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Challenges of Brush Management Treatment Effectiveness in Southern Great Plains, United States

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Abstract
Woodland expansion is a global challenge documented under varying degrees of disturbance, climate, and land ownership patterns. In North American rangelands, mechanical and chemical brush management practices and prescribed fire are frequently promoted by agencies and used by private landowners to reduce woody plant cover. We assess the distribution of agency-supported cost sharing of brush management (2000–2017) in the southern Great Plains, United States, and evaluate the longevity of treatment application. We test the general expectation that the current brush management paradigm in the southern Great Plains reduces woody plants and conserves rangeland resources at broad scales. This study represents the most comprehensive assessment of treatment longevity following brush management in the southern Great Plains by linking confidential private lands management data to a national inventory program (US Department of Agriculture Natural Resources Conservation Service National Resources Inventory). We observed regional differences in the types of brush management techniques used in cost-sharing programs throughout the study area. Mechanical brush management was the most common practice cost shared in Texas, while a mixture of mechanical and chemical application was most common in Oklahoma. Prescribed fire was most common in Kansas with some areas receiving chemical treatment. Our analysis showed brush management, as implemented, did not reduce tree cover long term and minimally reduced shrub cover. Evidence to support the current brush management paradigm only existed at local site-level scales of analysis (40- to 50-acre area), but treatment effectiveness was short-lived. At regional scales, observed changes in woody plant cover showed little to no overall net reduction from 2000 to 2017. These findings bring into question the philosophy of the current brush management paradigm, its implementation as the default rangeland conservation practice, and its prioritization over alternative practices that prevent new woody plant establishment and enhance resilience of rangelands in the southern Great Plains region.

Keywords: Brush management, Great Plains, rangelands, restoration, scale, woody encroachment

Introduction

Brush management in rangeland systems can generally be defined as the “active control of woody plants by removal, reduction, or manipulation” (Natural Resources Conservation Service 2017). Over the past few decades, rapid increases in woody plants in US rangelands have been well documented (Van Auken 2000; Eldridge et al. 2011; Archer et al. 2017). Records of brush management implementation date back to the 1930s (Bovey 1998). The main reasons for its implementation are the adverse effects of woody encroachment on water cycles (Zou et al. 2014; Zou et al. 2015), multiple ecosystem services (Twidwell et al. 2013b; Archer and Predick 2014), ecological diversity (Ratajczak et al. 2012), and commercial forage production (Fuhlendorf et al. 2009). However, methods for brush management on US rangelands such as mechanical, chemical, and prescribed fire have been largely criticized as ineffective because their costs preclude implementation over large areas (Archer et al. 2011; Twidwell et al. 2013a). Despite governmental cost-share programs (e.g., assistance provided to landowners performing these tasks) associated with brush management techniques, such as mechanical treatment or herbicide application, recovery of ecosystem services may be absent or short-lived (Archer and Predick 2014). This has been observed in many parts of the southern Great Plains of North America (e.g., Ratajczak et al. 2016) and the encroached savannas of southern Africa (e.g., Smit et al. 2016), particularly where resprouting species are encroaching. Consequences of woodland encroachment, both ecological and social, may be exacerbated by the effects of increased climate variability and global change (Stroh et al. 2018; Wilcox et al. 2018), especially given that most endeavors in rangeland restoration fail to incorporate the complexity of socioecological systems (Fuhlendorf et al. 2018).

Several studies have demonstrated that woody cover can vary with patterns of rainfall and fire across global scales (Bucini and Hanan 2007; Sankaran et al. 2008; Scholtz et al. 2018a). In encroached rangelands of the Great Plains, United States, areas receiving > 800 mm mean annual precipitation (MAP) have the potential to become closed-canopy woodlands, while areas receiving < 800 mm MAP are generally rainfall limited but can still support substantial woody cover (as much as 20–40%, Scholtz et al. 2018a). Fire alone can be used to manage woody cover. However, conserving rangelands over the entire rainfall gradient requires frequent fire application (Twidwell et al. 2015) and initiation of prescribed fires before recognition of the invasion (Ratajczak et al. 2014). Concomitantly, fire alone as a treatment application is context dependent. For example, once woody cover reduces herbaceous fuels, the effectiveness of prescribed or controlled low-intensity fires may be diluted (Twidwell et al. 2016b). In the US Great Plains, where grasslands and large tracts of agricultural land are interspersed, ecological processes such as fire can be easier to manage in smaller fragments but may be less effective at reducing woody cover because fire moves discontinuously through fragmented landscapes and many areas will remain unburned (Scholtz et al. 2018c).

Studies have identified that the effect of current brush management effort s and fire on woody plant cover in the southern Great Plains are short-lived (Archer et al. 2011; Archer and Predick 2014; Ratajczak et al. 2016). Common, applied options for restoring or conserving North American rangelands via woody biomass removal involve large machinery (e.g., bulldozers) and chemical application (e.g., herbicide) (Archer and Predick 2014). Chemical application, particularly in isolation, has displayed variable success in reducing woody cover, although in combination with fire it can reduce woody plant cover (Scholtz et al. 2018b). Also, although wildfire cannot be considered a brush management tool, it does substantially reduce woody cover (Walker et al. 2018) and has increased substantially in the Great Plains in recent years (Donovan et al. 2017). Nevertheless, whether clustering patterns of certain brush management types are observed at state levels remains unknown.

Advances in remote sensing now make it possible to track continuous change in woody vegetation in response to brush management at an unprecedented range of scales. In this study, we use the US rangeland analysis platform (Jones et al. 2018) to access vegetation data of moderate spatial resolution and repeated through time. We did not use current field data woody cover estimates collected by the National Resources Inventory (USDA 2018) to avoid common data extrapolation pitfalls using site-level field inventory data to predict broader-scale geographic (Miller et al. 2004). In general, both field and remotely sensed data have their limitations in vegetation monitoring. For example, field data are limited spatially and remotely sensed data are limited by classification and spatial/temporal resolution even though both approaches have benefits. Field data also allow for fine-scale observation and species identification while remotely sensed products generally cover a large area. The Jones et al. (2018) dataset provides a favorable balance between spatial and temporal resolution and extent in vegetation monitoring. With a temporal extent of 1984–present, a temporal resolution of 1 yr, a spatial extent of western US rangelands, and a spatial resolution of 30 m, it opens a new dimension in vegetation monitoring and provides opportunities for assessment of brush management. We used the Jones et al. (2018) dataset and field data collected in the southern Great Plains to address the following three questions regarding brush management:

1) Does the type of cost-share treatment (mechanical, chemical, prescribed fire) supported on private land vary across states in the southern Great Plains?
2) What are the long-term (between 2000 and 2017) vegetation responses to brush management application and wildfire at site and regional scales?
3) Does localized implementation of brush management scale up to conserve rangeland resources at broader regional extents?

