products were derived to increase contrast between woody invasive plants and background image components (e.g., grass, shrubs, soil). Increasing image contrast between the objects of interest (i.e., woody plants) and background image components (e.g., grass, shrubs, soil) improves object detectability and thus enhances object detectability. Also, vegetation indices such as NDVI remove (or lessen) the impacts of tree shadowing in remotely sensed imagery, which have been identified as a source of error in tree crown detection approaches (Smith et al., 2008).

Mapping Approaches

Two types of native invasive woody species are present in the study areas: conifers (multiple juniper and pine/fir species) and mesquite trees and shrubs. Conifers are present across the entire SGI mapping area and the northeastern portion of the LPCI mapping area, while mesquite is the dominant invasive woody in the southwest portion of the LPCI mapping area. We employed two different mapping approaches based on target species being mapped.

Conifer Detection and Mapping—Spatial Wavelet Analysis

We employed the SWA OBIA mapping technique to extract individual conifer locations and crown diameters from the NAIP images. The SWA algorithm is often used to estimate the size and location of individual trees from remote sensing data including both LiDAR data and high-resolution imagery such as NAIP (e.g., Falkowski et al., 2006, 2008; Strand et al., 2006; Smith et al., 2008; Poznanovic et al., 2014). SWA uses a dynamically scaled, wavelet-based image filter to decompose digital images into individual objects or features, which in this case corresponds to individual woody plants. The principal advantage of SWA over traditional OBIA techniques is that it is not restricted to analyzing features of a characteristic scale (i.e., often the operator or kernel size), which allows extraction of image features that have a characteristic shape but lack a characteristic size (e.g., tree crowns of multiple sizes).

Following previously published methods (e.g., Falkowski et al., 2006; Strand et al., 2006; Poznanovic et al., 2014), we convolved a series of two-dimensional (2D) Mexican hat wavelets of progressively larger sizes (1 − 10 m in 0.5-m increments) with NAIP-derived NDVI images. This wavelet size range was chosen to match the spatial resolution of the NAIP imagery at the low end and to approximately equal the maximum expected juniper crown diameter at the high end (i.e., juniper crown diameters rarely exceed 10 m). Mexican hat wavelet was chosen because its circular shape approximates that of individual coniferous trees within an NDVI image. The wavelet algorithm records three parameters, namely wavelet size (which is analogous to tree crown diameter), object location (x, y position of the conifer tree), and a goodness-of-fit metric (i.e., how well the image filter matches the size of a conifer

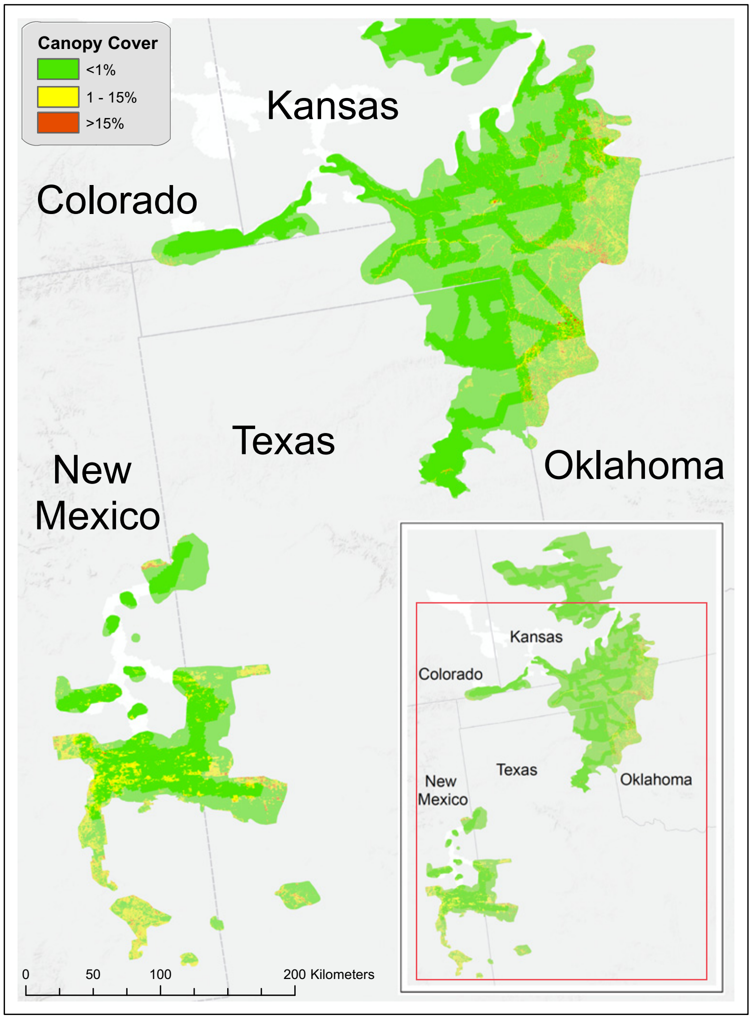

Figure 2. Range canopy cover map for the LPCI mapping extent. To highlight focal areas and connectivity zone (FACZ) areas, non-FACZ areas are displayed with a gray transparency. Overall mapping extent is displayed in the inset map.

tree in the image). When conifer trees within the NDVI image are similar in both shape and size to the 2D Mexican hat wavelet of a specific size (between 1 and 10 m), the (x, y) location of each tree and wavelet size (i.e., tree crown diameter) associated with the highest goodness-of-fit metric for each separate tree are then retained and recorded. The 2D wavelet algorithm was coded and executed within Matlab software. Output from SWA analysis was subsequently used to create a raster layer representing individual conifer tree locations and their associated tree crown diameters (Figs. 3A — 3B).

