THESIS

THE EFFICIENCY AND EFFECTIVENESS OF MARKING METHODS ON SPATIALLY HETEROGENEOUS FOREST TREATMENTS

Submitted by

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ABSTRACT

THE EFFICIENCY AND EFFECTIVENESS OF MARKING METHODS ON SPATIALLY HETEROGENEOUS FOREST TREATMENTS

Fire suppression, historic grazing, past logging, and climate change have resulted in increased tree densities and fuel loads, greater forest homogeneity, and large, uncharacteristic wildfires in the lower montane forests of Colorado’s Front Range. The Pike and Arapahoe-Roosevelt National Forests are currently restoring forest structure through the implementation of forest thinning. Historically these forests were more heterogeneous with individual trees, groups of trees varying in quantity, and openings. The silvicultural prescriptions required for these restoration treatments are complex, and foresters are experiencing difficulties conveying these complex prescriptions to the contractors implementing the treatments. The forest service has used three different marking methods to implement this prescription: individual tree marking (ITM), designation by prescription (DxP), and designation by description (DxD). The objective of this study was to investigate the effectiveness and efficiency of these marking methods. A combination of quantitative and qualitative methods were used to address the objective. The quantitative methods investigated the heterogeneity of pre- and post-treatment forest structures at eight sites within the lower montane zone of the Colorado Front Range. The qualitative methods investigated the facilitators and constraints among stakeholders with respect to marking methods. These methods were implemented by conducting semi-structured interviews with stakeholders (n=10) who were involved in the treatments being analyzed in the quantitative portion.

The results of the quantitative portion indicated that each of the three marking methods created more heterogeneity than the control (traditional fuels treatment). The marking method creating the largest increase in heterogeneity depended on the metric that was being utilized. This was a result of the scales of measurement being different for each of the metrics. With each marking method creating heterogeneity, marking method selection criteria should be utilized to choose the most appropriate marking method. The qualitative analysis identified selection criteria in the following categories: experience of the stakeholders, marking vs. designation, DxP vs DxD, and hybrid marking methods. These categories should be considered when selecting a marking method for a spatially heterogeneous treatment.

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Chapter 1: Introduction

As forest fires continue to grow larger and more catastrophic in the western US, the need for proactive approaches in forest management has become increasingly important (Westerling et al. 2006, Brown et al. 2004). The proactive approaches that have been implemented by forest managers in this region have ranged from mechanically reducing fuel in the forest to re-introducing fire to the landscape. Fuels reduction practices have been carried out for many years in this region, however until recently, many of these treatments did not focus on the horizontal structure of the resulting forest. Currently, many forest managers are adding objectives that aim to achieve a more spatially heterogeneous horizontal structure. This addition to fuels prescriptions has complicated the process of communicating the desired result for implementation. This study examines the efficiency and effectiveness of current communication processes.

The lower montane zone of Colorado's Front Range is one area where larger and catastrophic wildfire occurrences have triggered more proactive management. This area has experienced a dramatic change in the fire regime over the past 100 years. Before European settlement occurred in this area, the lower montane zone of Colorado experienced a mixed-severity fire regime (Goldblum and Veblen 1992). This fire regime had an average return interval of less than 30 years with fire severities that varied from low severity to high severity (Sherrif and Veblen 2007). These fires maintained an open woodland forest structure that consisted of openings in the forest canopy between groups of trees with interlocking crowns and isolated individuals (Brown et al. 1999). This structure varied across the landscape with most of the regeneration being held in check by periodic surface fires (Kaufmann et al. 2001).

In contrast, currently the average fire return interval is longer than 30 years with larger, higher-severity fires (Veblen et al. 2000). This increase can be primarily attributed to fire suppression, past logging, grazing, and climate change (Sherriff and Veblen 2006). Each of these factors have had an effect on the quantity and distribution of fuels within the forest (Kaufmann et al. 2000). Fire suppression over the last 100 years along with contrasting grazing pressures has promoted regeneration in ponderosa pine forests; which in turn has resulted in a more homogeneous horizontal forest structure (Stott et al. 1998). Climate change also appears to be a factor with fire weather in the region having more high fire danger days on average compared to what climate reconstruction models estimate pre-European settlement (Brown et al. 2004).

