Effects of restoration treatments and collaborative adaptive management on forest structure in ponderosa pine forests of the Colorado Front Range

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1 INTRODUCTION

1.1 Background

Prior to settlement by Euro-Americans, many dry conifer forests of the western United States were historically characterized by frequent surface fire regimes that have recently been altered by a suite of land management activities (Keeley & Zedler, 1998; Stephens et al., 2003). Beginning in the late 1800s, settlers logged large trees and intensively grazed herds of livestock, removing grasses and forbs which assisted the spread of low-severity surface fires (Swetnam & Baisan, 1996; Allen et al., 2002; Waltz et al., 2003; Fulé et al., 2012). In part to protect timber and livestock, the U.S. Forest Service adopted active fire suppression policies, resulting in denser forests with a high proportion of young trees (Allen et al., 2002; Waltz et al., 2003). In the Colorado Front Range, modern ponderosa pine (*Pinus ponderosa*) stands, selected as dense stands for restoration treatments by the Front Range Collaborative Landscape Restoration Program (FR-CFLRP), have average densities of approximately 200 and 360 trees ac^{-1} on wet and dry sites, respectively (Cannon et al., 2018). Randomly-selected ponderosa pine plots in the Colorado Front Range currently have an average tree density of 168 trees ac^{-1} (Battaglia et al., 2018). Using dendrochronological stand reconstruction techniques, these randomly-selected ponderosa pine stands in the Front Range were found to have historical average densities of 53 trees ac^{-1} in 1860 (Battaglia et al., 2018). These recent changes in forest structure are thought to lead to large, severe fires in some ponderosa pine forests (Westerling et al., 2006; Schultz et al., 2012; Harvey et al., 2016). In some cases, severe wildfires can convert previously forested ponderosa pine stands into grassland or shrubland, threatening resilience in these forests (Allen et al., 2002; Savage & Mast, 2005; Chambers et al., 2016). Large, severe fires can also result in loss of topsoil, which lessens productivity of the stand and can impact municipal water supplies (Moody & Martin, 2001).

A resilient stand is one that retains its basic functions and structure after disturbances (Walker et al., 2004; Fulé et al., 2012; Churchill et al., 2013). Fuel reduction and restoration treatments are frequently implemented to reduce wildfire risk and increase forest resilience. Fuel reduction treatments often include additional objectives to restore elements of forest structure and composition toward the historic ranges of variability (Allen et al., 2002; Keane et al., 2009; Dickinson, 2014). Mechanical thinning, prescribed burning, or a combination of thinning and burning treatments are commonly used in restoration. Thinning and/or burning treatments can help restore the historical surface fire regime (Fulé et al., 2012) and reduce basal area and tree density (Waltz et al., 2003). Such treatments can also restore heterogeneous stands and landscapes (Cooper, 1960; White, 1985). Fine-scale heterogeneity increases forest resilience (Allen et al., 2002; Binkley et al., 2007) in part because the spread of insect disease and mortality is slowed (Olsen et al., 1996; Fettig et al., 2007). Lastly, stand heterogeneity provides diversity important for ~~in~~ wildlife habitat~~s~~ (Reynolds et al., 2013) and understory plant growth (Laughlin et al., 2006). Restoration programs established to achieve such goals are being adopted more frequently and on greater spatial and temporal scales as the urgent need to restore forests across the United States is being realized.

1.2 Collaborative Forest Landscape Restoration Program

The Collaborative Forest Landscape Restoration Program (CFLRP) is a federal program supporting landscape-scale forest restoration in landscapes vulnerable to fire across the U.S. The primary goals of this program are to improve old-growth forests, support local economies, and restore natural fire regimes to forests (Schultz et al., 2012). CFLRP restoration programs require at least five years of post-implementation monitoring (Schultz et al., 2012) to track restoration outcomes and provide ecological information on the extent to which treatments have desired outcomes (Brown et al., 2004). One CFLRP project is the Colorado Front Range Collaborative Forest Landscape Restoration Project (FR-CFLRP) implemented by the Front Range Fuel Treatment Partnership Roundtable. This project emphasizes collaborative restoration of ponderosa pine forests in the Colorado Front Range. In addition to landscape-scale ecological objectives, this project also aims to restore elements of historical structure to treated stands, implementing treatments that:

- reduce density and basal area of stands;
- favor removal of Douglas-fir (*Pseudotsuga menziesii*) over ponderosa pine;
- maintain or improve forest structural variability and size complexity; and
- restore stand variability across productivity gradients (Dickinson, 2014).

In addition to landscape-scale restoration, the CFLRP emphasizes collaborative adaptive management (CAM) as a method of improving fuels and restoration treatments (Schultz et al., 2012). CAM provides flexibility and collaborative learning structures that can lead to improved restoration outcomes and identify treatments that better accomplish objectives (Allen et al., 2002). CAM attempts to connect research with practical outcomes by using input from a collaborative of stakeholders and scientific understanding to inform management decisions

(Schreiber et al., 2004) and by quantifying the extent to which treatments achieve desired objectives (Schultz et al., 2012). Forest managers and researchers who adopt CAM recognize that the breadth of knowledge about forest ecosystems is incomplete (Allen et al., 2002). In order to gain more comprehensive understanding, researchers can use the CAM process to study and compare outcomes of various treatments (Allen et al., 2002). In this way, a CAM approach, such as the one currently employed by the FR-CFLRP, encourages progress and refinement of fuels reduction and forest restoration treatments (Allen et al., 2002).

1.3 Study objectives

This study evaluates a subset of complete treatments with available pre-treatment and post-treatment data on forest density and composition. To evaluate impacts of large-scale restoration treatments and collaborative adaptive management, we address the following research questions:

1) Are FR-CFLRP fuels and restoration treatments of the FR-CFLRP changing forest structure toward desired conditions, as defined by the collaborative?
2) Is there evidence for changes in treatment outcomes of the FR-CFLRP over time suggesting collaborative adaptive management occurred?