This study does not aim to evaluate cost-share programs but rather to detect regional responses of brush management application using moderate-scale remotely sensed data. We also provide several considerations for future efforts in brush management.

Methods

Study area

The study area covered rangelands of three states (Kansas, Oklahoma, and Texas), with rangelands delineated according to Reeves and Mitchell (2011) within the United States (**Fig. 1)**. The area was once considered mainly as grassland, except for certain areas in Texas, which could be considered as a savanna. However, over the past few decades, woodland expansion has increased from the east in the higher rainfall areas into other areas with less rainfall. Overall, MAP over our study sites ranges from around 600 mm to 1 000 mm (PRISM Climate Group 2020).

Data Acquisition

Vegetation cover was represented by the four plant functional groups: annual grasses and forbs, perennial grasses and forbs, trees and shrubs, as well as litter and bare ground, all sourced from Jones et al. (2018). Data for the yr 2000 and 2017 within a 1-ha buffer surrounding n = 380 unique sampling points within Kansas (n = 41), Oklahoma (n = 154), and Texas (n = 185) were used. Sampling points were sourced from the National Resources Inventory (NRI; NRI Survey 2013) survey, in which information on brush management was recorded for the yr

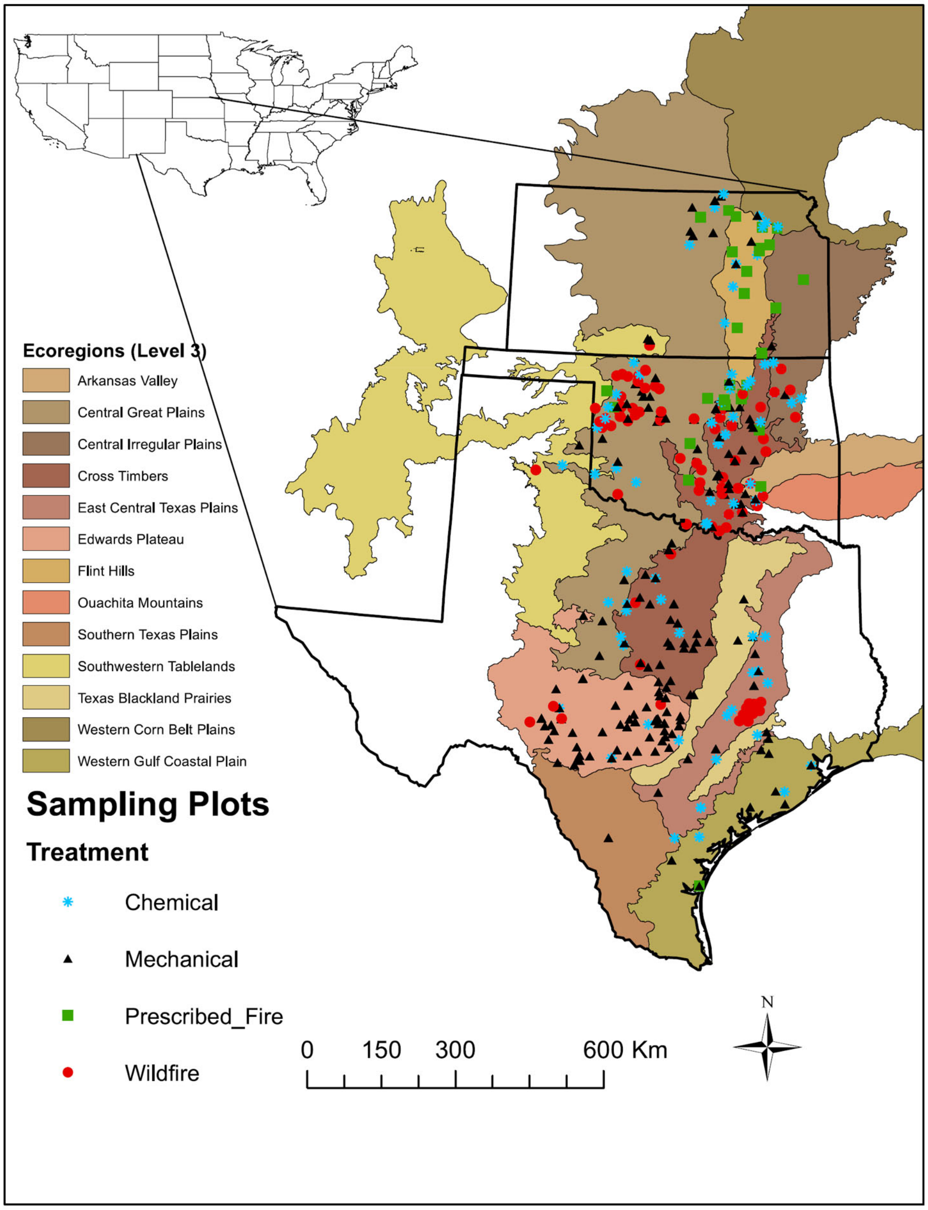

Fig. 1. Distribution of brush management types (chemical, mechanical, and prescribed fire) and wildfire in the portion of the southern Great Plains addressed in this study. Both state boundaries and ecoregions (level 3, Omernik 1995) are depicted. (Data sourced from the US Department of Agriculture Natural Resources Conservation Service National Resources Inventory program.)

2004 –2014. Using a slightly longer temporal extent for vegetation functional groups (2000 –2017) helped ensure the analysis would capture any legacy effects of brush management. To test whether the size of the buffer drawn around sampling points drastically influenced percent woody cover response to treatment application, we compared five buffer sizes around NRI sampling sites. Results from different buffer areas (1, 5, 20, 80, and 160 ha) around these NRI sample points showed minimal differences with respect to relative woody cover change between 2000 and 2017. However, the 1-ha buffer tended to capture changes in relative woody cover more frequently than the other buffer sizes (Fig. S1); therefore, we used the 1-ha buffer percent cover measurements for the rest of this study.