Table 1
National Agriculture Imagery Program imagery acquisition years.

State	SGI NAIP Yr	LPCI NAIP Yr
CA	2012	NA
CO	2013	2011
ID	2013	NA
KS	NA	2010
MT	2013	NA
OR	2012	NA
NM	NA	2011
NV	2013	NA
OK	NA	2010
TX	NA	2010
UT	2011	NA

SGI indicates Sage-Grouse Initiative; NAIP, National Agriculture Imagery Program; LPCI, Lesser Prairie-chicken Initiative.

Following this step, technicians performed manual image interpretation of SWA output to ensure proper detection of conifer trees and to identify false detections (e.g., nonconifer tree species, shrubs). Although SWA is effective for detecting conifer trees, it can also generate false detections along abrupt linear features in the imagery (e.g., roads, riparian areas) and detect deciduous species in certain situations. Once areas of false detection were identified, we created image masks to remove false detections in areas with nontarget tree species or cover types. Image masks were developed from multiple sources including preexisting landcover maps (2012 National Land Cover Dataset), hydrography layers (USGS National Hydrography Dataset), road layers (from each individual state), and manual identification. When areas of underdetection were identified, SWA mapping was repeated with different object detection parameters, and in some situations alternative NAIP image derivatives (e.g., image compliment) were used that were better suited for detecting conifers given inconsistencies in ecosystem characteristics and image quality across the mapping areas.

Mesquite Detection and Mapping—e-Cognition

Because mesquite canopies have irregular rather than circular shapes, SWA could not be used. Instead we employed the eCognition Developer software package (Trimble, 2011) to implement an image segmentation and classification approach for mesquite identification from NAIP images. We used eCognition to develop a bottom-up

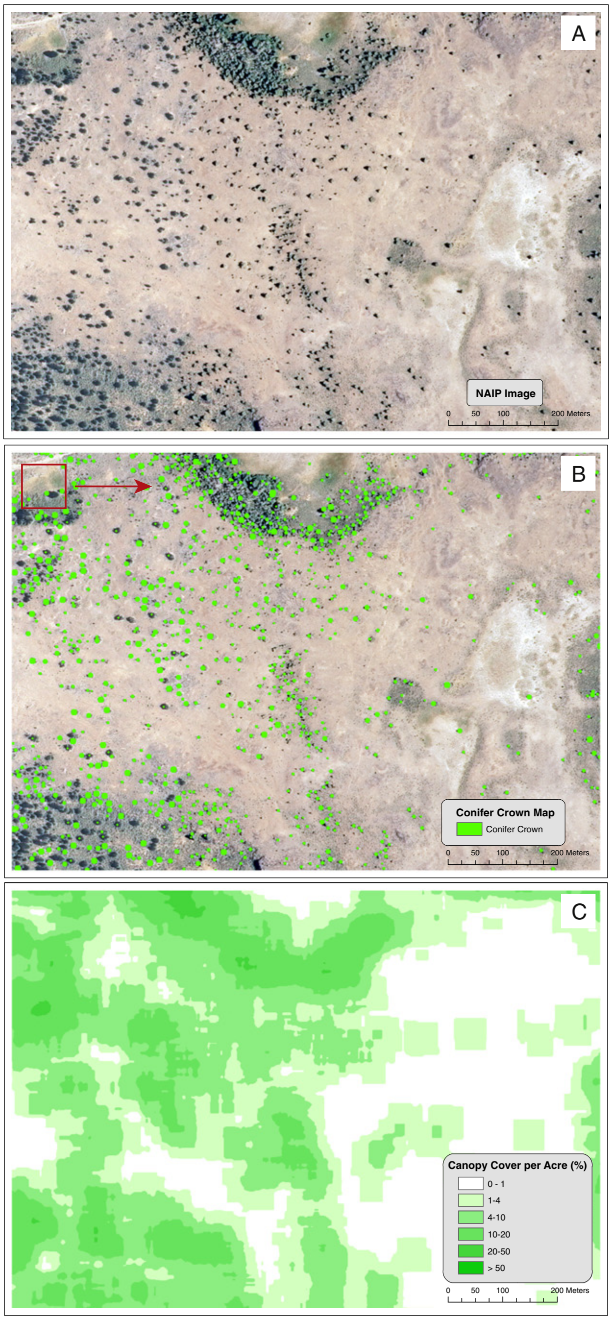

Figure 3. Canopy cover mapping process first uses a National Agriculture Imagery Program image depicting an area experiencing juniper encroachment (**A**) and then the spatial wavelet analysis—derived conifer locations and crown diameter (**B**). The red square represents the moving window used in the canopy cover calculation to produce the final classified canopy cover estimates for the area (**C**). Note: The canopy cover mapping approach is similar for mesquite, but the location and crown areas are irregularly shaped polygons outlining mesquite canopies.