To answer these questions, we analyze how restoration treatments altered elements of forest structure including basal area, tree density, mean tree diameter, and tree size structure of stands from both pre- and post-treatment ponderosa pine stands. For each forest metric, we compare pre-treatment to post-treatment stand attributes in order to determine if treatments are resulting in desired forest structure, and we compare post-treatment data over time in order to assess whether FR-CFLRP treatments are improving over time. We expect to find that basal area and tree density decreased after treatments and mean tree diameter and size complexity increased after treatments, according to desired conditions defined by the collaborative. We also expect that as a result of collaborative adaptive management, outcomes of recent (i.e., 2016) treatments have outcomes more congruent with desired conditions relative to early (i.e., 2010) treatments.

2 METHODS

2.1 Overview

To determine if FR-CFLRP treatments are changing forest structure toward desired conditions, we assessed changes in forest density and composition after restoration treatments were accomplished. To analyze how treatments are changing over time, we compared post-treatment stand density and composition as a function of the date that treatments were reported as "accomplished" by the Forest Service in the US Forest Service Activates Tracking System (FACTS). The date accomplished is assigned when contracts are completed by the Forest Service and is not necessarily the day that monitoring or treatments were actually completed. However, the date accomplished is representative of the time at which treatment prescriptions were finalized.

2.2 Structural data

Data was collected by the US Forest Service using Common Stand Exam methods before and after restoration treatments, which were accomplished between 2010 and 2016. Treatments consisted of thinning stands, with machinery or by hand, following approved treatment implementation plans. Large trees were measured using variable radius plots, whereas smaller trees were measured and counted in fixed radius subplots ("Common Stand

Exam," 2014). At the time of data analyses, some plots had only pre- or post-treatment data and were discarded from the analyses. We included only plots with both pre- and post-treatment data. In total, we summarized data from 1,212 inventory plots in 71 treatment units of the FR-CFLRP management area. For each plot, we included all trees with a height greater than 4.5 feet.

For each plot, we summarized density and composition metrics: total basal area and density; basal area and density by species; quadratic mean diameter; and size complexity. Basal area was calculated by summing trees and multiplying by an expansion factor appropriate to the basal area prism used. Species were binned into one of three categories for analysis: 'ponderosa pine,' 'Douglas-fir,' and 'other.' The 'other' category included the species: subalpine fir (*Abies lasiocarpa*), Rocky Mountain juniper (*Juniperus scopulorum*), lodgepole pine (*Pinus contorta*), Engelmann spruce (*Picea engelmannii*), limber pine (*Pinus flexilis*), blue spruce (*Picea pungens*), and quaking aspen (*Populus tremuloides*). We summed plot-level density as trees per acre using tree counts and expansion factors from the variable radius prism and repeated the process to sum the trees into their respective species categories. We calculated quadratic mean diameter using the equation,

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where *QMD* is quadratic mean diameter (in), *BA* is basal area (ft^2 ac^{-1}), and *TPA* is tree density (trees ac^{-1}). Last, we calculated size complexity as the complement of the ratio of Reineke's and Shaw's stand density indices (SDI), where SDI_R is stand density index derived by Reineke, SDI_S is stand density index derived by Shaw, and d_i is diameter of individual trees (in). Because Reineke's SDI was designed for even aged stands, and the summation method was an SDI refinement for unevenaged stands, the ratio of these metrics has been used as an index of size complexity (Long & Shaw, 2010). Once summaries of each structural metric were complete, we summarized plot-level data by 71 subunit boundaries identified using the FACTS database.

2.3 Data analyses

For each structural metric, we conducted paired *t*-tests to assess changes between pre-treatment and post-treatment forest structure metrics. We used paired *t*-tests comparing 71 pairs of subunit summaries of stand structure for each metric. To analyze changes in post-treatment forest structure over time, we conducted linear regressions on post-treatment density and composition metrics. Additionally, for forest metrics that had high pre-treatment variability, we conducted linear regressions using the percent change from pre-treatment to post-treatment. This was to account for both stand variability and how pre-treatment density and composition may have changed in later treatment subunits. We conducted *t*-tests and linear regressions in R~~Studio~~ using all plots from 71 subunits that included both pre-treatment and post-treatment data and were accomplished between 2010 and 2016.

3 RESULTS

3.1 Restoration outcomes

Front Range CFLRP treatments generally reduced basal area and tree density (Table 1). Treatments significantly reduced basal area of all species by 34% from 84.9 to 56.0 ft^2 ac^{-1} ($p < 0.001$; Figure 1). Significant decreases in basal area were also observed for each species group: ponderosa pine basal area decreased by 28% from 49.5 to 35.5 ft^2 ac^{-1} ($p < 0.001$); Douglas-fir basal area decreased by 39% from 18.7 to 11.5 ft^2 ac^{-1} ($p < 0.001$); and basal area of other species decreased by 46% from 16.7 to 9.0 ft^2 ac^{-1} ($p < 0.001$; Figure 2). Treatments significantly reduced tree density of all species by 52% from 409 to 194 trees ac^{-1} ($p < 0.001$; Figure 3). Treatments also significantly reduced tree density of each species group: ponderosa pine density was reduced 53% from 133 to 63 trees ac^{-1} ($p < 0.001$); Douglas-fir density was reduced 62% from 116 to 44 trees ac^{-1} ($p < 0.001$); and tree density of other species was reduced 45% from 160 to 87 trees ac^{-1} ($p < 0.001$; Figure 4).

Treatments increased tree size but reduced tree size complexity. After treatments, quadratic mean diameter significantly increased by 24% from 8.4 to 10.4 in ($p < 0.001$; Figure 5). Treatments significantly reduced size complexity by 33% from 0.096 to 0.064 ($p < 0.001$; Figure 6).