This change in fire regimes has had many negative impacts within the Lower Montane Zone along the Front Range, including destruction to the wildland urban interface (WUI), a decrease in the biodiversity in the forest, and large flooding events. The WUI has increased in size over the last 100 years in this region, which in turn has endangered lives of people and caused destruction to homes during wildfires (Radeloff 2005). The change in the horizontal structure of the forest has led to a decrease in biodiversity within the forest (Carey 2003). After these high-severity fires have burned, the landscape is more prone to catastrophic flooding events which also impacts the WUI (Moody et al. 2008).

These potential negative impacts have led to over 150,000 hectares of land being deemed in need of restoration in the lower montane zone of the Front Range in Colorado (see figure 1, Front Range Fuels Treatment Partnership Roundtable 2006). A large portion of this land is located on National Forest Land. The US Forest Service (USFS), which manages this land, is currently involved in a 10 year stewardship contract to address fuels and restoration issues through mechanical treatment on over 12,000 hectares of forest within the Pike and Roosevelt National Forests (CFLRI 2010). These treatments aim to reduce fuels and bring the forest within the historic range of variability. This historic structure can be referred to as spatially heterogeneous with the structure varying in groups, openings, and individuals throughout the landscape (Churchill et al. 2013, Larson and Churchill 2012).

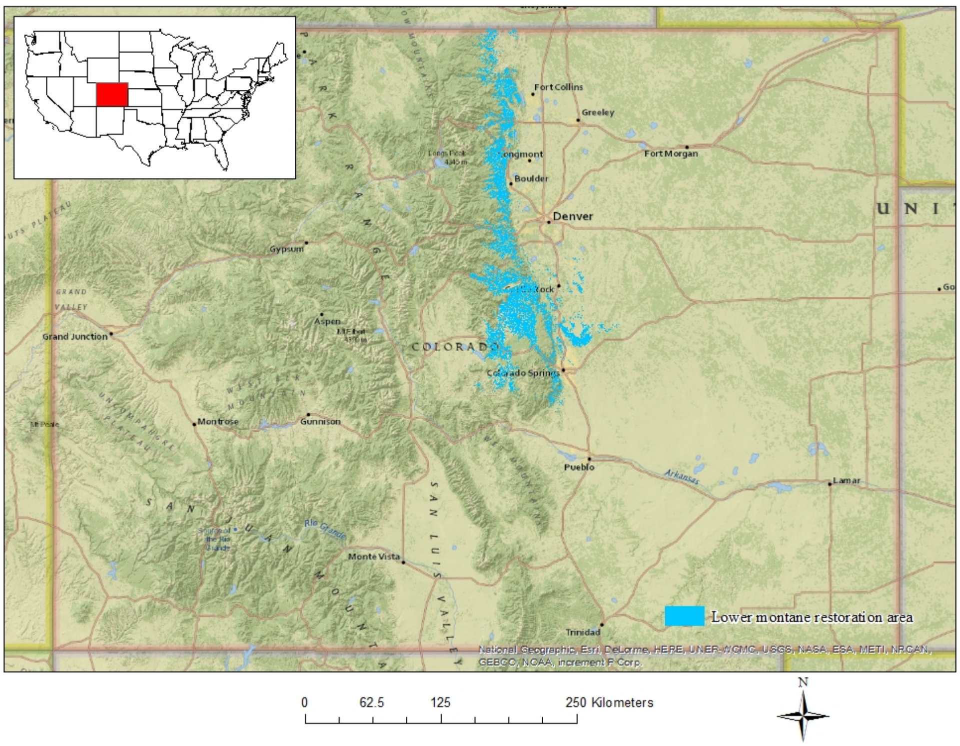

Figure 1. Area of the lower montane forest in the Front Range of Colorado that is currently outside of its historic range of variability. Data from Front Range Fuels Treatment Partnership Roundtable, 2006.