region-merging hierarchical classification approach to derive polygons outlining mesquite canopies (individual canopies or patches of mesquite). We used a set of decision rules in which smaller-segmented image objects were progressively grouped into larger segments representing homogenous features (i.e., mesquite canopies). Up to three tiers of hierarchical refinement were used to derive mesquite canopy polygons. Multiresolution segmentation, in which shape = 0.1 and compactness = 0.5 (user-defined eCognition parameters), was performed for each tier of the segmentation process. Resulting image objects were classified at each tier using a combination of image texture (Texture after Haralick), area geometry, brightness, and NAIP-derived NDVI thresholds. Specifically, an NDVI threshold was used at each tier to identify all of the image objects that could potentially represent mesquite. Texture after Haralick, area geometry, and brightness thresholds were used at each tier to remove image objects from the NDVI classification results that did not meet the threshold requirements. The final classified image objects in the last tier were then merged to create a raster layer representing individual mesquite tree locations, or clumps of mesquite, and their associated crown areas or patch sizes (i.e., similar to SWA output; see Fig. 3B).

Canopy Cover Calculation and Classification

The conifer and mesquite crown maps (see Fig. 3B) were then used to calculate canopy cover via a moving window approach. Specifically, a 64 × 64 pixel moving window approximating a 0.4-ha (1 ac) area was used to estimate percent canopy cover (0—100%) across mapped regions (see Fig. 3C). Continuous canopy cover output was classified into categories: 0—1%, 1—4%, 4—10%, 10—20%, 20—50%, and > 50% to inform woody plant management (see Fig. 3D).

Accuracy Assessment

We quantified accuracy of the canopy cover product for prairie-chickens in both conifer and mesquite sites. To support the field validation, independent mesquite canopy cover was collected across twenty-nine 30-m transects. Along each transect we estimated canopy cover within four 2-m^2 quadrats evenly spaced 5 m apart. Canopy cover was recorded as an ocular estimate of the percentage of mesquite, shinnery oak *(Quercus havardii),* woody, grass, bare ground, and other. Juniper cover was calculated across eleven 0.04-ha (0.1-acre) circular plots where location and crown diameters of individual trees were measured. We compared these field measures to mapped canopy estimates using Pearson's correlation coefficients and root mean square errors. Mapping accuracy was not assessed for the 11-state sage-grouse canopy coverage because costs were prohibitive and because efficacy of SWA in these and other forested habitats is largely known; see "Discussion" later for accuracies reported in the literature.

Results

Mapping Current Extent of Conifer and Mesquite

We mapped conifer and mesquite tree canopy cover across an 11-state region (508 265 km^2; Tables 2—4; see Figs. 1—2). Of the occupied prairie-chicken habitats we mapped, > 90% were largely treeless for conifers and 67% and 79% treeless for mesquite in New Mexico and Texas, respectively (< 1% canopy cover; Tables 3—4; see Figs. 1—2). Early to moderate levels of tree cover (< 15% canopy) for prairie-chickens were variable among states but generally had a low prevalence for conifers (range 1—8% of occupied distribution) and higher for mesquite (range 16—28% of occupied distribution; see Tables 2—4 and Figs. 1—2). Conifer in the higher canopy cover classes (> 15%) was scarce (< 2% of occupied distribution, see Tables 3—4 and Figs. 1—2), as was mesquite (< 5%, see Tables 3—4 and Figs. 1—2).

The proportion of treeless canopy cover (< 1%) in mapped occupied sage-grouse habitats was variable across the SGI mapping extent ($\bar{x}$ = 71 SE = 5%; Table 2 and see Fig. 1). Low to medium levels of conifer cover (< 20% canopy) were most prominent ($\bar{x}$ =23, SE = 5%), but conifers in the highest cover class (> 50%) were scarce ($\bar{x}$ = 6, SE = 2%; see Table 2 and Fig. 1).

Our results show that both invasive conifer and mesquite cover is widely distributed across the respective ranges for sage grouse and prairie-chickens (see Figs. 1—2). However, the distribution of both invasive woody plants within the species' ranges does not follow an even distribution but instead appears to be regionally localized with some geographic areas relatively free of major encroachment (see

Table 2
Estimated extent and proportion of conifer canopy cover classes by state in sage-grouse occupied range and priority areas of conservation (PACs).