Classified (restricted) information on brush management practices were obtained from the Natural Resources Conservation Service (NRCS) NRI Grazing Land On-site Data Study, which is a branch of the NRCS that conducts annual field-based statistical inventory of natural resource conditions on US nonfederal lands. It is used to inform decision makers and assess conservation priorities and actions (NRCS USDA 2017). The NRCS also has a division to manage cost-shared brush management activities on private lands through an application and review process (NRCS–Environmental Quality Incentives Program). Most treatments are applied on 40- to 50-acre (16- to 20-ha) patches of private land (Twidwell et al. 2013a). Brush management practices recorded over the survey years included mechanical, chemical, and prescribed fire. Surveyors also noted signs of wildfire at the study site. Mechanical brush management included the use of any mechanical equipment to reduce or remove woody cover. Chemical refers to the act of chemical application on woody plants. Prescribed fire is the use of an intentional, controlled fire to meet ecological objectives. Several sites contained signs of more than one management type, and because it was not possible to ascertain which management type was applied first, these sites were omitted from the study. The exact year of treatment application for the sites retained in the study was unknown. We also excluded sites that did not require brush management according to the surveyor, because our study focused on brush management treatment effectiveness.

Data analysis

To quantify changes in vegetation cover as a result of various brush management practices, we compared percent cover changes under all brush management types for all functional groups (annual grasses and forbs, perennial grasses and forbs, trees, shrubs, litter and bare ground) between 2000 and 2017 at sampling sites using paired *t* -tests. While we are aware that the brush management program is set out to target woodland encroachment, we assessed all functional groups including litter and bare ground to identify any additional effects of treatment application. A site consisted of all 30-m pixels within a 1-ha buffer of the NRI sample location. Furthermore, we compared percent tree and shrub cover change of brush management sites and sites burned by wildfire between 2000 and 2017 using a generalized linear model framework following Venables and Ripley's (2002) binomial approach with percent data. Here, the response variable was either % tree or shrub cover and the independent variables were the brush management types and year. This model was used to identify trends in brush management effects among treatment types across states.

To assess the general expectation that localized implementation of brush management conserves rangeland resources experiencing woody encroachment at broader extents, we compared site-level to regional-level changes in woody cover. To do this, we first aggregated NRI sites within 1-degree by 1-degree cells. We then averaged shrub (or tree) cover over all sites within each cell to produce the site-scale aggregated shrub (or tree) cover for the 63 cells covered by the NRI sites. This was done for both 2000 and 2017. Thereafter, using a similar approach, but including all 30-m pixels within each 1-degree cell for all cells within the whole study area (i.e., covering all three states), we refer to this as "regional-scale aggregation." We calculated the change in shrub (or tree) cover from 2000 to 2017 at the pixel level, then averaged over all sites or pixels within a cell to assess the cell-level change in cover. Data were extracted using Google Earth Engine (Gorelick et al. 2017), and data analysis was conducted in R. v3.4.3 (R Development Core Team 2017) using the packages MASS (Venables and Ripley 2002), raster (Hijmans and van Etten 2015), and rgdal (Bivand 2013). Plots were created using the package ggplot2 (Wickham 2009).

Table 1 Number of sites and percent brush management applied within each state of the southern Great Plains, United States.

	Chemical	*Mechanical*	*Prescribed fire*	*Wildfire*	*Total*
Kansas	12 (29%)	14 (33%)	15 (36%)	1 (2%)	42
Oklahoma	34 (22%)	47 (31%)	14 (9%)	59 (38%)	154
Texas	33 (18%)	123 (66%)	1 (1%)	28 (15%)	185
Total	79	184	30	88	

Results

Variation in cost-share treatments

Across the entire study area, the most frequent treatment was mechanical (48% of sites), followed by wildfire (23% of sites), chemical (21% of sites), and prescribed fire (8% of sites) (**Table 1)**. Woody cover in the yr 2000 was highest at sites with mechanical treatment (22% shrubs and 41% trees). This was followed by wildfire (15% shrubs, 34% trees), chemical application (17% shrubs, 23% trees) and prescribed fire (16% shrubs, 18% trees). Treatment application including wildfires was mostly documented in Texas (49%) and Oklahoma (40%). In Texas, mechanical management was the preferred application treatment, particularly in the Edwards Plateau where shrub encroachment has been extensively documented (Berg et al. 2015). Oklahoma showed a preference toward chemical or mechanical treatment over prescribed fire while Kansas did not show any strong preferences for any treatment type (see Table 1, Fig. 1).

Brush management treatment effectiveness and plant functional group response

Almost all brush management types and wildfires had mixed responses for the various functional groups throughout the study area. A long-term reduction in tree cover was not detected over the entire time period (**Fig. 2)**; instead, inconsistent patterns in % tree and shrub cover were observed among treatment types and wildfire in each state (**Fig. S2**). In general, all sites with brush management types or wildfire in Kansas had a significant increase in average % tree cover from 4% to 9.5% (t