3.2 Treatment change over time

During treatment implementation from 2010 to 2016, some density and compositional metrics changed over time, and some did not. Over time, there was a significant decrease in residual basal area of post-treatment plots ($p = 0.04$; Figure 7). In these plots, pre-treatment basal area did not significantly change ($p = 0.7$), suggesting that a higher percentage of basal area was removed from more recent plots, resulting in significantly lower residual basal area~~s~~. For ponderosa pine, there were no significant changes in residual basal area during the six years of treatments ($p = 0.4$; Figure 8). However, residual basal area of Douglas-fir in post-treatment plots was significantly lower in recent treatments than early treatments ($p < 0.001$; Figure 9b). This was not due to decreasing pre-treatment Douglas-fir basal area, which remained unchanged ($p = 0.09$; Figure 9a), but rather due to increasing percentage of Douglas-fir removed ($p = 0.006$; Figure 9c). Last, there were significant decreases in residual basal area of other tree species in treatment plots ($p = 0.02$; Figure 10).

Over time, there were no significant changes in residual tree density ($p = 0.6$; Figure 11). There were also no changes in residual tree density of ponderosa pine ($p = 0.3$; Figure 12). However, there was a significant decrease in residual Douglas-fir tree density from 2010 to 2016 ($p = 0.02$; Figure 13b). This correlates to treatments removing significantly higher percentages of Douglas-fir trees in later treatments compared to earlier treatments ($p = 0.01$; Figure 13c) because there was not a significant decrease in pre-treatment Douglas-fir density ($p = 0.3$; Figure 13a). Last, there were no significant changes in residual tree density of other species ($p = 0.7$; Figure 14).

Post-treatment quadratic mean diameter ($p = 0.4$; Figure 15) and size complexity ($p=0.98$; Figure 16) did not change during the lifetime of the treatments. For both of these structural metrics, there were also no significant changes in percent quadratic mean diameter increase ($p=0.2$) or percent size complexity decrease ($p=0.9$).

4 DISCUSSION

Restoration treatments of the FR-CFLRP generally reduced basal area, tree density, and size complexity and increased quadratic mean diameter of treatment stands. During the years of treatments thus far (2010 – 2016), there were significant reductions in residual total basal area, in residual Douglas-fir basal area, and in residual basal area of other species. Ponderosa pine residual basal area and percent reduction did not change. As treatments progressed, they favored removal of Douglas-fir by leaving lower residual Douglas-fir densities in post-treatment stands. There were no significant changes over time in the other two structural metrics (quadratic mean diameter and size complexity).

4.1 Collaborative adaptive management

An evaluation of early FR-CFLRP treatments (2010 – 2013) indicated there was a 28% reduction in basal area in both ponderosa pine and Douglas-fir (Cannon et al., 2018). An initial objective of FR-CFLRP treatments was to favor removal of Douglas-fir over ponderosa pine (Dickinson, 2014), and results of the Cannon et al. (2018) study show that this was goal was not met. Here, we found that Douglas-fir basal area was decreased by 39% compared to 28% for ponderosa pine basal area. These percent reductions include data from early (2010 – 2013) treatments also included in the Cannon et al. (2018) study. This change suggests that adaptive management is affecting basal area reductions, and more recent treatments were more congruent with the desired condition of favoring Douglas-fir for removal over ponderosa pine.

The FR-CFLRP is attempting to refine forest restoration techniques through collaborative adaptive management (CAM). By monitoring treatment outcomes for five years after treatments completion, forest managers can directly assess the impacts of treatments and analyze treatment strengths and benefits. This process should result in improved restoration treatments because it is based on continuous feedback and institutional learning. To assess treatment outcomes, the FR-CFLRP group meets frequently for collaborative site field trips and data reviews that include a diverse group of forest managers, resource specialists, treatment implementers, forest ecologists, and interested members of the community (Shultz 2012). These informal processes allow discussion and a means of CAM to refine future forest treatments. By measuring changes in outcomes over time, the results of this study suggest that the CAM process may be positively affecting treatment outcomes so that they are more congruent with collaboratively developed desired conditions.

4.2 Constraints

Early FR-CFLRP treatments were constrained by the initial NEPA permits. Many fuels reduction treatments had already been approved for implementation prior to the CFLRP program. To date, all restoration treatments implemented by the FR-CFLRP were implemented under NEPA planning that pre-dated the collaborative effort, and resource specialists worked within existing constraints to achieve treatments with outcomes approaching those of the collaboratively defined desired conditions (Colavito, 2017). Notwithstanding these limitations, many objectives related to spatial structure were achieved and improved over the course of the program.

No FR-CFLRP treatments had explicit objectives of restoring forest structure to historical structure and composition. Historical reconstructions of Front Range ponderosa pine forests were not available at the time treatments were designed and implemented, but they are now available for comparison (Battaglia et al., 2018). In many cases, it may be appropriate to leave higher residual forest density relative to historical conditions. One reason for this is to account for post-treatment mortality from windfall, insects, disease, or other stresses resulting from treatments (Waltz et al., 2003). A second reason is to account for underestimations of historical density reconstructions due to decomposition legacies. Finally, conditions present in the historic range of variability may not be applicable in the future due to a changing climate.

Lastly, one important logistical constraint may have affected results in this study and may affect results in future treatments. On steep slopes and/or in dense stands, treatments may be constrained by the ability to use machinery to complete the thinning. Hand-thinning on steep slopes has been found to leave higher tree densities than treatments conducted by machinery (Underhill, 2014). For this reason, we reported percentages of trees and basal area removed relative to pre-treatment stand densities for the metrics with significant results.

4.3 Future research questions

Many questions about FR-CFLRP treatments remain to be answered. Evaluating spatial heterogeneity of post-treatment plots would provide information about the success of FR-CFLRP spatial objectives. Cannon et al. (2018) investigated some spatial patterns of early treatments (2010 – 2013) but larger scale questions related to the structure and pattern of gaps resulting from restoration treatments remains unknown. Related to this, comparing residual stand density and composition on wet and dry slopes, on north- and south-facing slopes, and in lower montane and upper montane zones would provide more insight into the achievement of FR-CFLRP spatial goals. Lastly, further study on future treatments may show that treatments are changing now that NEPA permits include CFLRP objectives. We would expect to see continued collaborative adaptive management and changing of treatments aligned with CFLRP structural and spatial objectives.