Achieving a spatially heterogeneous structure has presented difficulties with the implementation of prescriptions. Traditionally, fuels treatments have been applied to the forest uniformly, which often results in a homogeneous structure (O’Hara et al. 2012). Implementing this type of prescription is much easier due to the ease of using stand average measurements to describe the desired stand structure (Churchill et al. 2013). Adding the restoration objective of spatial heterogeneity has been more difficult as stand average measurements are not relevant for obtaining a variable forest structure. This difficulty can be traced to the communication from the forester to the contactor. This communication process is referred to as the marking method in this study.

Currently, the USFS is implementing three different marking methods to achieve spatial heterogeneity. These marking methods are described below:

- Individual Tree Marking (ITM): Trees are either marked to be cut or left.
- Designation by Description (DxD): A description of the trees that are to be removed based on characteristics that can be confirmed after removal.
- Designation by Prescription (DxP): A description of the desired end result of the treatment.

The main objective of this study was to examine the efficiency and effectiveness of marking methods used by the USFS to achieve a more spatially heterogeneous forest structure. To examine this, we will focus on two overarching research questions:

1) How do the marking methods influence the aggregation of the stand from pre- to post-treatment?

2) How do the marking methods influence the communication process and job duties among stakeholders involved these treatments?

A mixed methods approach was used to resolve these questions (Creswell 2003). To examine the first question, quantitative methods were used to compare the three marking methods to the control in terms of the change in forest structure from pre-treatment to post-treatment. The second question utilized qualitative methods to examine marking methods from the facilitators and contraints that were identified by stakeholders.

Chapter 2: Methods

2.1 Study Region

This study examined marking methods of restoration treatments in the lower montane zone of Colorado's Front Range. The Front Range extends from the Wyoming border south past Colorado Springs along the continental divide. The Lower Montane Zone is located on the eastern side of the divide, and includes the area deemed in need of restoration included in figure 1.

The lower montane zone receives between 40 and 70 cm of precipitation annually. This zone occurs between the elevations of 1800 and 2800 meters (Front Range Fuels Treatment Partnership Roundtable, 2006). The dominant, overstory species that occur in this zone include *Pinus ponderosa*, *Pseudotsuga menziesii*, *Picea pungens*, and *Populus tremuloides*. Below the Lower Montane Zone, the ecotone shifts from forested to grassland ecotone. Above this zone is the upper montane zone, which transitions in to forest primarily composed of *Pinus contorta*, *Abies lasiocarpa*, and *Picea engelmannii*.

2.2 Quantitative Methods

Quantitative methods were used to investigate how the marking methods influenced the aggregation of the stands from pre- to post-treatment (research question 1). To assess this, the variation of measurements within stands were analyzed along with a spatial index.

A. Study design

Six restoration treatments implemented using one of three marking methods (two for each method) were compared to two control treatments to understand which of the marking methods resulted in the largest increase of spatial heterogeneity. The marking methods studied were: individual tree marking (ITM), designation by description (DxD), and designation by prescription (DxP). The control sites selected for this study were sites that were thinned using traditional fuels treatments that thinned from below without regards to spatial structure. All sites were treated mechanically by West Range Reclamation, and were all part of a ten year stewardship contract with the Arapaho-Roosevelt and Pike-San Isabel National Forests.

B. Study sites

A 25 hectare unit was sampled within each treatment site. These sample units were chosen in areas that were applicable to the study (ex. Desired marking method, mechanical treatment). The 25 hectare sample areas were selected in parts of the unit that were more flat and even to avoid major forest changes associated with aspect changes and density changes in drainages.

Transects were established throughout the 25 hectare sample units. Transects started closest to the access road and were constructed to cover the most area in the sample unit. A random number generator was used to establish plot locations along the transects. 30 plots were measured within each sample unit, resulting in a consistent plot density of 0.83 plots/hectare. Each plot consisted of two measurement protocols: prism plots and the distance to the nearest tree.