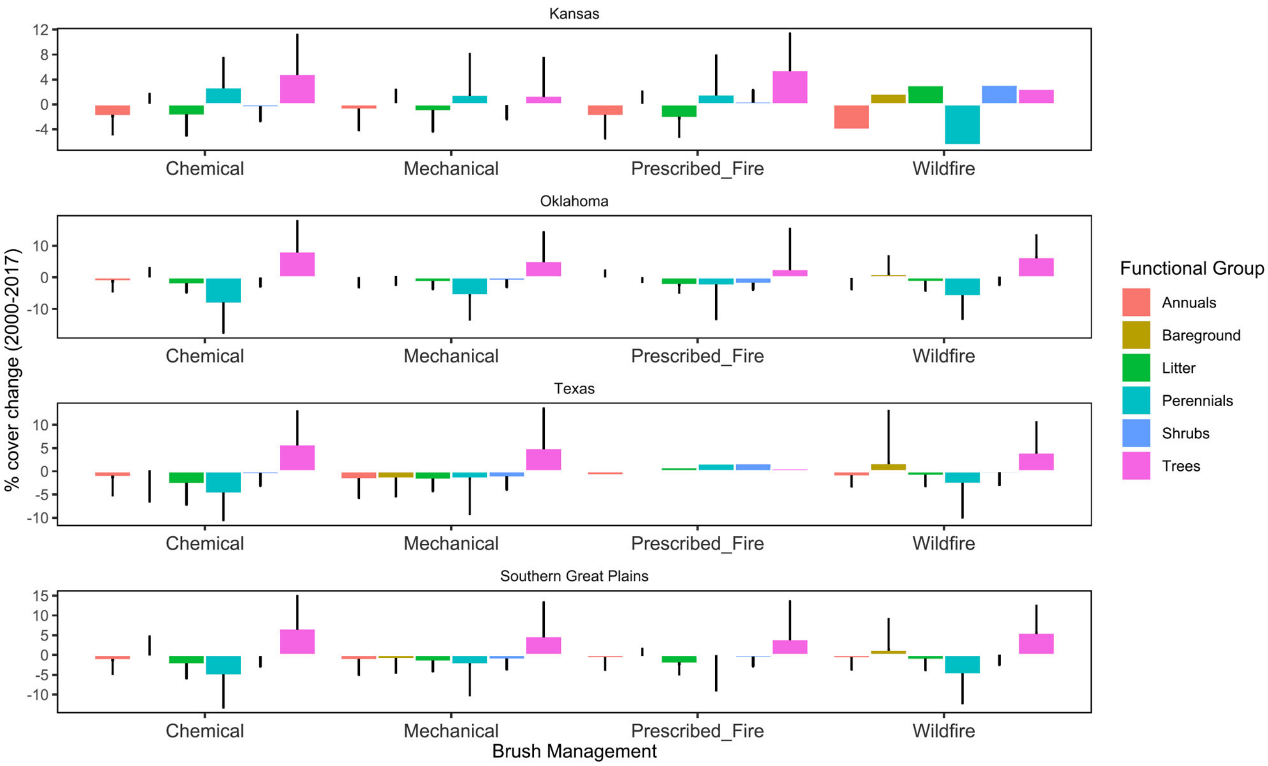

Fig. 2. Mean + standard deviation % cover change for all functional groups—annual forbs and grasses, bare ground, litter, perennial forbs and grasses, shrubs, and trees—between the yr 2000 and 2017 for each state and all sites combined (southern Great Plains) under various brush management types and wildfire. When no error bar is present, this suggests that the sample size equaled 1. (Data sourced from Jones et al. [2018]).

$_{51} = -5.43$, $P < 0.001$). In Oklahoma average % tree cover increased significantly from 6.5% to 13.25% ($t_{214} = -10.71$, $P < 0.001$) and in Texas, average % tree cover increased significantly from 9.7% to 14.3% ($t_{326} = -10.82$, $P < 0.001$) between 2000 and 2017 (see Table S1 for results of the remaining functional groups). On average across the entire study area, all other functional groups except tree and shrub cover decreased between 2000 and 2017 (see Table S1).

Scaling up of localized brush management implementation

Regional scale aggregated shrub cover was highest in the South and decreased northward in both 2000 (**Fig. 3a)** and 2017 (Fig. 3b). Areas showing a reduction in shrub cover (cool colors) at site scales also

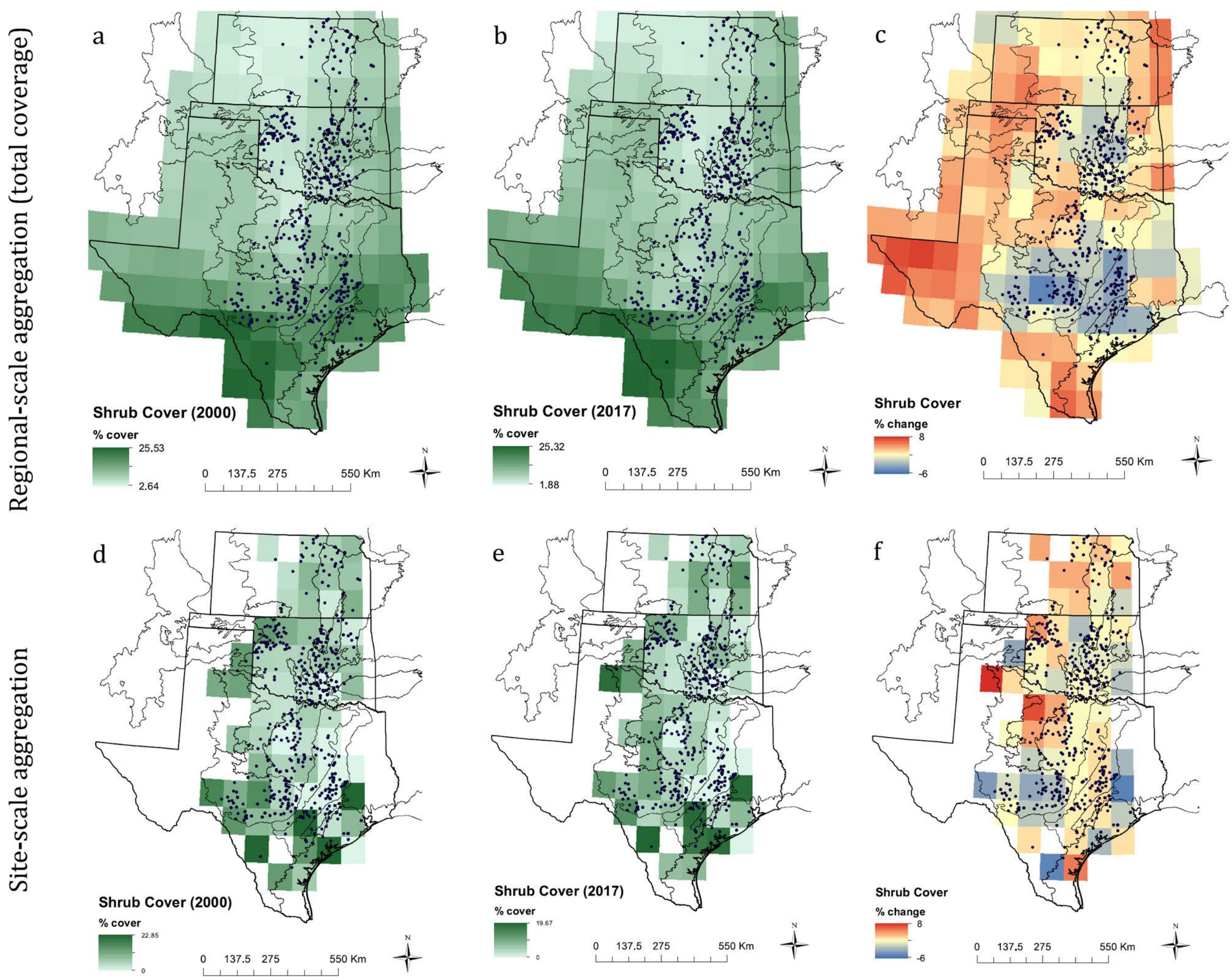

Fig. 3. Two methods of % shrub cover aggregation to 1°×1° grids. Top panel shows regional scale aggregated (i.e., total coverage) % shrub cover in the a) yr 2000, b) yr 2017, and c) % change between 2000 and 2017. The bottom panel shows site-scale aggregated (site-information only) % shrub cover in the a) yr 2000, b) yr 2017, and c) % change between 2000 and 2017. In panels (c) and (f), warm colors represent increases in shrub cover while cool colors represent decreases. Ecoregions (level 3, Omernik 1995) within the study area are outlined along with state borders. (Data from Jones et al. [2018] and aggregated from 30-m pixels to 1°×1° grids.)

