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Coarse Woody Debris Following Silviculture Treatments in Southwest Mixed-Conifer Forest

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Abstract: Coarse woody debris (CWD) is an important component in the structure and function of southwestern mixed-conifer forest ecosystems. However, fire suppression and exclusion policies have changed the structure and fuel loads, including CWD, during the last 130 years. Consequently, managers are faced with the threat of stand replacement fires over large spatial areas and are seeking solutions to these challenges using silvicultural techniques. Our paper presents CWD characteristics based on 100-h and 1000-h time-lag fuels before (2006) and after (2016) silvicultural treatments including harvest, prescribed fire, and no treatment (control) on mixed-conifer forests in southcentral New Mexico, USA. Results indicated late-season broadcast burns characterized by mild fire behavior reduced 100-h CWD (Mg ha^{-1}) and potentially 1000-h CWD. However, because control sites also saw reduced 1000-h CWD, this result was confounded. Harvest treatments maintained 1000-h CWD, which could be considered a compensatory response given the decrease in CWD on adjacent control sites over the same time period. This was supported by an increase in 1000-h logs per 75 m transect on harvest sites as compared to control sites. Silvicultural prescriptions including prescribed fire are useful tools to increase or decrease CWD to meet management objectives.

Keywords: commercial harvest; prescribed fire; rotten/sound decay; time since treatment

1. Introduction

Forest management practices, particularly combinations of thinning and burning, are being recommended and used across the Southwest in response to management objectives targeting desired future conditions. Coarse woody debris (CWD), defined as fallen, dead woody material that is greater than 2.54 cm in diameter, is an important ecological component in forested ecosystems that is potentially impacted by silvicultural treatments [1,2]. In addition to management activity, accumulation of CWD depends on multiple factors including climate, fire regime, insects, disease, and forest composition, age, and structure. Despite once being considered a nuisance by earlier foresters, CWD has been well documented to play an important role in forest productivity, site protection, and wildlife habitat [1]. As a result, federal agencies tasked with managing forested landscapes must account for CWD. Specifically, federal managers are writing silvicultural prescriptions in attempt to meet established CWD guidelines that are a part of desired future conditions. So called "desired conditions" are required in overarching management documents (i.e., Forest Plans) as directed by the 2012 Forest Planning Rule. Federal forests across the Southwest are rewriting their Forest Plans. In the Southwest, little information exists on long-term dynamics of CWD with and without silvicultural disturbance especially in dry mixed-conifer forests.

Changes in CWD loading, arrangement, and decay condition influence important ecological mechanisms such as nutrient cycling and decomposition [3], forest floor respiration [4], carbon flux [5,6], tree regeneration [7], ground cover vegetation [8,9], biodiversity [10], and wildlife habitat [11]. Specific wildlife species of concern in the Southwest that depend on CWD include the northern goshawk (*Accipiter gentilis*) [12], Mexican spotted owl (*Strix occidentalis lucida*) [13], and Sacramento Mountain salamander (*Aneides hardii*) [14]. Coarse woody debris also acts as surface fuel and affects the timing, spread, and severity of wildfires [15,16]. Given the biological functions and fire behavior impacts of CWD, it is useful for managers to better understand how specific disturbance activities may influence CWD over time.

We examined CWD response to common forest management treatments including commercial harvest and broadcast burning in mixed-conifer stands in southcentral New Mexico. Data were collected from permanently established plots on north and south aspects from the Sacramento Mountains, New Mexico, USA. We quantified and examined variation in CWD before (2006) and after treatment (2016) with additional analysis looking at time since treatment effect. Our objective was to quantify CWD response to multiple silvicultural treatments given time since treatment and discuss implications for meeting management guidelines.

2. Materials and Methods

2.1. Study Area

Three distinct study sites, each with a north and south aspect, were located within the central Sacramento Mountains (approximately 32°57′ N, 105°44′ W) on the Sacramento Ranger District of the Lincoln National Forest in Otero County, New Mexico. The north–south running Sacramento Mountains cover approximately 5200 km^2. The study sites were at an elevation between 2438–2895 m within the upper montane coniferous forest, also known as dry mixed-conifer, and characterized by Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), white fir (*Abies concolor* (Gordon) Lindley ex Hildebrand), and ponderosa pine (*Pinus ponderosa* Douglas ex C.Lawson) overstory [17]. Mean annual precipitation (rainfall only) for the study-site region was 75.1 cm; mean annual snow depth was 178.6 cm [18]. During the summer months, precipitation in the form of high-intensity, short duration afternoon thundershowers were common to the study area. Average maximum and minimum temperatures were 14.2 and 0.2 °C, respectively. Soils in the study site were generally classified as Argiborolls [19].