C. Study site description

Of the eight sites being studied, two were located in the Roosevelt National Forest and the other six sites were located in the Pike National Forest. All sites were classified as ponderosa pine forests using the forest type classification from Arner et al. (2001). The locations of these treatments sites within the Front Range of Colorado can be viewed in Figure 2. All sites studied consisted of ponderosa pine (*Pinus ponderosa*) as the dominant species with varying degrees of Douglas-fir (*Pseudotsuga menziesii*), aspen (*Populus tremuloides*), and blue spruce (*Picea pungens*). All of the study sites were located between 2300 and 2800 meters above sea level and had relatively low slopes ranging from 0 to 17%. Precipitation among these sites ranges from 43 to 62 cm annually. The soils range from sand loam to rock outcrop complex (table 1).

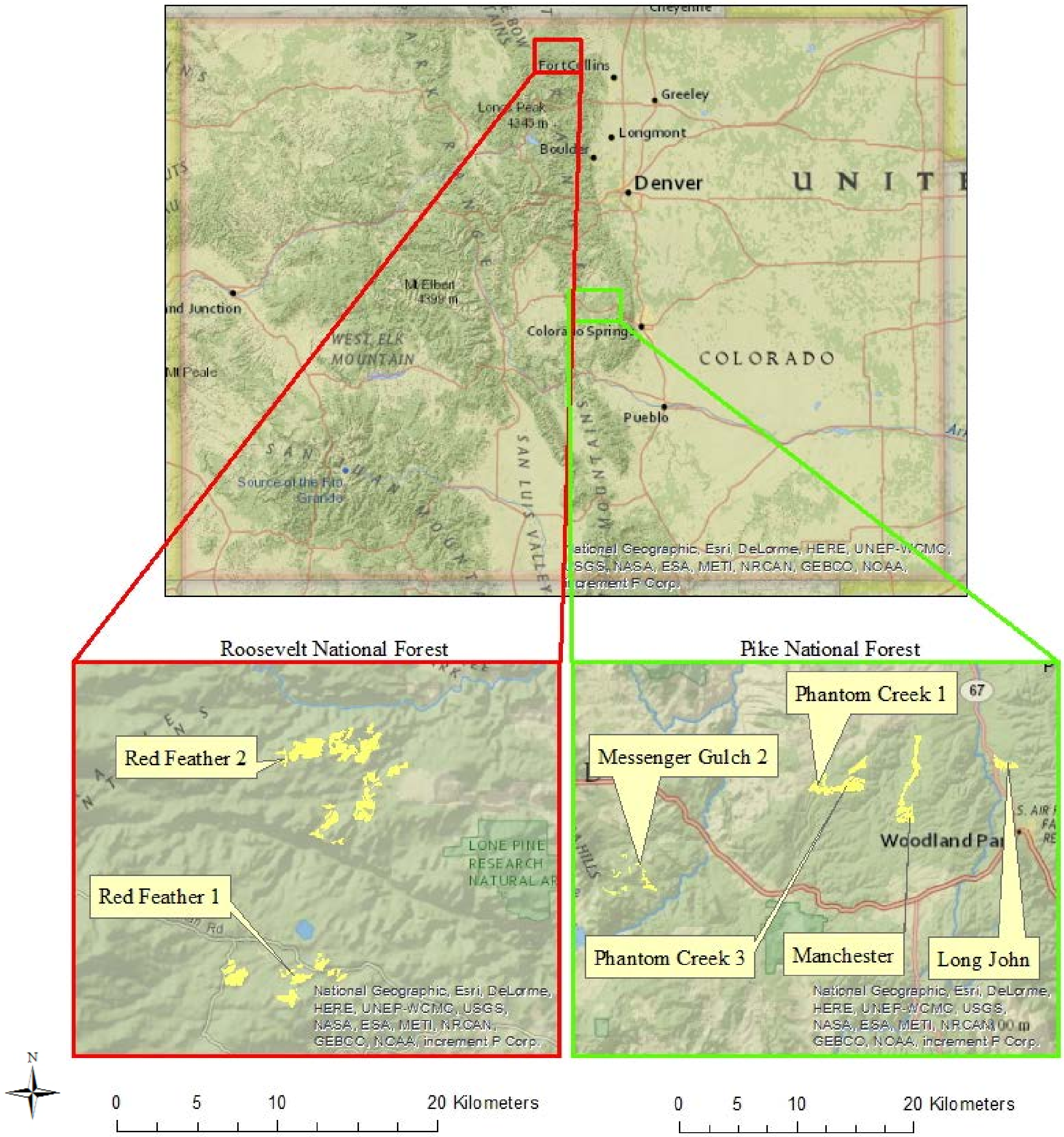

Figure 2.Treatment sites studied in the lower montane zone of the Front Range. Two sites were sampled in the Roosevelt National Forest, and six sites were sampled in the Pike National Forest.

Table 1. Study site characteristics from the lower montane zone of the Front Range. Values from this table are averages from the sample areas.

	Prescription type	Marking Method	Forest	Elevation (meters)	Precipitation (cm)	Soils	Slope (degrees)
RF 1	Spatially Heterogeneous	DxD	Roosevelt	2457.97-2560.24	43.43	Wetmore-Boyle-Rock outrcrop complex	0.28-14.28
RF 2	Spatially Heterogeneous	DxD	Roosevelt	2397.66-2439.21	44.56	Redfeather sandy loam	0.02-16.27
PC 1 (SH)	Spatially Heterogeneous	DxP	Pike	2698.61-2747.42	52.71	Sphinx gravelly coarse sandy loam	0.30-14.56
PC 3	Spatially Heterogeneous	DxP	Pike	2732.44-2783.52	51.18	Sphinx gravelly coarse sandy loam	0.11-16.47
LJ	Spatially Heterogeneous	ITM	Pike	2450.38-2481.98	61.23	Boyett-Frenchcreek	0.30-12.90
MG 2	Spatially Heterogeneous	ITM	Pike	2620.22-2637.91	35.57	Merino-Edloe-Rock outcrop complex	0.22-9.86
PC 1 (C)	Thin From Below	DxP	Pike	2730.02-2783.52	48.76	Sphinx gravelly coarse sandy loam	0.02-15.10
Man	Thin From Below	DxP	Pike	2719.46-2758.97	55.46	Sphinx gravelly coarse sandy loam	1.02-13.82

D. Data Collection