showed a reduction at regional scales (Fig. 3c). Considering site-scale aggregation for shrub cover (Figs. 3d–3f), patterns of % shrub cover in both years (2000 and 2017) broadly followed a precipitation gradient in which highest % cover was recorded in the Southeast, where the highest rainfall is received. % Shrub cover change in Fig. 3f compared with Fig.

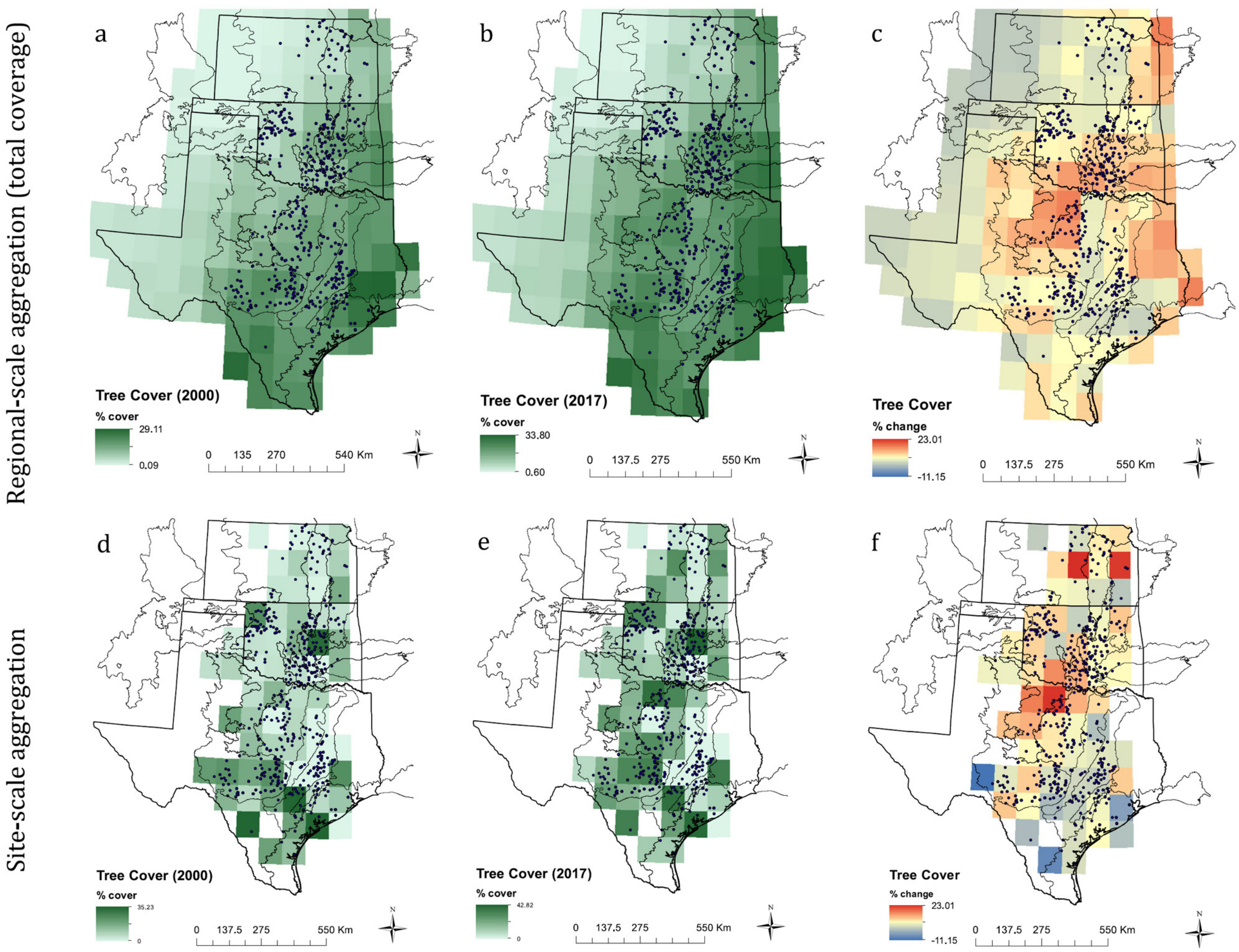

Fig. 4. Two methods of % tree cover aggregation to 1°×1° grids. Top panel shows regional scale aggregated (i.e., total coverage) % tree cover in the a) yr 2000, b) yr 2017, and c) % change between 2000 and 2017. The bottom panel shows site-scale aggregated (site-information only) % tree cover in the a) yr 2000, b) yr 2017, and c) % change between 2000 and 2017. In panels (c) and (f), warm colors represent increases in tree cover while cool colors represent decreases. Ecoregions (level 3, Omernik 1995) within the study area are outlined along with state borders. (Data from Jones et al. [2018] and aggregated from 30-m pixels to 1°×1° grids.)

3c appeared to be in partial agreement, representing a weak relationship in overlapping areas (R^2 = 0.10, root-mean-square error [RMSE] = 2.13%). However, there appears to be some evidence of % shrub cover reduction in the southern section (e.g., South Texas) (Figs. 3c and 3f).

Regional scale tree cover in 2000 (**Fig. 4**a) and 2017 (Fig. 4b) was highest in the Southeast, where the highest rainfall and woody plant cover potential is found (Scholtz et al. 2018a). Percent change in tree cover using the regional scale aggregation method (total coverage) showed no areas of cover reduction (min = 0.5%, max = 13% change, Fig. 4c), implying that increases in % tree cover were recorded even where brush management was applied. Throughout Fig. 4, comparison of regional- and site-scale aggregations showed major discrepancies between the two aggregation approaches. Despite no reduction identified at the regional scale (Fig. 4c), site-level aggregation (Fig. 4f) showed a large range between areas of encroachment and reduction (min = −11%, max = 23%). Where the areas overlapped, the relationship in % tree cover change (R^2 = 0.15, RMSE = 4.87%) was weak. For most of the study area, weak correlation relationships and relatively high mean square errors between aggregation methods for % tree and shrub cover and % cover change were observed.