		Occupied range		PAC area (km^2)	
Canopy cover	State	Area (km^2)	Proportion (%)[1]	Area (km^2)	Proportion (%)[2]
< 1%	CA	6 860	52	4 896.2273	56
1-4%		1 154	9	832.5497	10
4-10%		1 311	10	862.447	10
10-20%		1 512	11	871.556	10
> 20%		2 421	18	1 212.3091	14
CA Total		*13 258*	*100*	8 675	100
< 1%	CO	18 191	71	8 307.82	87
1-4%		1 857	7	572.66	6
4-10%		1 965	8	337.91	4
10-20%		2 183	8	215.58	2
> 20%		1 561	6	91.49	1
CO Total		*25 757*	*100*	9 525	100
< 1%	ID	61 607	85	35 793	91
1-4%		3 795	5	1 824	5
4-10%		3 228	4	1 204	3
10-20%		2 607	4	610	2
> 20%		835	1	118	0
ID Total		*72 072*	*100*	39 549	100
< 1%	MT	12 685	80	5 236	87
1-4%		484	3	143	2
4-10%		642	4	176	3
10-20%		989	6	236	4
> 20%		1 125	7	196	3
MT Total		*15 924*	*100*	5 987	100
< 1%	NV	123 050	73	60 927	74
1-4%		9 570	6	5 308	6
4-10%		9 768	6	4 844	6
10-20%		13 526	8	5 899	7
> 20%		13 607	8	5 806	7
NV Total		*169 522*	*100*	82 783	100
< 1%	OR	64 484	81	23 277	88
1-4%		4 272	5	1 267	5
4-10%		4 153	5	991	4
10-20%		4 200	5	750	3
> 20%		2 185	3	283	1
OR Total		*79 293*	*100*	26 568	100
< 1%	UT	22 457	*52*	13 997	46
1-4%		5 398	*13*	3 721	12
4-10%		5 871	*14*	3 773	12
10-20%		8 702	*20*	5 107	17
> 20%		629	*1*	3 701	12
UT Total		*43 057*	*100*	30 299	100
Grand Total		***418 883***		***203 387***	

[1] Total occupied range area refers to the total area of the mapping units in each state.
[2] Total PAC area refers to the total PAC area within the mapping units in each state.

Table 3
Estimated extent and proportion of conifer canopy cover classes by state in lesser-prairie chicken—occupied range and focal areas, connectivity zones.

		Occupied range		FACZ	
Conifer canopy cover	State	Area (km^2)	Proportion (%)[1]	Area (km^2)	Proportion (%)[2]
< 1%	NM	1 859	93	718	100
1-5%		68	3	1	0
6-10%		21	1	0	0
11-15%		11	1	0	0
16-30%		21	1	0	0
31-50%		14	1	0	0
> 50%		6	0	0	0
Total NM		*2 001*	100	719	100
< 1%	TX	10 560	97	4 264	99
1-5%		145	1	12	0
6-10%		73	1	6	0
11-15%		45	0	4	0
16-30%		65	1	7	0
31-50%		17	0	2	0
> 50%		2	0	0	0
Total TX		*10 907*	100	4 296	100
< 1%	OK	18 442	90	5 088	96
1-5%		803	4	101	2
6-10%		513	2	56	1
11-15%		320	2	31	1
16-30%		414	2	39	1
31-50%		74	0	8	0
> 50%		0	0	0	0
Total OK		*20 566*	100	5 324	100
< 1%	CO	1 001	99	829	100
1-5%		7	1	0	0
6-10%		2	0	0	0
11-15%		1	0	0	0
16-30%		1	0	0	0
31-50%		0	0	0	0
> 50%		0	0	0	0
Total CO		*1 011*	100	829	100
< 1%	KS	30 957	95	14 050	97
1-5%		615	2	199	1
6-10%		362	1	107	1
11-15%		230	1	65	0
16-30%		355	1	90	1
31-50%		83	0	17	0
> 50%		1	0	0	0
Total KS		*32 603*	100	14 528	100
Grand Total		***67 088***		***25 695***	

[1] Total occupied range area refers to the total area of the mapping units in each state.
[2] Total FACZ area refers to the total area mapped within each FACZ in each state. Some FACZ areas were unmapped.

Figs. 1 – 2). For example, in the occupied sage-grouse distribution, northern Nevada, Idaho, and large portions of southeast Oregon provide relatively treeless sage-steppe habitats on which grouse depend (see Fig. 1). Other parts of the range, however, are experiencing variable levels of encroachment including large portions of Utah, eastern and southcentral Nevada, northeast California, central Oregon, and habitats along the border of California and Nevada (see Fig. 1). The northeastern portions of the prairie-chicken's distribution contained the greatest conifer tree cover and included southeastern Kansas and Oklahoma east of the panhandle. Mesquite canopy cover estimates of > 30% were mapped predominantly in the southern portions of the prairie-chicken's distribution in western Texas and eastern New Mexico and indicate that mesquite encroachment is a widespread problem over much of the mapped southern range (Table 4 and see Fig. 2).

The proportion of sage-grouse distribution supporting invasive woody plants was twice that of habitats occupied by prairie-chicken (20.5% vs. 9.7%; see Tables 2 – 4). Additionally, the proportion of area occupied by invasive woody plants was lower inside than outside priority habitats for both species (19.4% and 9.7% for sage-grouse PACs and prairie-chicken FACZs, respectively; see Tables 2 – 4). By absolute area, Nevada, Idaho, and Utah hold the greatest opportunities for sage-grouse restoration inside of PACs (see Table 2). Kansas and Texas have the most area of early tree invasion within prairie-chicken priority areas (20 368 km^2 combined), followed closely by New Mexico (see Tables 3 – 4). Alternatively, Kansas and Oklahoma have the largest area of tree invasion within currently occupied habitat. For prairie-chickens inside of FACZs, amount of early invasion is proportionally higher for mesquite (9 – 13%) than for conifer (0 – 4%).