The Front Range CFLRP achieved its goals of reducing basal area, reducing tree density, and increasing quadratic mean diameter. Treatments improved over time (2010 – 2016) for residual basal area, residual Douglas-fir basal area, residual basal area of other species, and residual Douglas-fir density. With the focus on collaborative adaptive management and improvement of NEPA permits, treatments will likely improve in the future, resulting in post-treatment forest structure that is more congruent with desired FR-CFLRP objectives.

5 TABLES AND FIGURES

Table 1. Treatments significantly reduced basal area, size complexity, and tree density, and significantly increased quadratic mean diameter (in). All p-values of changes were < 0.001.

	Species	Pre	Post	% Change
Basal Area (ft^2 ac^{-1})	all	84.9	56.0	-34%
	P. ponderosa	49.5	35.5	-28%
	P. menziesii	18.7	11.5	-39%
	other	16.7	9.0	-46%
Tree Density (ac^{-1})	all	409	194	-52%
	P. ponderosa	133	63	-53%
	P. menziesii	116	44	-62%
	other	160	87	-45%
Quadratic Mean Diameter (in)	all	8.4	10.4	+24%
Size Complexity	all	0.096	0.064	-33%

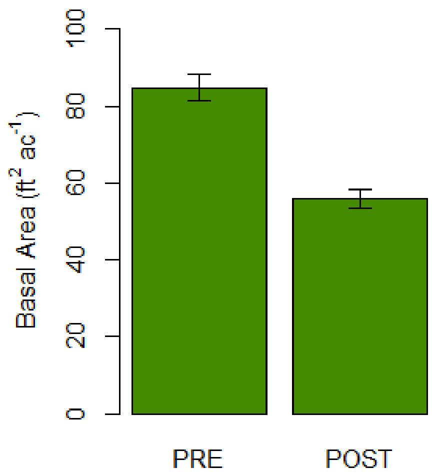

Figure 1. Treatments significantly decreased basal area by 34% (84.9 to 56.0 ft^2 ac^{-1}).

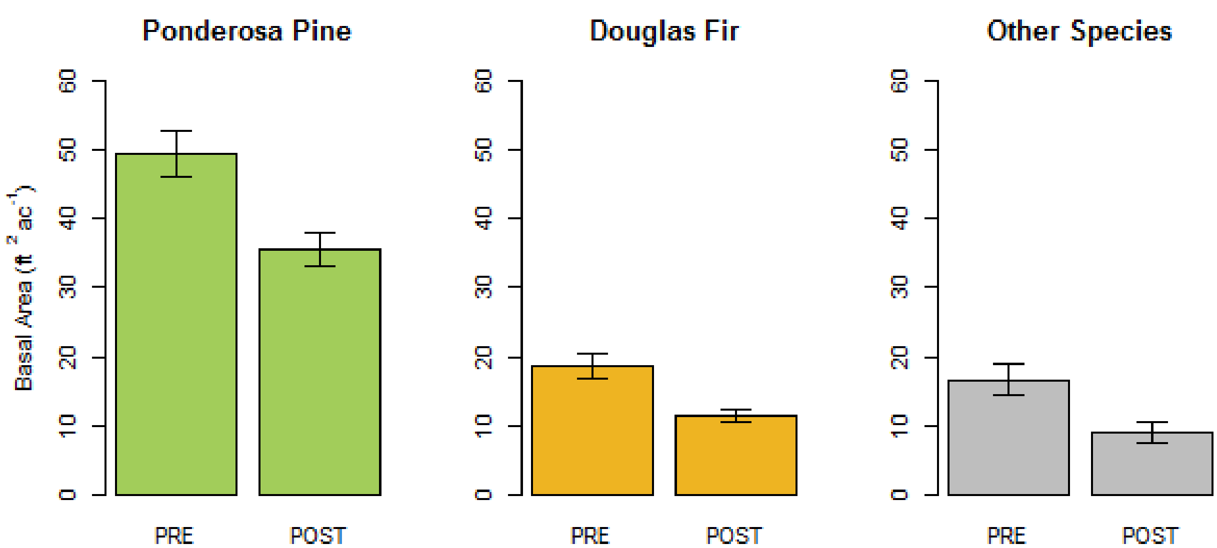

Figure 2. Treatments significantly decreased basal area of ponderosa pine by 28% (49.5 to 35.5 ft^2 ac^{-1}), of Douglas-fir by 39% (18.7 to 11.5 ft^2 ac^{-1}), and of other tree species by 46% (16.7 to 9.0 ft^2 ac^{-1}).

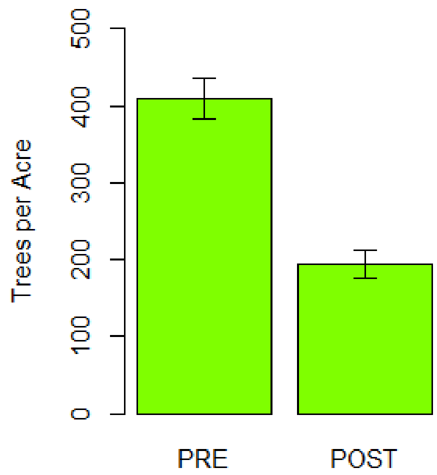

Figure 3. Treatments significantly reduced total tree density by 52% (409 to 194 trees ac^{-1}).