Discussion

Not many opportunities exist to test whether regional responses to brush management practices are evident using fine-scale remotely sensed data. This study is timely given recent trends in woodland expansion, particularly in US rangelands and technological advancements that have enabled fine-scale rangeland monitoring (Dietze et al. 2018; Jones et al. 2018). For this program, we found that prescribed fire was mostly applied in Kansas and Oklahoma, while mechanical application was mostly applied in Texas and Oklahoma. Areas with signs of wildfires were recorded mostly in Oklahoma and Texas while areas with chemical application were recorded throughout the study area. Patterns of brush management application may be a combination of factors such as landscape requirements but also largely linked region-specific cultural values (Symstad and Leis 2017). In areas such as the Edwards Plateau, Texas, which contains high levels of woodland encroachment generally by juniper-oak savanna and mesquite-Acacia savanna, mechanical treatment is preferred. In contrast in the Flint Hills of Kansas, woody cover is relatively low even though threatened by juniper expansion and fire is the preferred brush management tool. These patterns provide insight to better understand woodland expansion by bridging the varied biophysical and social domains within the southern Great Plains (Wilcox et al. 2018).

Several studies show that brush management practices in encroached rangelands may be effective at small scales (Ansley and Castellano 2006; Archer et al. 2011; Scholtz et al. 2018b), but our study suggests that this outcome is not reflected at regional levels generally required for conservation planning. Despite brush management application, many areas showed net increases in percent tree cover over the time period. Responses in the shrub layer, however, were less consistent, with some reduction observed under specific treatments (e.g., mechanical, chemical) but not others (e.g., prescribed fire). While shrub cover generally followed the rainfall gradient, this pattern became more heterogeneous due to topography and soil at finer scales (Monger and Bestelmeyer 2006).

Furthermore, localized implementation of brush management to conserve broader landscapes revealed disparate patterns of woody cover at regional scales. The concern is the extent to which patterns of woody cover are altered when considering site-scale aggregation versus regional-scale aggregation. This mismatch suggests that we should be cautious when aggregating site-level data to regional scales for landscape management purposes. A caveat of this approach could be to include more sites per 1 °×1 ° grid, but this is not a feasible long-term solution for field surveyors sampling a limited area.

Tree cover showed no signs of decrease for the 18-yr period despite brush management and wildfire (see Fig. 2). Our current strategy may be setting us up for rapid re-encroachment of the species targeted for restoration. Brush management has been implemented at small scales (i.e., sites), which potentially leaves a site prone to rapid recovery of woody species because of multiple surrounding sites. Many sites are not clearcut or individuals could be left unattended and escape the fire trap. Current monitoring and inventorying approach have been insufficient to allow strategic targeting to manage woody encroachment at larger scales (Uden et al. 2019; Jones et al. 2020). User-related errors such as inaccurate tracking of locations where treatment was applied could also contribute to this finding. These are major limitations to the current cost-share program in controlling encroaching woody species throughout the southern Great Plains.

Given the geographic extent of this study, our findings suggest the current strategy for managing woody encroachment is largely ineffective at large scales for both resprouting and nonresprouting woody species. Species such as *Juniperus virginiana* (Eastern redcedar) do not have the ability to resprout after top-kill by some forms of brush management or wildfire. In areas where Eastern redcedar is the dominant encroaching species, brush management does (Fogarty et al. 2020). However, without repeat application or physical removal of these plants, some of these individuals escape treatment and can contribute to rapid spread. Other species are capable of resprouting and may recover as quickly as 2 or 3 yr (Harrell et al. 2001). This has also been documented in parts of southern Africa, where species such as *Dichrostachys cinerea* (sicklebush) are aggressive resprouting encroachers also deemed to require repeated treatment (e.g., high-intensity fires, Smit et al. 2016). In contrast to common brush management practices, wildfires in the Great Plains are generally of higher intensity (compared with prescribed fires), occur in both rangeland and forested areas, and have the potential to substantially reduce woody cover (Twidwell et al. 2016a). Wildfires have increased in over recent decades (Dennison et al. 2014; Donovan et al. 2017) and have great potential to reduce woody cover. However, our study suggests that conditions used during prescribed fire have not been as effective. Prescribed fire may be more useful at maintaining reduced woody cover than restoring an area back to a grassland (Twidwell et al. 2019). Rather, prescribed fire has the potential to reduce wildfire risk to society, particularly when combined with grazing (Johnson et al. 2018; Starns et al. 2019).

Landowner decision making is a priority for cost-share programs such as those provided by local or federal government (e.g., Natural Resources Conservation Service). This trade-off between restoration and conservation is a spatiotemporal balancing act, as areas that initially may require restoration activities would require further conservation activities for potential long-lasting effects in woody plant reduction (Archer et al. 2011). Without landowners actively engaging with one another (e.g., prescribed burn associations [Toledo et al. 2014]) and the local government to reduce woody plant cover, cost-share programs would not exist. However, decision making can be influenced by a number of factors such as cultural heritage or physical ability to perform a particular management action, which are beyond the scope of this study. Furthermore, humans rarely engage in prevention practices and typically respond to a crisis. We are limited by data to accurately quantify how much land is managed via cost-share programs or managed privately. Our study highlights geographic patterns suggesting that mechanical and chemical application appears to be applied in "already encroached" areas, where the highest woody plant cover was initially found, in an attempt to aggressively restore grasslands or reduce woody cover rapidly.

Improving data quality and access is a major challenge that would benefit large-scale conservation effort s in rangelands. For the program featured in this study, surveyors only visit a site once, while information on pretreatment conditions, initial impact, midterm impacts, and long-term impacts of brush management are unavailable. We acknowledge that responses to brush management are strongly influenced by numerous attributes such as initial vegetation conditions, ecological site, type of treatment, and variation within type of treatment (e.g., spatial variability in fire severity with prescribed fire from one site to another); land use before and after treatment; and post-treatment precipitation trends. As such, there is tremendous variability in the data regarding the effectiveness of brush management treatments. A lack of repeat visits on managed sites is one of the largest knowledge gaps in the monitoring programs' current form. Furthermore, the inability to quantify the effect of landowners who manage woody cover without the assistance of cost-share programs remains a challenge. In many instances, private landowners may not require or desire assistance and choose to manage woody plant cover anyway, perhaps using the same brush management principles and techniques. However, the ability to assess effectiveness of treatment application using classified information, such as when treatment was applied, is perhaps one of the biggest shortcomings of this dataset.