2.2. Study Design

We selected three sites (i.e., Benson, Fork, Pump) that were separated by ~9 km each. Each site had a north and south aspect separated by a common mountain meadow. At each site with like aspect, four units (i.e., distinct forest stands) were randomly selected from a list provided by the Forest Service. These units, 8–20 ha in size, were separated by natural terrain features (i.e., draw or meadow) and had not been silviculturally treated for at least 50+ years (personal communication with Mickey Mauter, U.S. Department of Agriculture Forest Service). Baseline data were collected on each unit over the course of two growing seasons in 2006 and 2007. Following baseline data collection, each experimental unit on both north and south aspects was randomly assigned to one of four common management treatments, specifically, (1) no treatment/control; (2) prescribed fire; (3) timber harvest; and (4) harvest and burn. Due to federal regulatory challenges, burning on north aspects and burning following thinning on both aspects was never initiated. Therefore, the study design included control, harvest, and burn on south aspects (n = 9) and control and harvest on north aspects (n = 6). Mechanical thinning and prescribed burn treatments were conducted in different years. Although we desired to implement treatments in the same year, the logistics of working within the federal system precluded this reality. Mechanical treatments were completed in 2008, 2012, and 2013 on Pump, Fork, and Benson, respectively. Prescribed burns were conducted in 2008, 2009, and

2010 on Fork, Pump, and Benson, respectively. Mechanical harvest treatments consisted of on-site delimbing, piling slash, and then skidding logs to landings. Prescribed burns were conducted in late fall (October to December) using strip head fires resulting in low surface fire behavior (i.e., <0.7 m flame heights) and no canopy torching.

2.3. Field Methods

Experimental units were overlaid with a grid of Modified-Whittaker plots [20] located on a 50 × 50-m spacing (50-m side of Modified-Whittaker plot was oriented perpendicular to the contour). Eight randomly selected plots per experimental unit were permanently marked for overstory (>12.7 cm diameter at 1.37 m) vegetation measurements. Five of the eight overstory plots were randomly selected in 2006 and 2016 to estimate CWD (Mg ha^{-1}) (i.e., sampling with replacement). CWD was calculated utilizing the number of CWD intersections from line transects, the corresponding diameters, and estimates of specific gravity for sound (0.40) and rotten (0.30) CWD as described by Brown [21]. CWD transects were systematically located utilizing overstory plot boundary lines. CWD > 7.6 cm in diameter (hereafter, 1000-h fuels) was measured along five 15 m transects/plot. CWD 2.54 to 7.6 cm in diameter (hereafter, 100-h fuels) was measured along five 4 m transects/plot. Transects on post-harvest treatments that intersected mechanically constructed slash piles were randomly rerouted; this circumstance was rare. Baseline measurement of CWD was done in 2006. Post treatment measurements were conducted in 2016. Fuel classes correspond to time-lag fuel which is based upon how long it would take for two-thirds of the dead fuel to respond to atmospheric moisture. As outlined in Brown et al. [22], we assigned each 1000-h fuel as either sound or rotten. However, this criterion was largely subjective and lacked quantified thresholds. Future studies would benefit from using a sound/rotten rating system following Maser et al. [23] that incorporates five classes of decay.

2.4. Statistical Analysis

For estimating 1000-h CWD loading, we followed Brown et al.'s [22] suggestion to increase transect length in order to reduce variability. Specifically, we combined the five 15 m transects/plot to achieve a 75 m transect/plot. In two pre-harvest stands, we excluded outlier legacy logs that measured 101 and 102 cm in diameter. Because determining decay class can be subjective for 1000-h logs (which can therefore significantly affect CWD loading results), we also reported the number of 1000-h logs counted per 75 m transect to better understand treatments effects on 1000-h CWD.