Accuracy Assessment of Mapping Products

Our conifer canopy cover product for prairie-chickens was strongly correlated ($r = 0.98$; root mean square error (RMSE) = 4%) with the canopy cover derived from the conifer plot measurements (Fig. 4). The mesquite canopy cover product was also positively correlated ($r = 0.79$) with independent field measurements, and errors were relatively low (RMSE = 6.62%; see Fig. 4). In general, the mapping approach underestimated mesquite canopy cover in areas with cover < 15%. To assess whether the mesquite cover mapping approach was falsely detecting nontarget woody plants (e.g., shinnery oak), we also compared the mesquite canopy cover product to field measurements of nonmesquite woody plant cover. The mesquite canopy cover product was weakly related to field measurements to nonmesquite woody plant cover ($r = 0.21$; RMSE = 10.3%), indicating that false detections were rare.

Table 4
Estimated extent and proportion of mesquite canopy cover classes by state in lesser-prairie chicken—occupied distribution and focal areas, connectivity zones.

Mesquite canopy cover	State	Occupied distribution Area (km^2)	Occupied distribution Proportion (%)[1]	FACZ Area (Km^2)	FACZ Proportion (%)[2]
< 1%	NM	10 508	67	4 268	86
1-5%		2 362	15	459	9
6-10%		1 350	9	166	3
11-15%		676	4	53	1
16-30%		680	4	32	1
31-50%		138	1	4	0
> 50%		19	0	1	0
Total NM		15 733	100	4 982	100
< 1%	TX	5 168	79	1 385	90
1-5%		518	8	79	5
6-10%		348	5	41	3
11-15%		200	3	19	1
16-30%		234	4	16	1
31-50%		82	1	3	0
> 50%		12	0	0	0
Total TX		6 561	100	1 544	100
Grand Total		***22 294***		6 526	

[1] Total area refers to the total area of the mapping units in each state.
[2] Total area refers to the total area mapped within each FACZ in each state. Some FACZ areas were unmapped.

However, in areas with canopy cover < 15%, mesquite canopy estimates were approximately equal to field measurements of all woody plant cover (see Fig. 4), indicating that the potential for false detections in areas of low canopy cover exists. False detections were minimal when canopy cover exceeded 15%.

Discussion

Our study represents the most geographically complete, high-resolution assessment of conifers and mesquite across the western United States. The canopy products described herein measure conifer cover at one point in time and thus are not a direct indicator of conifer expansion (i.e., measurements at two points in time would be required to directly measure expansion). However, the canopy products can be used as a general inference to where expansion may have occurred across any given landscape. The conifer and mesquite canopy cover maps provide the first synoptic, geographical display of woody plant cover as a top-down threat to the western sage-steppe and prairie ecosystems (see Figs. 1—2). For the first time, the maps presented herein capture the complexity in patterns of fragmentation for both grouse species across their respective geographic distributions. Prairie-chickens are being squeezed from the eastern edge of their occupied distribution by conifer encroachment and from the southwest by mesquite, while sage-grouse habitat connectivity is being impeded by conifer cover between mid- and upper-elevation habitats and between PACs (Miller et al., 2008) (see Figs. 1—2). Alternatively, approximately 40% of extant prairie-chickens, and the only increasing population segment, occupy their northernmost stronghold in Kansas, where a largely treeless and intact shortgrass prairie ecosystem is bolstered by old tillage fields planted back to Conservation Reserve Program (CRP) grasslands (McDonald et al., 2014; Garton et al., 2016). The absence of a top-down stressor, such as tree encroachment, and the reduction of fragmentation through grassland restoration via CRP (Park and Egbert, 2008) appears to provide adequate landscape-level conditions to support population stability (Fuhlendorf et al., 2002).

In the Southern Great Plains, redcedar encroachment has increased between 50% and 600% from 1965 to 1995 (Coppedge et al., 2001). Because of the overall productivity in the region, prairie can be converted to a redcedar woodland in as little as 20 yr (Fuhlendorf et al., 2008). Woody species encroachment reduces the primary productivity and grassland plant species diversity and subsequently may alter nutrient cycling and the hydrology of these ecosystems (Engle et al., 2008 and references therein). Commensurate with such conversion is a loss of grassland obligate species as tree cover exceeds 10% (Chapman et al., 2004). Maintaining prairie as a herbaceous-dominated site requires appropriate stocking rates and the use of prescribed fire (Fuhlendorf et al., 2008). Because of the relatively productive ecological sites throughout