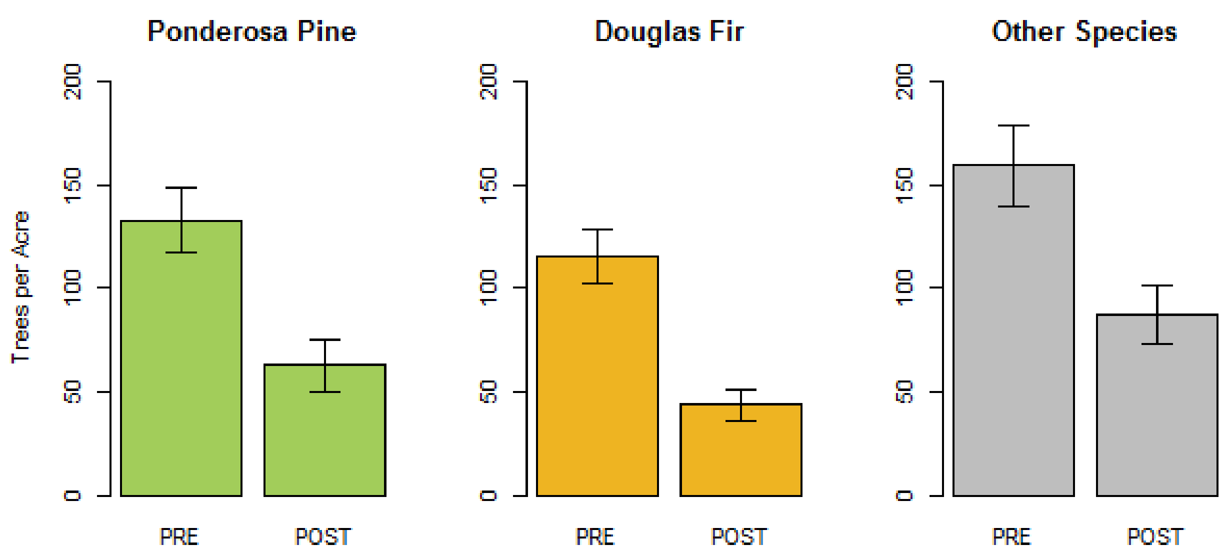

Figure 4. Treatments significantly decreased tree densities of ponderosa pine by 53% (133 to 63 trees ac^{-1}), of Douglas-fir by 62% (116 to 44 trees ac^{-1}), and of other tree species by 45% (160 to 87 trees ac^{-1}).

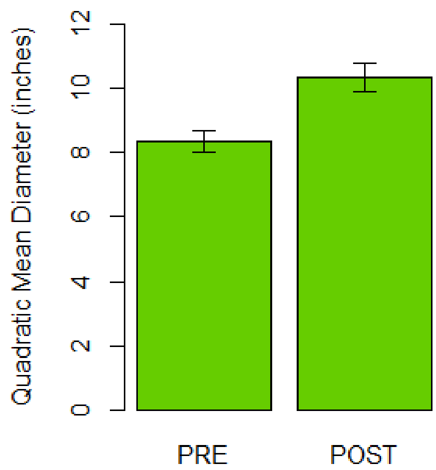

Figure 5. Treatments significantly increased quadratic mean diameter by 24% (8.4 to 10.4 inches).

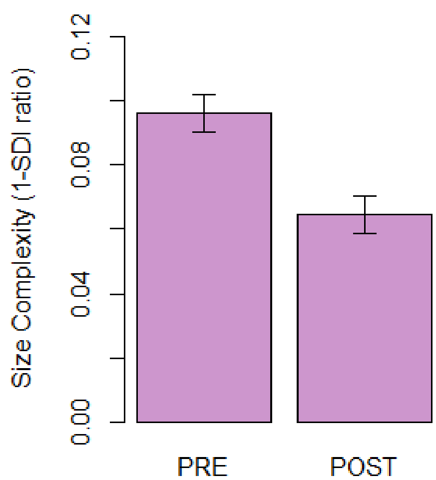

Figure 6. Treatments significantly reduced size complexity by 33%.

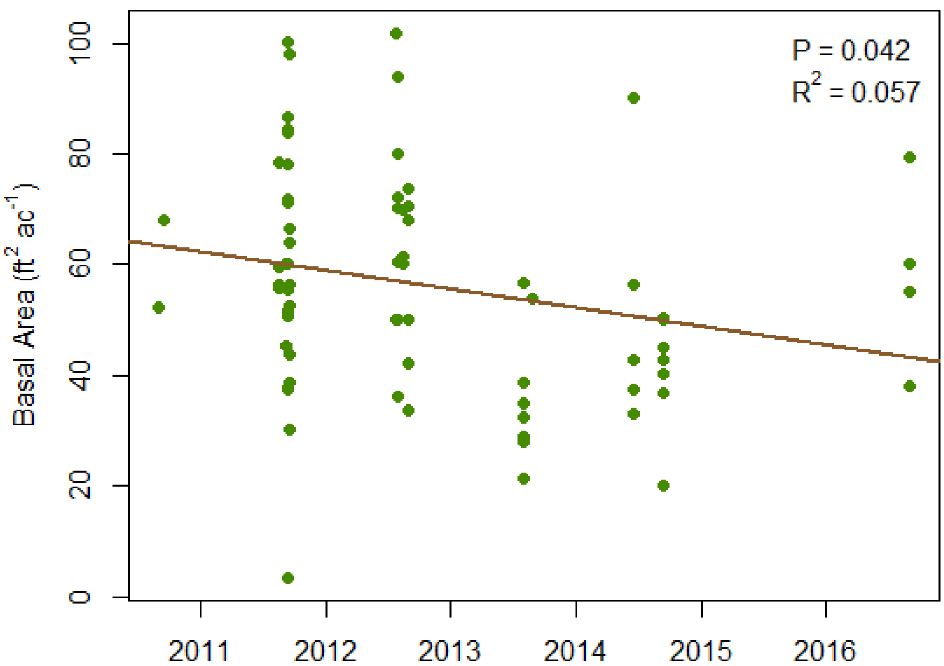

Figure 7. Post-treatment plots had lower residual basal areas in recent treatments than in early treatments.