Data were analyzed using SAS Enterprise Guide 7.1 [24]. The mean difference in weight (Mg ha^{-1}) of 100-h and 1000-h CWD between aspects, pre- and post-treatment, and among treatments was tested using least square means at $\alpha = 0.05$. The weight of 100-h and 1000-h CWD were modeled assuming a Gaussian distribution of errors using a generalized mixed effects model where aspect, treatment, and time since treatment were used as covariates. The random effect was the nested effect of experimental unit within site and aspect, given that sample plots within an experimental unit were assumed to be correlated and site and aspect have a blocking effect.

To account for on-the-ground treatments being implemented in different years, we devised a time since treatment covariate (TST) (Figure 1). Time since treatment was modeled by assigning the year of treatment as zero, the years before treatment as negative deviation in years, and the years after treatment as positive deviation in years. The range of years was bounded between 2006 (i.e., base-line data collection) and 2016 (i.e., post-treatment data collection). For example, control treatment had only positive deviation in years because the reference point was 2006. For burned units, TST ranged from negative to positive years depending upon the year of treatment (i.e., 2008, 2009, 2010). Similarly, for harvest units, TST ranged from −7 to +7 years (given the three different treatment years: 2008, 2012, 2013).

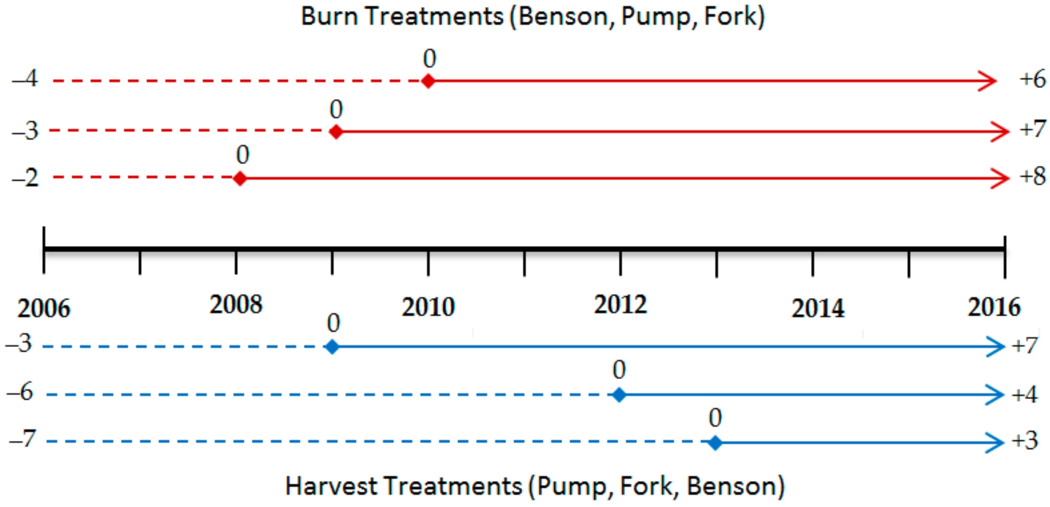

Figure 1. Timeline showing when treatments were implemented and how the time since treatment (TST) variable was constructed (i.e., negative number at time of baseline data collection and positive number at time of posttreatment data collection). Burn and harvest treatments are listed respectively (i.e., top line corresponds to first listing and so forth).

3. Results

Mean overstory attributes prior to treatment (i.e., 2006) at the tree and stand level are shown in Table 1. Prior to treatment, there were no differences in overstory attributes (e.g., basal area and tree density) between stands within the same aspect (Table 1) [25]. Following harvest treatment, mean basal area and tree density, as measured in 2016 on north and south aspects, were significantly reduced. Mean basal area and tree density on north aspects in 2006 were 29.2 (m^2 ha^{-1}) and 216 (stems ha^{-1}) prior to harvest and 12.6 and 100 post-harvest, respectively. Mean basal area and tree density on south aspects in 2006 were 23.8 (m^2 ha^{-1}) and 218 (stems ha^{-1}) prior to harvest and 10.5 and 80 post-harvest respectively.

Table 1. Mean tree and stand level attributes ± standard error of overstory plots assigned to different silvicultural treatments on north and south aspects prior to treatment on dry mixed-conifer forest stands, Sacramento Mountains, Lincoln National Forest, New Mexico, USA.