1. Diameter at breast height (DBH) Estimation

With the sites all being measured post-treatment, we used a logistic regression to estimate pre-treatment DBH from stump diameter. The regression compared measurements of the diameters at ten centimeters off of the ground to the diameters at breast height of living trees on sites near treatments.

2. Plot measurements

a. Prism Plot

A prism with a basal area factor of 10 was used and the species and DBH of each in-tree greater than 7 centimeters was recorded.

b. Distance to nearest tree

The distance to the nearest tree was measured from plot center.

E. Data analysis

All data were analyzed using R version 3.0.1 (R Core Team 2013). An α of 0.10 was used to find differences within the small sample size. The plot data was analyzed using two different approaches: stand average comparisons, and within site variability.

1. Stand average comparisons

Stand averages for basal area (m^2/ha) and trees per hectare were compared among the treatments for the pre-treatment averages, post-treatment averages, and the difference from pre- to post-treatment. A ranked one-way ANOVA was used to test for statistically significant differences among the treatments in terms of basal areas and trees per hectare (n=8, df=3).

2. Spatially heterogeneous comparisons

Spatial heterogeneity was assessed by using three different analyses: tree density variability within each site, basal area variability within each site and pielou's index of non-randomness. The variability of tree densities and basal areas within each site would be expected to be more consistent in situations with homogeneous structures. On the contrary, heterogeneous structures would be expected to be much more variable with these measurements.

Tree density variability was analyzed by comparing the coefficients of variation of the plot-wise trees per hectare. The pre-treatment values were contrasted using a ranked ANOVA to see if there were differences in tree density variation (n=8, df=3). The post-treatment coefficients of variation were also compared using the ranked ANOVA (n=8, df=3).

Basal area variability was analyzed using the same procedure as the tree density variability.