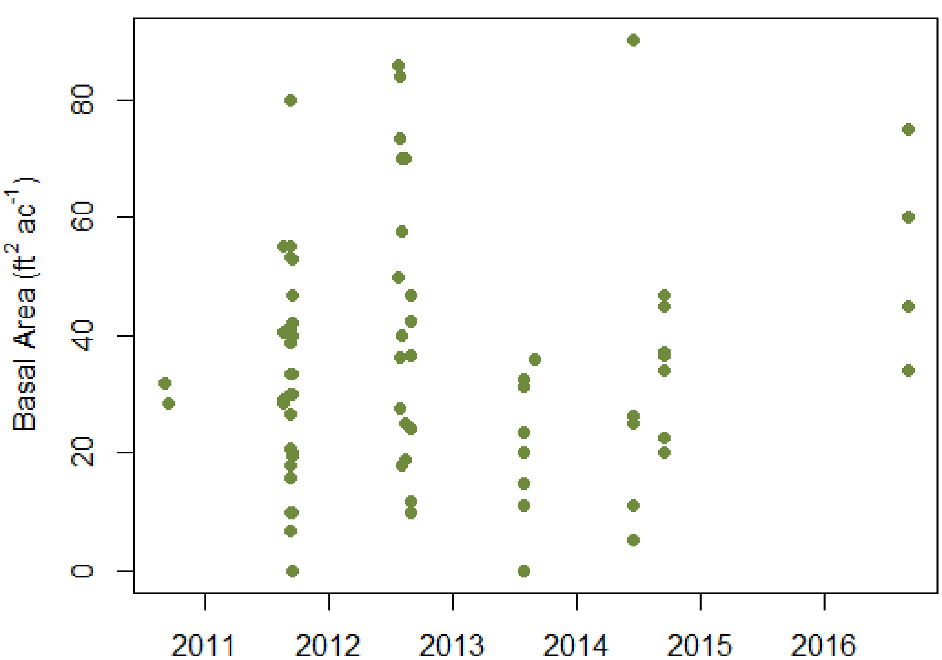

Figure 8. Ponderosa pine residual basal area remained unchanged from 2010 – 2016.

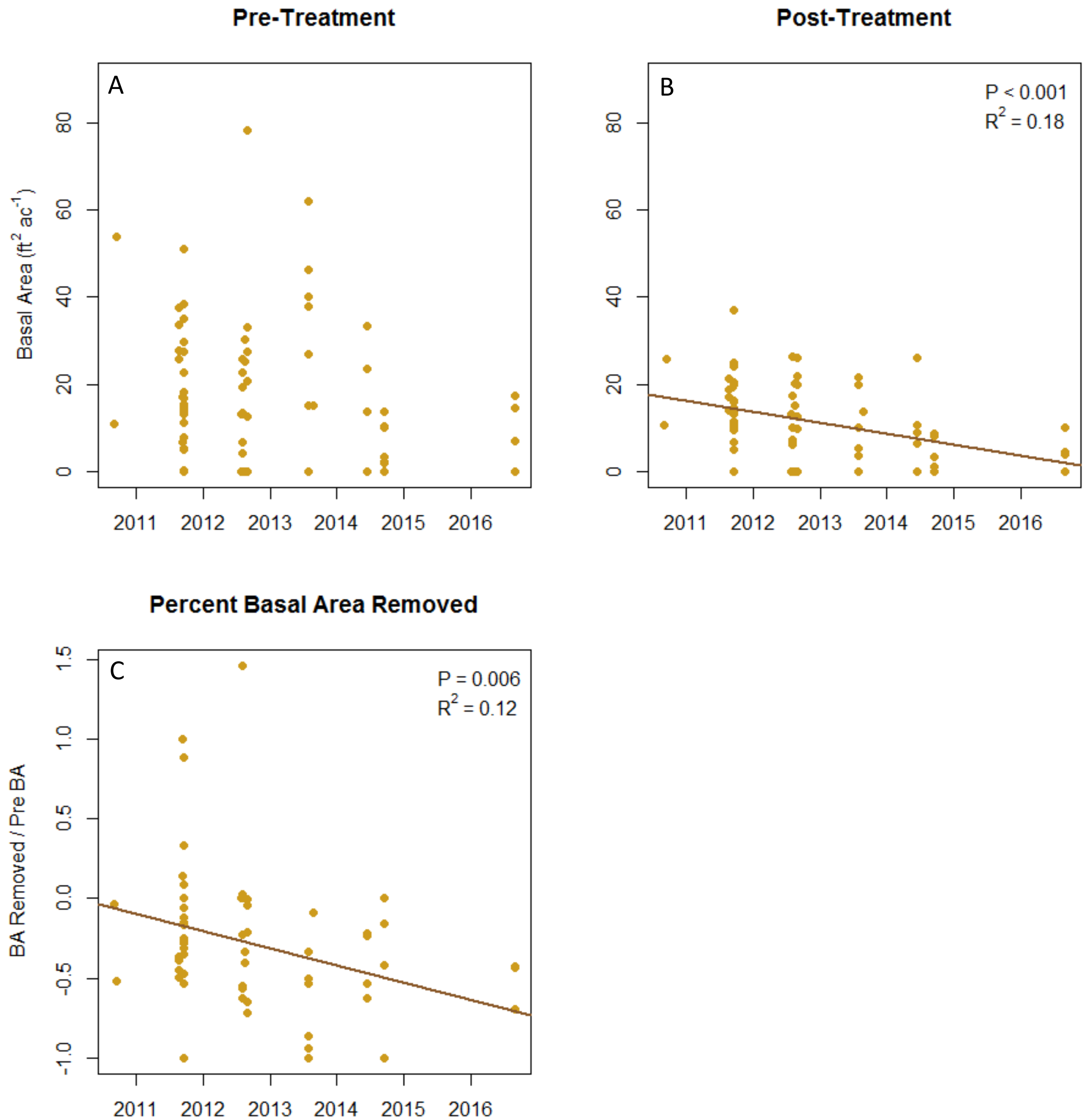

Figure 9. (A) Pre-treatment Douglas-fir basal area remained unchanged in the plots during the treatments (2010 – 2016). (B) Post-treatment Douglas-fir basal area decreased, and (C) the percent basal area removed increased (became more negative) from early (2010) to recent (2016) treatments.