Attributes	Before Treatment 2006				
	North		South		
	Control	Harvest	Burn	Control	Harvest
Tree level					
Crown area (m^2)	26.2 ± 2.2	27.9 ± 2.0	28.0 ± 2.0	27.5 ± 2.0	27.4 ± 2.1
DBH (cm)	43.7 ± 2.7	43.5 ± 2.2	42.1 ± 2.2	41.6 ± 2.8	38.7 ± 1.0
Stand level					
BA (m^2 ha^{-1})	29.3 ± 3.1 ^{a}	29.1 ± 2.2 ^{a}	26.3 ± 3.3 ^{ab}	24.5 ± 2.6 ^{ab}	20.7 ± 2.8 ^{b}
Density (stems ha^{-1})	182.0 ± 20	250.0 ± 42	219.0 ± 46	214.0 ± 41	222.0 ± 62
DH (m)	23.3 ± 0.7 ^{a}	22.4 ± 0.6 ^{ab}	20.3 ± 0.6 ^{c}	21.0 ±1.1 ^{bc}	19.9 ± 0.7 ^{c}
RSI	0.4 ± 0.02 ^{ab}	0.3 ± 0.02 ^{b}	0.4 ± 0.03 ^{ab}	0.4 ± 0.03 ^{ab}	0.4 ± 0.05 ^{a}
Conifer (%)					
Conifer BA (m^2 ha^{-1})	92.7 ± 4.1 ^{ab}	88.2 ± 5.5 ^{b}	98.9 ± 0.9 ^{a}	98.7 ± 0.5 ^{a}	98.4 ± 1.0 ^{a}
Conifer density (stems ha^{-1})	87.1 ± 5.6 ^{ab}	82.0 ± 7.1 ^{b}	97.0 ± 2.3 ^{a}	94.7 ± 2.6 ^{a}	95.5 ± 3.5 ^{a}

DBH = diameter at breast height; BA = basal area; DH = dominant height; RSI = relative spacing index. Row-wise values with superscript of different letters indicate significant difference ($p < 0.05$) of least square means between silvicultural treatments across aspects; values without superscript were not significantly different.

Mean CWD loading for each treatment-aspect combination before (2006) and after treatment (2016) is shown in Table 2. Because we collected pre-treatment data (i.e., 2006), we have two sources to compare treatment effects: (1) 2016 vs. 2006 (e.g., burn 2006 vs. burn 2016); and (2) within year among treatments (i.e., burn vs. harvest vs. control 2016).

3.1. CWD Response on Control Treatment

In order to interpret how CWD responded to burning and harvest treatments, it was important to first understand how control treatments responded over time (i.e., control 2006 vs. control 2016) on north and south aspects (Table 2). There was no change in 100-h CWD on north or south aspects (Table 2). Subsequently, this makes comparisons between treatments straightforward. However, as for 1000-h CWD, there was an interesting pattern on north and south control sites between 2006 and 2016; mean values decreased, in some cases statistically, and in other cases just in mean value (Table 2). Specifically, sound logs decreased between 2006 and 2016 on both aspects (Table 2). Likewise, logs per transect on south aspects also decreased between 2006 and 2016 (Table 2). Subsequently, this makes comparison and interpretation of results between treatments more intricate. This will be explored in the discussion section.

Table 2. Pre-(2006) and post-treatment (2016) mean coarse woody debris (CWD) (Mg ha^{-1}) (± standard error) response to control, burn only, and harvest only treatments in mixed-conifer forest stands, Sacramento Mountains, Lincoln National Forest, New Mexico, USA.