Pielou's index of non-randomness was calculated for each sample site to evaluate horizontal spatial structures (Pielou 1977). The equation for the index is:

$$\alpha=\pi\rho\varpi$$

α = index of non-randomness

ρ = average tree density per hectare

ϖ = mean squared distance between randomly selected points to their nearest neighbor

Pre- and post-treatment values were tested to describe structures that existed and how much they changed from treatment. This index indicates a spatial pattern calculated from the distance from plot center to the nearest tree (ϖ) as well as the average density (ρ). This index will indicate a spatial pattern of regular, random, or aggregated according to the relationship of the index to 1 (Figure 3). After the indices were calculated, a ranked ANOVA was utilized to compare the marking methods and control pre-treatment, post-treatment, and the difference between pre and post.

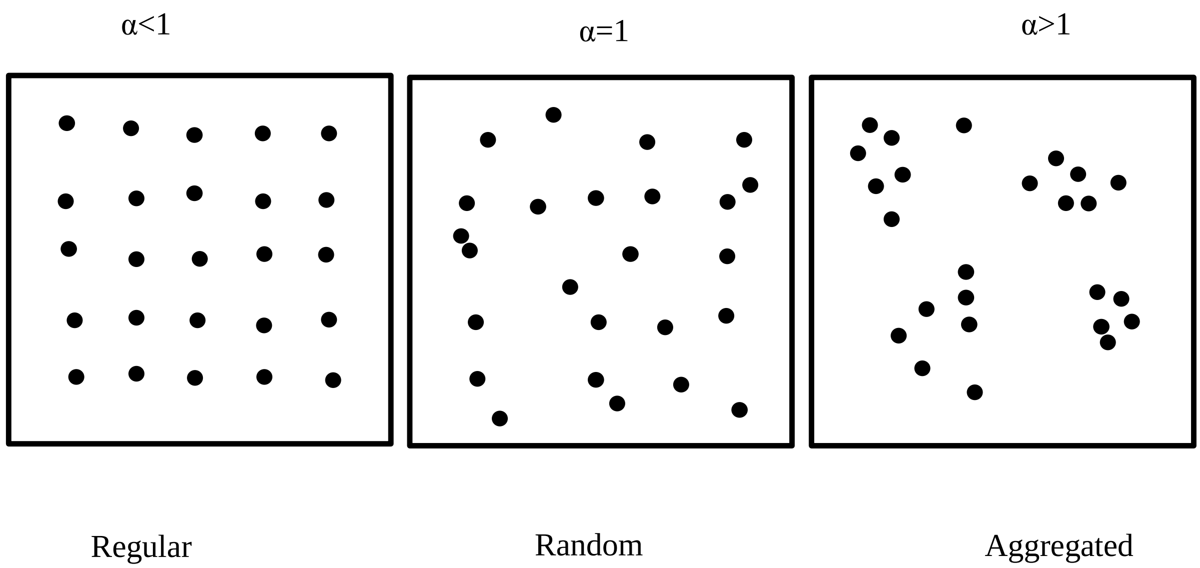

Figure 3. Spatial pattern interpretations of Pielou's index of non-randomness. Values near 1 indicate a random pattern. Values significantly higher than 1 indicate an aggregated pattern, and values significantly lower than 1 indicate a regular pattern.

2.3 Qualitative Methods

Qualitative methods were implemented to examine the facilitators and constraints that occur with each marking method among the stakeholders involved. This creates a triangulation of methods which helps to reduce the bias within a study (Decrop 1999). This portion of the study examines the marking methods from the stakeholder's perspective who are involved in implementing the treatments. All stakeholders involved in the qualitative portion of this study were involved with at least two treatments from the quantitative portion. This enhances the connection for triangulation.

A. Study design

A study by Grimble and Wellard (1997) was used to guide the identification of stakeholders and to develop interview questions. This study identifies the stakeholders involved in a natural resource project, and then develops interview questions to identify the facilitators and constraints that apply to that project. The stakeholder groups that were identified for this study were: silviculturist, sales preparation, sales administration, and contractor. The facilitators and constraints were analyzed further to identify themes among the stakeholder groups. The outcomes of these evaluations can highlight the difficulties and challenges of treatments involving multiple disciplinary stakeholders (Pooley et al. 2014).