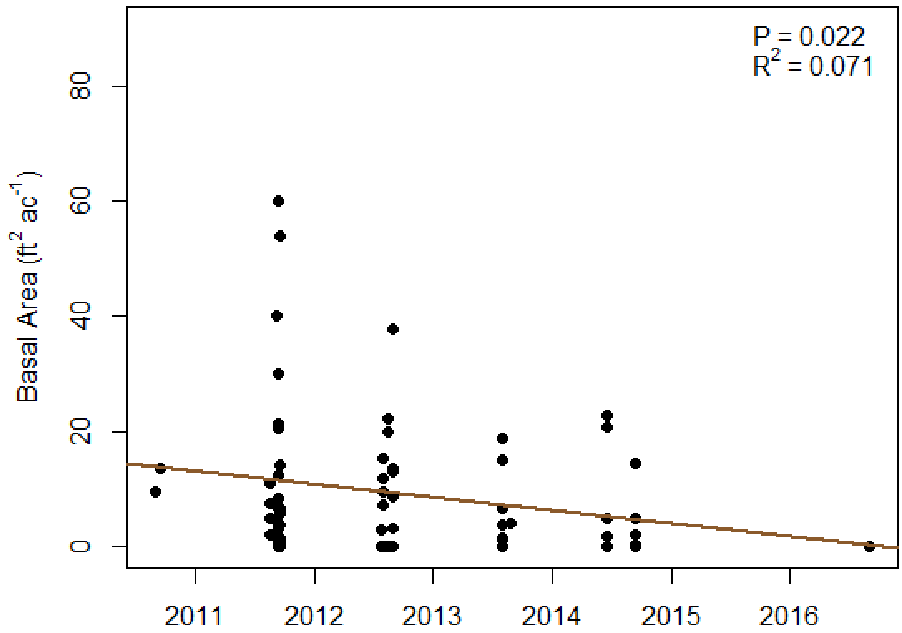

Figure 10. There was a significant decrease in post-treatment basal area for other species from 2010 – 2016.

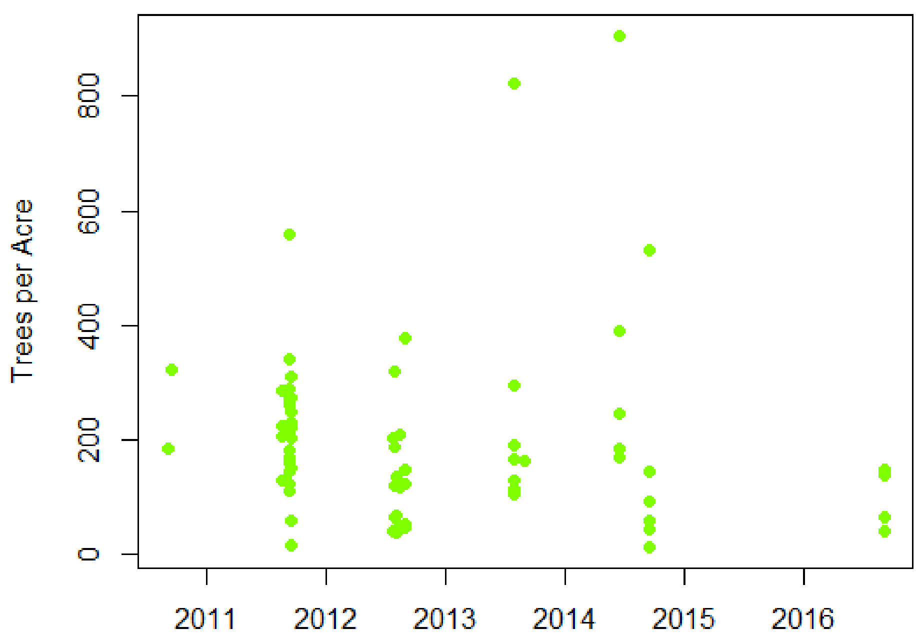

Figure 11. During the treatment period (2010 – 2016), residual tree density in post-treatment plots remained unchanged.

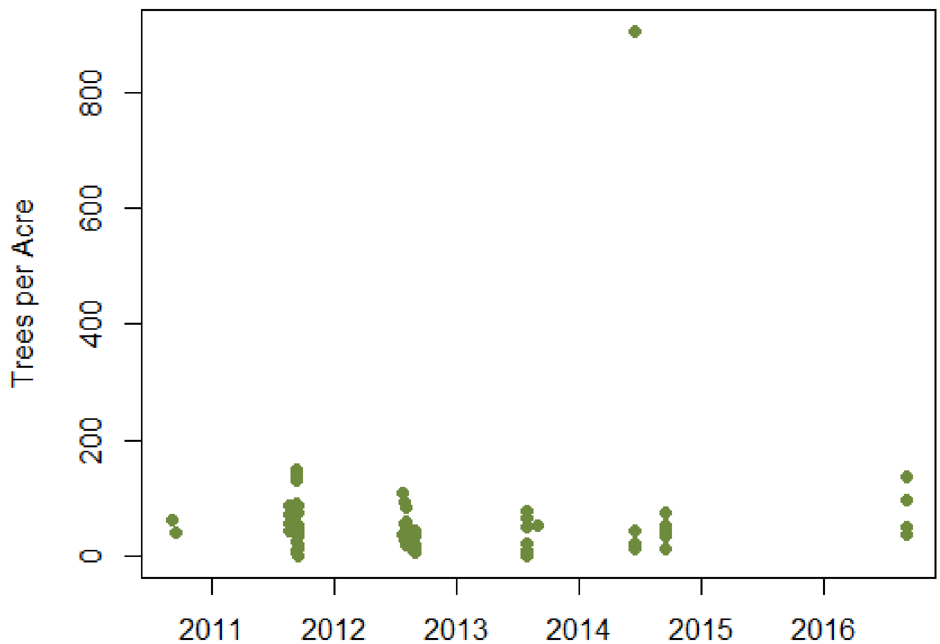

Figure 12. Ponderosa pine residual tree density remained unchanged from 2010 – 2016.