Year	Aspect	Treatment	CWD (Mg ha^{-1})				CWD (Count/Plot)
			100-h	1000-h			1000-h
				Rotten (a)	Sound (b)	Total (a + b)	Mean
2006	North	Control	16.5 ± 2.7 ^{ab}	18.8 ± 1.6 ^{b}	28.1 ± 3.4 ^{b}	46.9 ± 4.7 ^{ab}	11.3 ± 2.3 ^{a}
		Harvest	16.4 ± 1.6 ^{ab}	36.8 ± 16.6 ^{a}	20.8 ± 6.4 ^{bcd}	57.6 ± 13.1 ^{ab}	8.9 ± 1.4 ^{a}
	South	Burn	14.6 ± 4.4 ^{ab}	21.8 ± 9.7 ^{b}	12.5 ± 3.1 ^{bcd}	34.3 ± 12.7 ^{ab}	8.0 ± 1.3 ^{a}
		Control	9.6 ± 0.4 ^{bc}	24.9 ± 4.5 ^{ab}	24.6 ± 12.7 ^{bc}	49.5 ± 17.1 ^{ab}	8.8 ± 1.8 ^{a}
		Harvest	12.5 ± 1.4 ^{abc}	19.1 ± 10.9 ^{b}	30.2 ± 11.0 ^{ab}	49.3 ± 18.2 ^{ab}	8.5 ± 1.2 ^{a}
2016	North	Control	13.2 ± 3.3 ^{abc}	16.1 ± 5.5 ^{b}	8.2 ± 3.6 ^{cd}	24.3 ± 9.0 ^{b}	7.7 ± 1.5 ^{a}
		Harvest	15.6 ± 3.9 ^{ab}	19.8 ± 8.3 ^{b}	20.3 ± 8.5 ^{bcd}	40.2 ± 15.9 ^{ab}	9.7 ± 1.6 ^{a}
	South	Burn	4.9 ± 0.8 ^{c}	12.6 ± 3.9 ^{b}	8.7 ± 4.7 ^{cd}	21.4 ± 0.8 ^{b}	3.2 ± 0.8 ^{c}
		Control	9.6 ± 1.4 ^{bc}	17.1 ± 4.4 ^{b}	3.7 ± 3.7 ^{d}	20.8 ± 3.1 ^{b}	3.7 ± 0.4 ^{c}
		Harvest	18.9 ± 2.9 ^{a}	14.8 ± 2.9 ^{b}	48.2 ± 19.8 ^{a}	62.9 ± 22.5 ^{a}	8.4 ± 0.9 ^{a}

Column-wise values sharing the same superscript letter indicates mean vales are not significantly different at the 0.05 level (least-squares means).

3.2. Prescribed Fire Effects on CWD

Results indicated late fall burning, despite mild fire behavior, reduced 100-h CWD, but outcomes were more nuanced for 1000-h CWD (Table 2). Specifically, all post-burn 1000-h CWD loadings (sound, rotten, and total) were less than pre-treatment means, but not statistically different. However, the number of 1000-h logs per transect significantly decreased post burning (i.e., 8.0 ± 1.3 standard error (SE) pre fire vs. 3.2 ± 0.8 SE post fire) (Table 2).

3.3. Commercial Harvest Effects on CWD

Harvest treatment did not increase 100-h CWD on north aspects (Table 2). Likewise, harvest treatments did not statistically increase 100-h CWD on south aspects, but mean values were greater than 2006 levels (Table 2). As noted above, 100-h CWD on control sites did not change between years.

Harvest treatment maintained 1000-h sound CWD on north and south aspects (Table 2). Rotten logs on north aspects decreased following harvest treatments while there was no effect on rotten logs on south aspects (Table 2). Overall, total 1000-h CWD on south aspects increased after harvest treatments as compared to 2016 control sites (Table 2). This effect is also supported in count data whereby the number of logs per transect in control stands decreased between 2006 and 2016 on south aspects, but harvest logs did not change, indicating a compensatory-like response following harvesting (Table 2).

3.4. Time since Treatment Effect

Parameter estimates and model fit from generalized linear mixed-effects model for 100-h and 1000-h CWD showed time since treatment had a significant effect on CWD (Table 3). Specifically, greater years since treatment resulted in fewer CWD loading. In addition, the interaction of time since treatment and treatment had a significant effect on CWD. Specifically, time since treatment and prescribed burn had a decreasing effect on 100-h CWD, while time since treatment and harvest had an increasing effect on 100-h and 1000-h CWD. Aspect did not have a significant effect on CWD.

Table 3. Parameter estimates and significance of generalized linear mixed model showing the effects of covariates in predicting 100-h and 1000-h CWD (Mg ha^{-1}).

100-h CWD			1000-h CWD		
Effect	**Estimate**	**SE**	**Effect**	**Estimate**	**SE**
Intercept	16.5 ***	1.6	Intercept	49.8 ***	5.9
Time since treatment (TST)	−0.4 *	0.2	Time since treatment (TST)	−3.1 **	0.9
Aspect (S)	−4.1	2.1	Aspect (S)	−5.6	7.5
TST X Aspect (S)	0.4	0.2	TST X Aspect (S)	1.2	1.1
TST X Burn	−0.9 **	0.3	TST X Burn	<0.1	1.4
TST X Harvest	0.5 *	0.2	TST X Harvest	2.3 *	1.1
Covariance			Covariance		
Intercept	12.1		Intercept	75.6	
Residual	40.5		Residual	1062.4	
AIC	987.0		AIC	1459.0	

*, **, and *** is significant at p-value < 0.05, <0.001, and <0.0001, respectively; SE = standard error; S = south.