B. Data Collection

Ten interviews were conducted with stakeholders from the Pike/San Isabel National forest, Arapaho/Roosevelt National Forest, and West Range Reclamation LLC. All participants were involved in at least two of the treatments being studied. Five of these participants were involved in the treatments on the Roosevelt National Forest with the other five participants being involved in the treatments on the Pike National Forest. The interviewees consisted of two silviculturists, three sales preparation employees, three sales administrators, and two contractors.

The interviews were semi-structured and either conducted in person or over the phone. Interviews lasted between a half hour and an hour. All interviews were voice recorded with the consent of the interviewee. Questions were open-ended and relevant to the stakeholder group that the interviewee was classified as. These questions were created following the study design. This created questions that focus on identifying the conflicts and tradeoffs that arise for each stakeholder group among the relevant marking methods. A list of questions can be found in Appendix 1. These questions focused on aspects such as: how the different marking methods affect the stakeholder's job, the definition of spatial heterogeneity, communication of spatial heterogeneity, and how experience with these prescriptions has shaped their outlook.

In addition to the interviews, at the invitation of the contractors and USFS, a site observation was conducted to observe interactions that occur in the field during treatment. The observation was conducted in the Pike National Forest on two different treatment sites that were not included in the quantitative analysis. Although these sites were not included in the quantitative analysis, they both aimed to achieve spatial heterogeneity and are part of the same stewardship project.

Data Analysis

To better understand the conflicts and tradeoffs resulting from these treatments, interviews were transcribed verbatim from the voice recordings of the interviews. Notes were taken during the site observation and expanded upon directly after the site observation was complete. The interview transcripts along with site observation notes were then coded using open coding. These codes were then further analyzed using axial coding (Corbin and Strauss 2007). The software Nvivo 10 was utilized to organize codes and make connections between relevant themes.

Responses were not analyzed to find which marking method was preferred for each stakeholder group, but rather to better understand the facilitators and constraints of each marking method relevant to the stakeholder group. This helped to look at the process of communication of these prescriptions from writing the prescription to the implementation of the treatments. It helped to highlight the roadblocks that occur with each marking method relevant to the stakeholder group and identify where the roadblocks initiated. The total number of responses from each interview question was not analyzed due to the use of semi-structured interviews.

Chapter 3: Results

3. Results

All of the treatments, including the control treatments, reduced the basal area and tree density from pre- to post-treatment. On average, the basal area was reduced by 10.6 m^2/hectare among the treatments. The tree density on average was reduced by 261.2 trees/hectare among the treatments. Figure 4 displays this reduction from one of the DxP sites from this study.

Figure 4. Photo point comparison of before treatment (above) and after treatment (below) of DxP treatment on the Pike National Forest.

3.1 Quantitative results

1. Post-harvest DBH estimation

Regressions were constructed for the three species present in the treatments (*Pinus ponderosa*, *Pseudotsuga menziesii,* and *Picea pungens*). These linear regression equations were used to estimate DBH from stump diameter post-harvest. All linear regression equations were statistically significant ($p < 0.10$) and the relationship between base diameter and DBH of the three measured species was very strong with r^2 values all over 0.98. Regressions, coefficients, p-values and r^2 values can be found in Appendix 2.

2. Stand average comparisons

Both pre- and post-treatment mean tree densities were not significantly different among the marking methods. The pre-treatment average densities ranged from 309 to 561 trees ha^{-1} (Figure 5). After treatment, these averages dropped to between 137 to 290 trees ha^{-1}.

However, the difference from post- to pre-treatment means differed significantly between two pairs of marking methods: DxD and DxP (p=0.086); DxD and ITM (p=0.099). On average, the the DxD treatments had a reduction of 337 trees per hectare, compared to a reduction of 198 trees per hectare with the DxP marking method and 249 trees per hectare with the ITM marking method.