Implications

In the rangeland profession, the war on woodland expansion has been ongoing since the early 1900s (Bovey 1998) and brush management has been the preferred combat strategy. We did not find strong evidence to support brush management for regional-scale conservation. Treatments tend to be costly, so they have a small management footprint and their lifespan is short-lived. As a result, there is a clear need to evaluate how brush management is implemented and reassess current philosophies for managing woody encroachment in rangelands. A central need is to reconcile the scale of the woody encroachment problem relative to how rangeland ecology and management implement landscape level disturbances (Fuhlendorf et al. 2012; Fuhlendorf et al. 2017; Twidwell et al. 2020). As an example of the grand challenge that exists in the Great Plains, even one of the most frequently burned regions and where a relatively intact fire culture (the Flint Hills, Kansas) exists is susceptible to shrub expansion (Ratajczak et al. 2016). This is alarming because most regions in the southern Great Plains exhibit major departures from disturbance regimes needed to successfully manage woody encroachment. Advanced technologies can help support this effort (Jones et al. 2018; Uden et al. 2019; Jones et al. 2020). Tracking the longevity of treatments at multiple scales can be improved by aligning remotely sensed vegetation data with spatially explicit information of brush management treatment locations. Ultimately, this information should be used to prioritize the protection of rangeland resources rather than continuing to chase woody encroachment with the types of costly treatments that underpin the last half century of brush management (Twidwell et al. 2013a). Multiple scholars have been calling for this change in both rangelands and other ecological specializations (Holling and Meffe 1996; Briske et al. 2006; Bestelmeyer and Briske 2012). Given decades of research on woody encroachment and its known consequences to rangelands, it is critical to recognize the shortcomings of the brush management paradigm and adapt programs and practices to scale up conservation success in the future. This will be foundational to conserve rangeland-based ecosystem services for future generations.

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

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Supplementary materials Supplementary material associated with this article follows the **References**.

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Supplementary materials follow:

The challenges of brush management treatment longevity in southern Great Plains, USA

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Supplemental Material

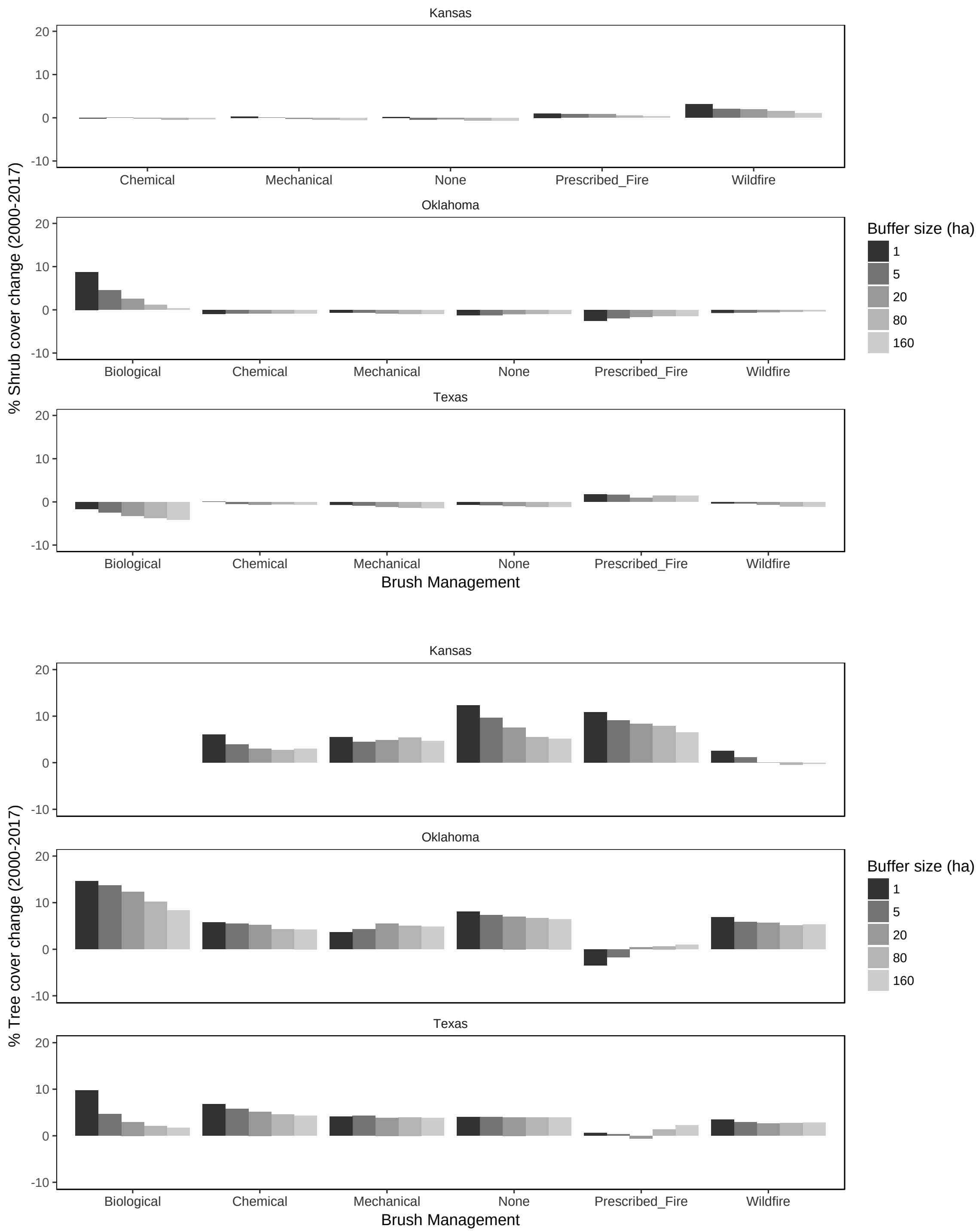

Fig S1. % Cover change in a) shrub and b) tree cover per buffer size (1-160ha) around the sampling point.