4. Discussion

4.1. Prescribed Fire Effects on CWD

As demonstrated in our study, mild fire behavior (i.e., surface fire with <0.7 m flame lengths; Figure 2) can be achieved with fall burning conditions characterized by greater live and dead fuel moistures. Our CWD burn results fit within the reported literature that fire reduces CWD [1,26,27] (Figure 3). However, technically, because CWD on north and south control sites decreased between 2006 and 2016, in some cases significantly and in others just in mean value, the effect of burning on 1000-h CWD within this time period is confounded, although models predict a negative relationship between fire and CWD (Table 3).

Prescribed fire is a useful tool to manage CWD in forested landscapes [15,26,28]. A CWD management target for warm/dry ponderosa pine and Douglas fir forests is reported to be between 11.2–44.8 Mg ha^{-1}. Prior to treatment, our mixed-conifer study site (i.e., burn only treatment) was within the upper range of the recommendation (i.e., 34.3 ± 12.7 Mg ha^{-1}). As part of our long-term research approach, we wanted to use multiple prescribed burns over the course of decades to manipulate forest structure including CWD. An alternative approach is to attempt to meet all objectives with a single fire entry. This typically calls for a more aggressive fire prescription leading to increased fire behavior (e.g., flame length, rate of spread) and severity. In addition, the historical culture of the federal management agency in charge was not to burn mixed-conifer stands. Given these two factors, we wrote a burn prescription that would limit fire behavior and severity.

Figure 2. Picture characterizing fire behavior in mixed-conifer stands from a fall prescribed fire on burn only treatment, Sacramento Mountains, Lincoln National Forest, New Mexico, USA. Picture by D. Cram.

4.2. Commercial Harvest Effects on CWD

Commercial harvest treatment effects on CWD can vary widely depending on multiple factors such as degree of basal area and stem density reduction, stand composition, skidding practices, and most notably, slash prescription [10,29,30]. Our sites were mechanically harvested, manually delimbed, slash mechanically piled, and logs skidded to a loading deck.

Commercial harvest treatments produced a nuanced 1000-h CWD response. This is because CWD on control sites, specifically sound logs on north and south aspects, decreased between 2006 and 2016 (Table 2). This can be attributed to natural attrition of sound to rotten logs and a lack of new trees and snags falling to the ground. In addition, this decrease may be magnified as a result of the imprecise dichotomy between assigning logs to sound and rotten decay classes. This same phenomenon is assumed to have impacted the adjacent harvest sites. Given this assumption, harvesting activities must have added CWD to the stand, but not at a rate that exceeded 2006 levels. In this case, harvest treatments resulted in a compensatory like addition of CWD. This effect is also evident in count data on Table 2.

Immediately following commercial harvest activities on similar south-aspect mixed-conifer sites in the Sacramento Mountains, Mason et al. [8] reported 1000-h CWD at 62 Mg ha^{-1} (58 sound + 4 rotten Mg ha^{-1}). They reported this was a significant increase over control sites. Our post-treatment 1000-h CWD loading on south aspects was the same mass (i.e., 62.8 Mg ha^{-1}) (48.1 sound + 14.7 rotten), but was collected four years (on average) post-harvest.