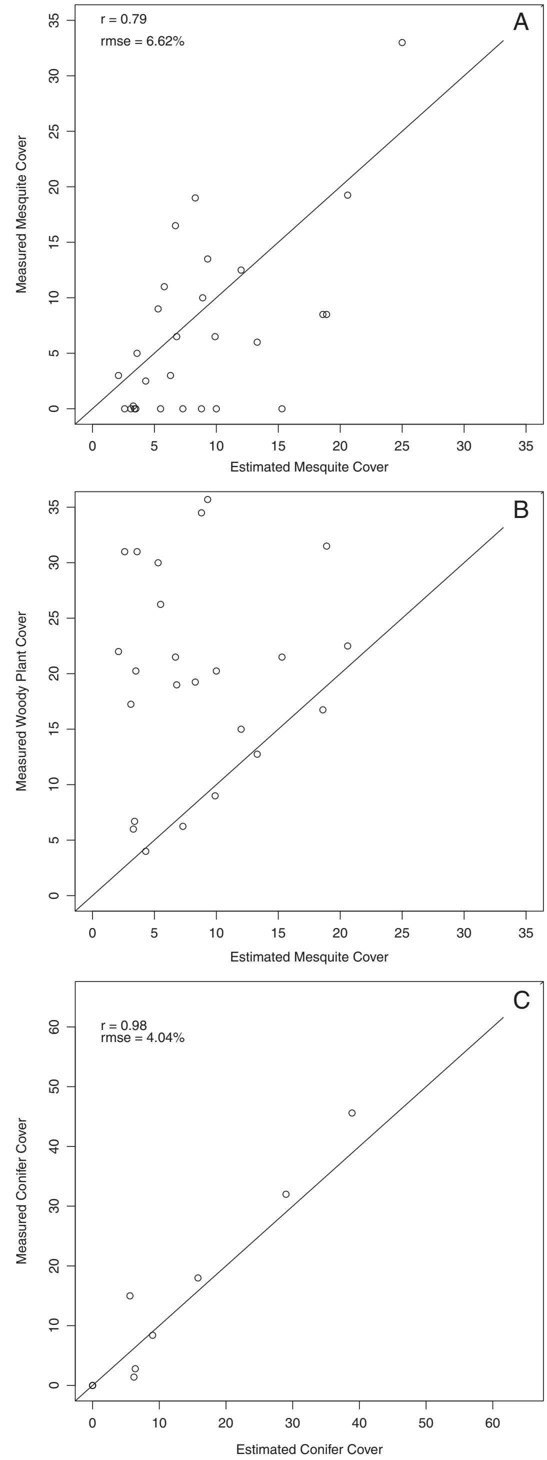

Figure 4. Mesquite and cedar canopy cover validation. **A,** Linear relationship between estimated mesquite canopy cover and field measured mesquite canopy cover with overestimations occurring below 15% cover. **B,** Relationship between estimated mesquite canopy cover and field measured total woody canopy cover. The nature of the relationship shows that false detections only occur in areas of low mesquite cover. **C,** Strong linear relationship between estimated conifer canopy cover values and field measured conifer canopy cover. The 1:1 lines are displayed in black on **A, B,** and **C.**

the Southern Great Plains, most plants are fire adapted and respond positively to periodic fire. However, as canopy cover exceeds 15%, more intensive methods, including mechanical removal, may be integrated with fire to restore the site to a herbaceous-dominated site.

Data on mesquite encroachment are limited to a few study sites outside the extant range of prairie-chickens. Nevertheless, its patterns are similar to those observed for *Juniperus* spp. throughout the West: marked increase in distribution and abundance since mid-20th century (Goslee et al., 2003) and reductions in herbaceous abundance and plant species diversity (Hennessy et al., 1983). Effective removal of mesquite can be elusive depending on plant density and size. A combination of herbicide, fire, and mechanical methods may be needed to remove existing stands with canopy > 15% (Scirfres and Polk, 1974; McDaniel et al., 1982; Martin and Morton, 1993). Prescribed fire and well-managed grazing may be cost-effective maintenance to suppress mesquite to low prevalence in grasslands (Ansley and Jacoby, 1998). Our mapping may assist in prioritizing those landscapes most suitable (canopy < 15%) for the reintroduction of fire and those that may require more intensive means of restoration.

In a dendrological study of pinion-juniper woodland expansion at several sites across the Great Basin, Miller et al. (2008) estimated about 80% of sagebrush sites affected by conifers were still in early to mid phases of woodland succession. Our study corroborates this finding across the mapped occupied sage-grouse range where only 20% of the area affected by trees supported advanced woodland conditions (> 20% tree canopy cover; see Table 2). Shrub and perennial herbaceous cover decreases with increasing tree cover, and these sites are expected to transition into closed canopy woodlands over the next 30 − 50 yr (Miller et al., 2008; Miller et al., 2011; Roundy et al., 2014). Our findings suggest a window of opportunity still exists on many sites to prevent further declines in sagebrush steppe vegetation through targeted treatment. Conifer removal has emerged as a primary conservation practice for maintaining extant sage-grouse populations through rapid restoration of degraded sage-steppe (Baruch-Mordo et al., 2013), and our mapping illustrates the greatest opportunities remaining to restore sage-steppe lie inside of sage-grouse strongholds (i.e., PACs) in Nevada and Utah, but each mapped state contains spatially explicit restoration hotspots (1 − 20% canopy cover; see Table 2 and Fig. 1). Given the correspondence between our mapping products and broad-scale patterns of conifer cover, we are confident in their applicability to successfully target conservation for such hotspots.