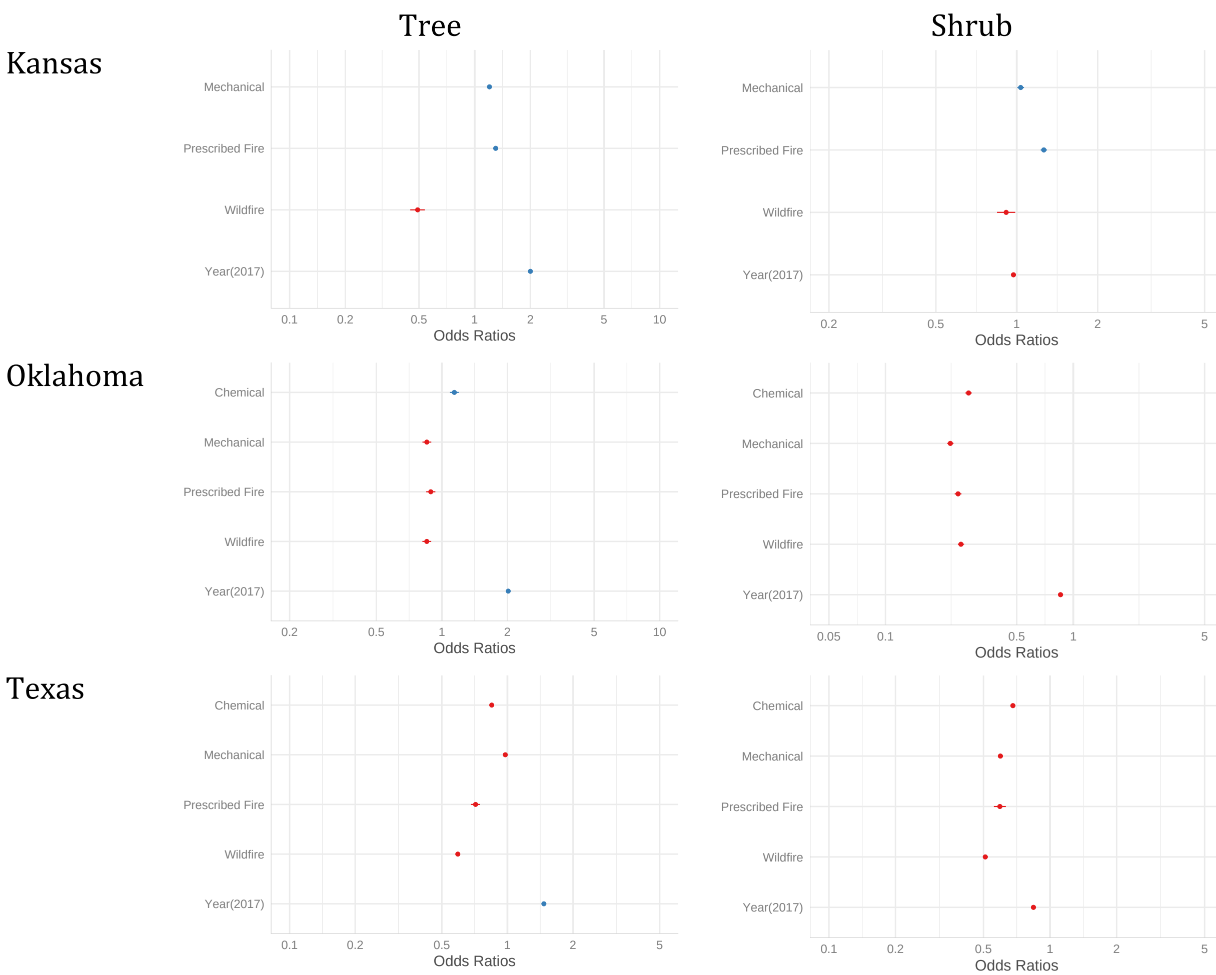

Figure S2. Model estimates from the generalized linear model showing exponentiated coefficients. The response variable was either % tree cover (left panel) or shrub cover (right panel) with brush management type and year are independent variables. A separate model was run for each state and functional group (tree and shrub cover only). Coefficients >1 are depicted in blue and <1 in red relating to probability of increases and decreases in % cover with respect to management type. All estimates were significant at ∝ = 0.05 level.

Table S1. Descriptive summary of mean % cover for each plant functional group, litter and bare ground per state in the year 2000 and 2017. The difference between the years is shown as mean cover in 2017 – mean cover 2000. A positive value indicates an increase in % cover and a negative value suggests a decrease between 2000 and 2017. Increases in trees and shrubs are highlighted in bold font. Results from the paired t-test comparing 2000 vs. 2017 mean cover across all brush management types are found in the last four columns.

State	Functional Group	Mean cover 2000	Mean cover 2017	Difference in mean cover	*T*-value	Degrees of freedom	*p*-value
Kansas	Annual grasses and forbs	11.45	9.72	-1.73	3.67	51	<0.01
Kansas	Perennial grasses and forbs	57.76	58.88	1.12	-1.36	51	>0.05
Kansas	Trees	4	9.5	**5.5**	-5.43	51	<0.01
Kansas	Shrubs	4.59	4.62	**0.03**	-0.11	51	<0.01
Kansas	Litter	5.47	3.28	-2.19	3.77	51	<0.01
Kansas	Bare ground	1.83	2.24	0.41	-1.76	51	>0.05
Oklahoma	Annual grasses and forbs	8.95	8.56	-0.39	1.97	214	<0.05
Oklahoma	Perennial grasses and forbs	33.85	27.59	-6.26	11.56	214	<0.01
Oklahoma	Trees	6.55	13.25	**6.7**	-10.79	214	<0.01
Oklahoma	Shrubs	4.37	13.25	**8.88**	4.94	214	<0.01
Oklahoma	Litter	4.22	2.6	-1.62	10.37	214	<0.01
Oklahoma	Bare ground	1.34	1.69	0.35	-1.5	214	>0.05
Texas	Annual grasses and forbs	6.89	5.38	-1.51	6.94	326	<0.01
Texas	Perennial grasses and forbs	19.69	19.09	-0.6	7.32	326	<0.01
Texas	Trees	9.72	14.3	**4.58**	-10.82	326	<0.01
Texas	Shrubs	5.85	4.95	-0.9	6.35	326	<0.01
Texas	Litter	6	4.21	-1.79	11.4	326	<0.01
Texas	Bare ground	3.06	2.28	-0.78	2.88	326	<0.01