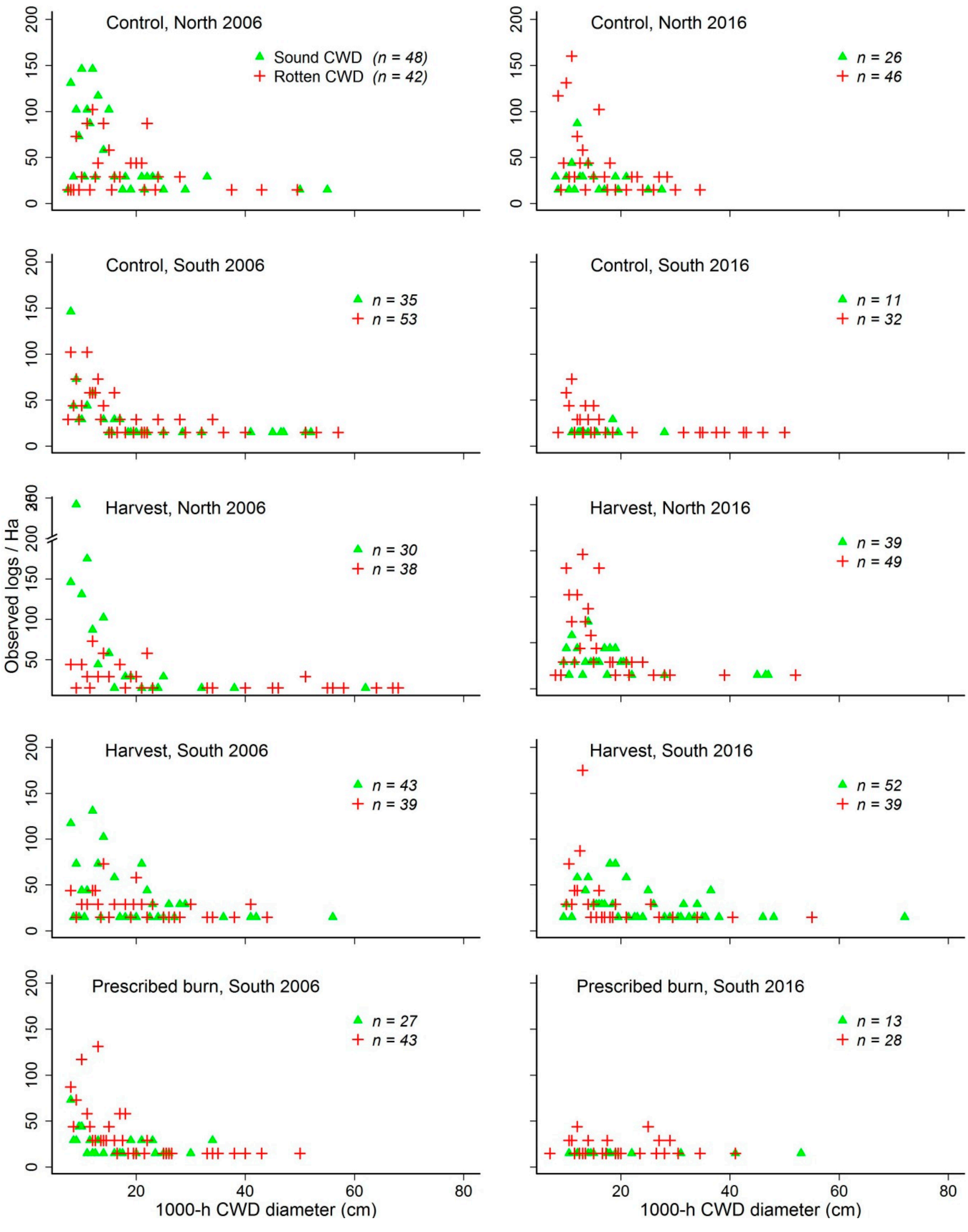

Figure 3. Decay class (i.e., sound and rotten) diameter distribution of 1000-h coarse woody debris (CWD) before (2006) and after (2016) silvicultural treatments on north and south aspects of dry mixed-conifer forests, Sacramento Mountains, Lincoln National Forest, New Mexico, USA.

5. Conclusions

Silvicultural prescriptions including prescribed fire are versatile tools managers can use to achieve management objectives. There are numerous categories of desired conditions that can be targeted (e.g., vegetation, watershed condition, wildlife habitat, fuels). Among these targets are CWD. Total CWD within a forested system represents the balance between inputs and deductions. Slow decomposition rates and erratic variations in input result in highly variable loading through time [29,31]. However, our study suggests that thinning and burning treatments are important determinants of 100-h and 1000-h CWD. Harvest and burning prescriptions can be written to maximize or minimize CWD response. Results presented here will be useful to forest managers that are writing specific silvicultural prescriptions in an attempt to meet established CWD guidelines which are a part of desired future conditions. So called "desired conditions" are required in overarching management documents (i.e., Forest Plans) as directed by the 2012 Forest Planning Rule. By using harvest or burning techniques managers can increase or decrease CWD as desired.

Author Contributions: D.C. and T.B. conceived and designed the experiments; D.C. collected field data; P.S. and D.C. analyzed the data; P.S., D.C., and S.S. wrote the paper.

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Conflicts of Interest: The authors declare no conflict of interest.

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