Our accuracy was relatively high ($r = 0.79 - 0.98$) within prairie-chicken habitats. However, because the accuracy assessment was conducted in small areas relative to the mapping extent, accuracy will vary across the entire extent of the mapping area. Despite congruence, mapping error is unavoidable. Previous studies have assessed conifer canopy cover mapping via SWA, demonstrating that canopy cover estimates were equivalent to independent measures at < 40% cover and biased low in areas with higher canopy cover (Poznanovic et al., 2014), likely a result of canopy clumping (Strand et al., 2008). SWA performed well ($r = 0.86$) estimating tree crown diameters in open canopy forests in Idaho (Falkowski et al., 2006) with highest accuracies at low canopy covers (< 20%; Falkowski et al., 2008). Similarly, in a juniper woodland, the mapping accuracy of SWA estimates of overall crown diameter was high ($r = 0.96$) with a well-balanced error in trees that were missed or incorrectly detected (< 8%; Strand et al., 2006). We fully acknowledge that the results of the aforementioned studies may not sufficiently reflect the accuracy of the products presented herein due to differences in data types and inference spaces. Users of these products should consider assessing the accuracy of the canopy cover products before use in specific areas of interest. Supplementing the canopy cover products with additional inventory data before restoration activities may provide a more precise characterization of the extent and absolute value of canopy cover for a typical restoration project area.

This mapping product is well suited for conservation planning, but at the site level a few trees may be missed or incorrectly identified. For example, previous research on the SWA algorithm demonstrated that successful tree detection depends on both tree size (i.e., crown diameter) and spatial resolution of the input imagery. Generally, SWA (or any other object-based remote sensing approach) cannot detect objects smaller than approximately two times the image spatial resolution (i.e., pixel size). In this case, because we leverage 1-m spatial resolution NAIP data, trees < 2 m in crown diameter (equivalent to 4 pixels in the NAIP imagery) were likely not successfully detected, which cloud certainly impact end users specifically targeting restoration strategies in early-phase invasion sites. Furthermore, end users should also be aware that because the digital sensors used for NAIP image acquisition are uncalibrated, radiometric properties of images vary across space and time, ultimately leading to variation in mapping accuracy. For example, variation due to uncalibrated NAIP can sometimes be seen along image seamlines or state boundaries (see Figs. 1 − 2). We attempted to maintain accuracy by compensating for variation in phenology using different image derivatives such as image complement, or by adjusting SWA detection thresholds. Two sources of variation for which we could not compensate include topographic shadowing that may have resulted in underdetection or omission of trees and the inability of OBIA mapping approaches to differentiate between woody plant species, which, despite using semiautomated approaches to remove false detections, may have detected nontarget species. Alternative image products such as those acquired by high-resolution satellite sensors may offer an effective image base for deriving improved canopy cover estimates. For example, data from the WorldView family of satellites offer improved spatial and spectral resolution and have higher geometric and radiometric fidelity as compared with NAIP imagery and thus may provide an opportunity to improve on the canopy cover product described herein. However, we are highly encouraged by the correspondence between the mesquite and conifer maps and areas of know woody plant locations at broad scales and encourage the application of these tools to improve the effectiveness of conservation delivery.

Implications

The results of our study provide wildlife and habitat managers digital maps they can use to balance trade-offs between costs and benefits of various treatment techniques across the landscape. Using the visualization and data portals at http://map.sagegrouseinitiative.com and http://kars.ku.edu/maps/sgpchat/, this new mapping information provides practitioners with direct access for planning their next project. Proactive removal of conifers during earlier phases of invasion, using mechanical techniques that minimize ground disturbance and retain shrub and herbaceous communities, are often preferred to delay-and-repair approaches in order to produce more immediate sagebrush-obligate wildlife benefits, maintain ecosystem resilience, and reduce risks of invasive annual grasses (Maestas et al., 2015; NRCS, 2015a, 2015b). Sagebrush-obligate songbird abundance increased 55 − 85% following shrub-retaining cuts designed to benefit sage-grouse in southern Oregon (Holmes et al., 2017-this issue), but no such response was evident on broadcast-burned sites where juniper skeletons remained (Knick et al., 2014). Fire has approximately twice the treatment life of cutting trees at time horizons approaching 100 yr but has high up-front conservation costs due to temporary loss of sagebrush (Boyd et al., 2017-this issue) and lowers resistance to invasive annual grasses (Miller et al., 2014). Regardless of treatment technique, early intervention to address conifers is economically prudent for livestock producers, especially when cost-shared with conservation partners, to prevent loss of available forage by up to 60% if targeted toward more productive soils.