A

B

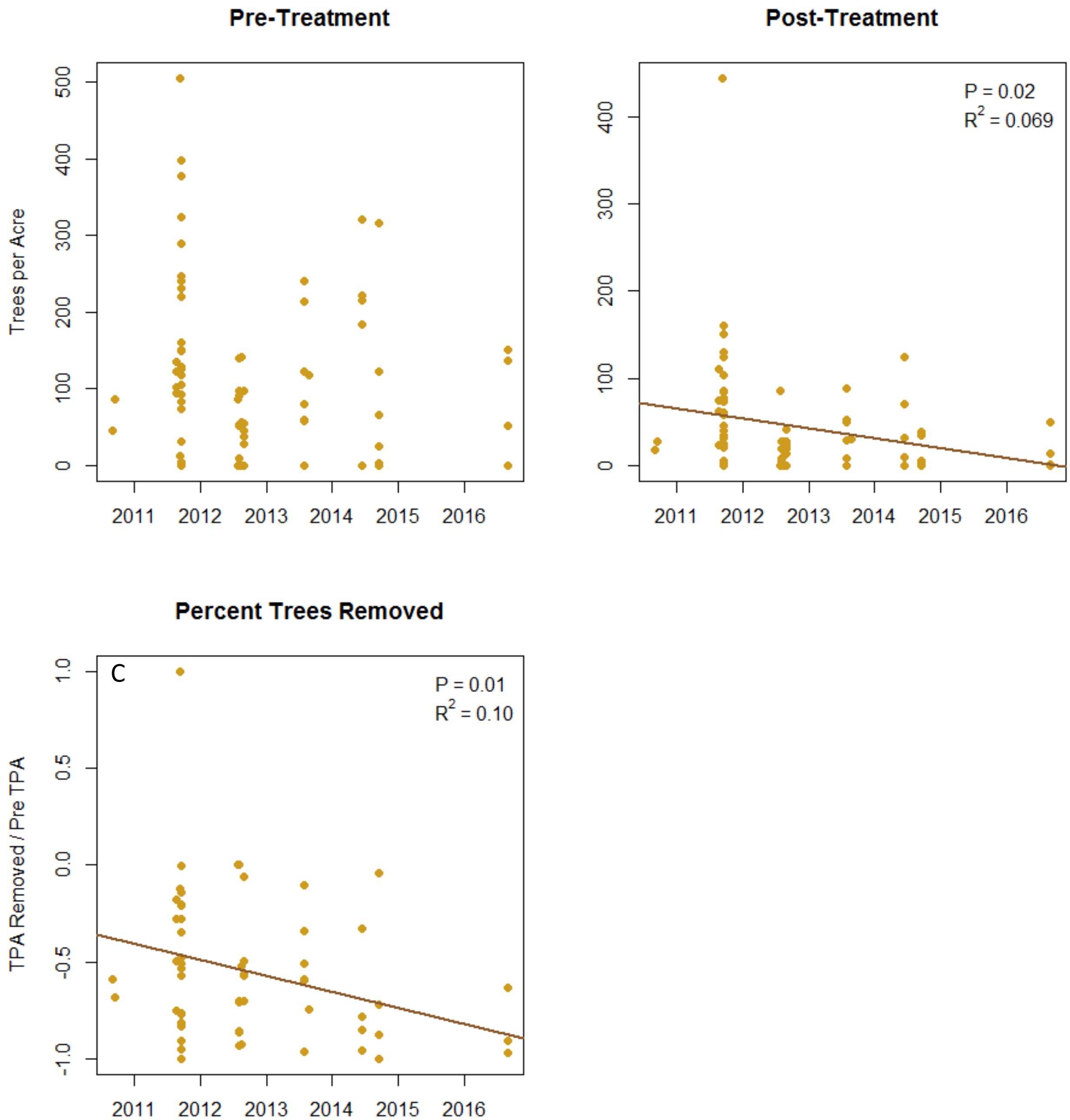

Figure 13. (A) Pre-treatment Douglas-fir tree density remained unchanged in the plots during the treatments. (B) Post-treatment Douglas-fir tree density decreased, and (C) the percent trees removed increased (became more negative) from early (2010) to recent (2016) treatments.

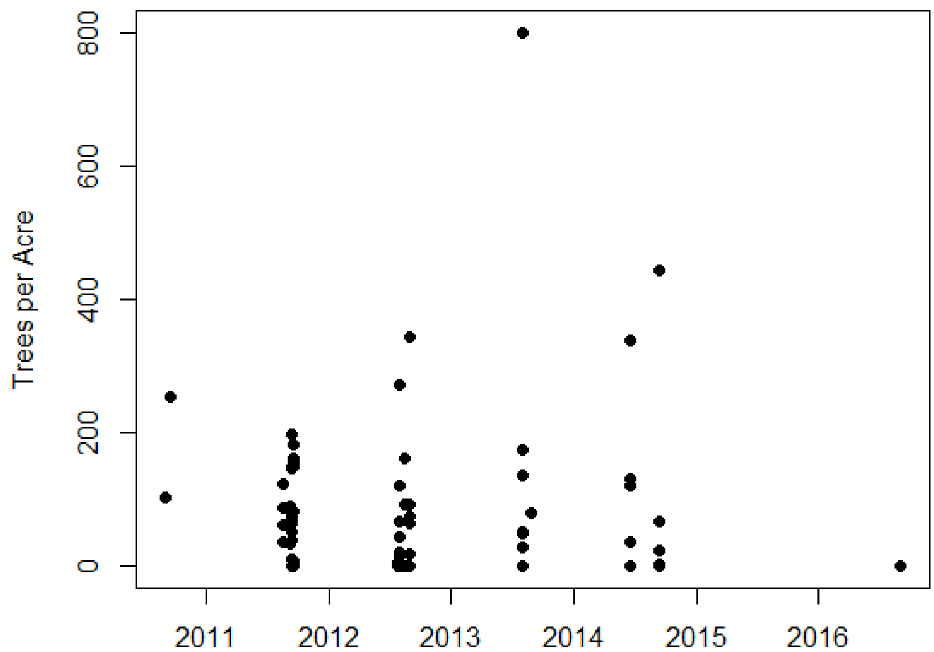

Figure 14. There was no significant change in the residual tree density of other tree species (trees that aren't ponderosa pine or Douglas-fir).

Figure 15. Post-treatment quadratic mean diameter did not change during the six years of FR-CFLRP treatments.

Figure 16. Post-treatment size complexity did not change over the lifetime of treatments.

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