Seizing upon restoration opportunities is perhaps most timely for prairie-chickens as they occupy only 16% of their historical distribution (80 500 km^2), an area equivalent to the occupied range of sage-grouse in Oregon and California (94 000 km^2; see Fig. 1). Practitioners can use this new mapping technology to show stakeholders that restoration

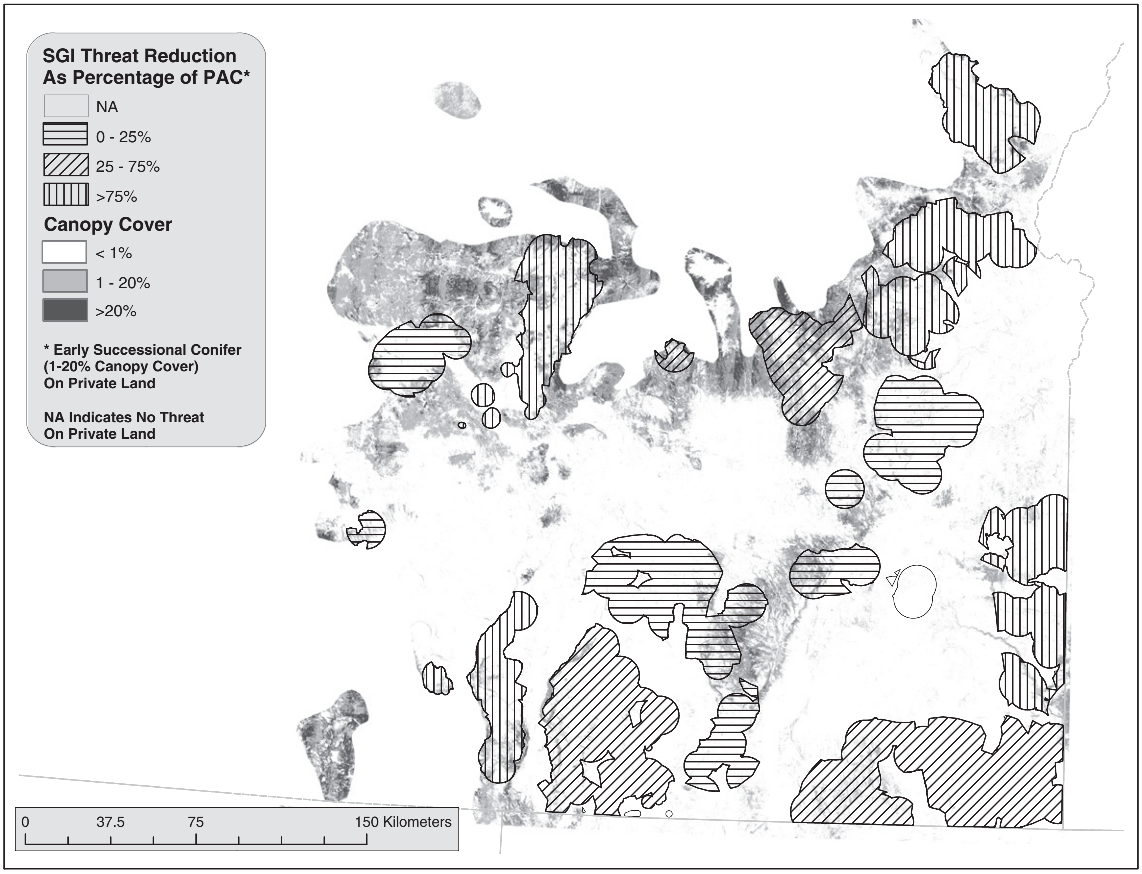

Figure 5. Tracking conifer threat reduction by priority areas of conservation (PACs) in Oregon. Represented is the proportion of early-to-mid succession conifer (1 − 20% cover) on private lands already ameliorated by landowners participating in the Sage-Grouse Initiative. Conifer removal has been primarily targeted in and around PACs where the threat is greatest on private lands.

goals are within reach; at $100 per hectare, careful targeting can alleviate prairie-chicken strongholds and their connective zones (FACZs; see Fig. 3) of invading tree threats (1 − 15% canopy cover; see Table 4) for an estimated $14US million, a comparatively small investment to recover an imperiled species (Evans et al., 2016). Wholesale restoration in landscapes such as those mapped in southern New Mexico would provide a major increase in the species historical distribution and would likely require translocating birds (McNew et al., 2012).

Digital maps used as targeting tools maximize biological return on investment by reducing cost of removal (Bottrill et al., 2009). Our high-resolution mapping provides a mechanism for quantifying and tracking threat reduction, thereby increasing transparency and accountability for conservation funding. For example, map products enabled partners implementing SGI in Oregon to better estimate the extent of the early conifer encroachment threat, which allowed development of a spatially explicit investment strategy for solving the problem in and around PACs (NRCS, 2015a, 2015b; Fig. 5). As a result, targeted conifer removal increased > 1 400% in 5 yr and resulted in a two-thirds reduction of the early-phase conifer threat on private lands (NRCS, 2015a). Conservation partners can now track progress toward threat-reduction goals by PACs (or focal areas in case of prairie-chickens), which aids future resource allocation and allows agency leadership to secure financial commitments necessary to finish the job (NRCS, 2015b).

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