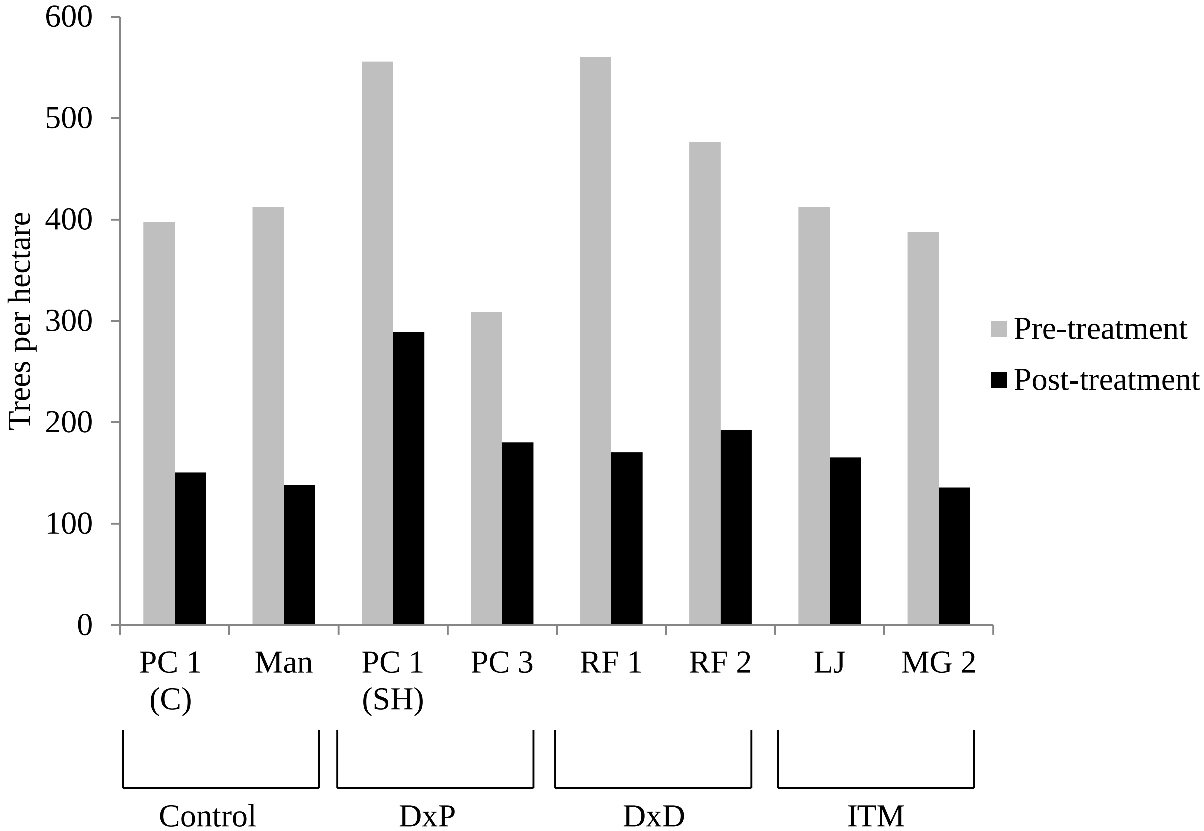

Figure 5. Mean tree densities among treated sites pre- and post-treatment. Pre-treatment and post-treatment densities did not differ among marking methods. The difference between post- and pre-treatment did result in two significant differences: DxD and DxP (p=0.086); DxD and ITM (p=0.099).

Similarly, the pre- and post-treatment mean basal areas were not significantly different among the different marking methods. The basal areas before treatment ranged from 14.1 to 23.6 m^2 ha^{-1} (Figure 6). After treatment, the range of values was reduced to 8.6 to 11.7 m^2 ha^{-1}.

The difference between post- and pre-treatment mean basal areas resulted in two significant differences among marking methods. These differences were between DxD and DxP (p=0.087) along with DxP and ITM (p=0.066). On average, the the DxD treatments had a reduction of 11.7 m^2 ha^{-1}, compared to a reduction of 7.1 m^2 ha^{-1} with the DxP marking method and 12.3 m^2 ha^{-1} with the ITM marking method.

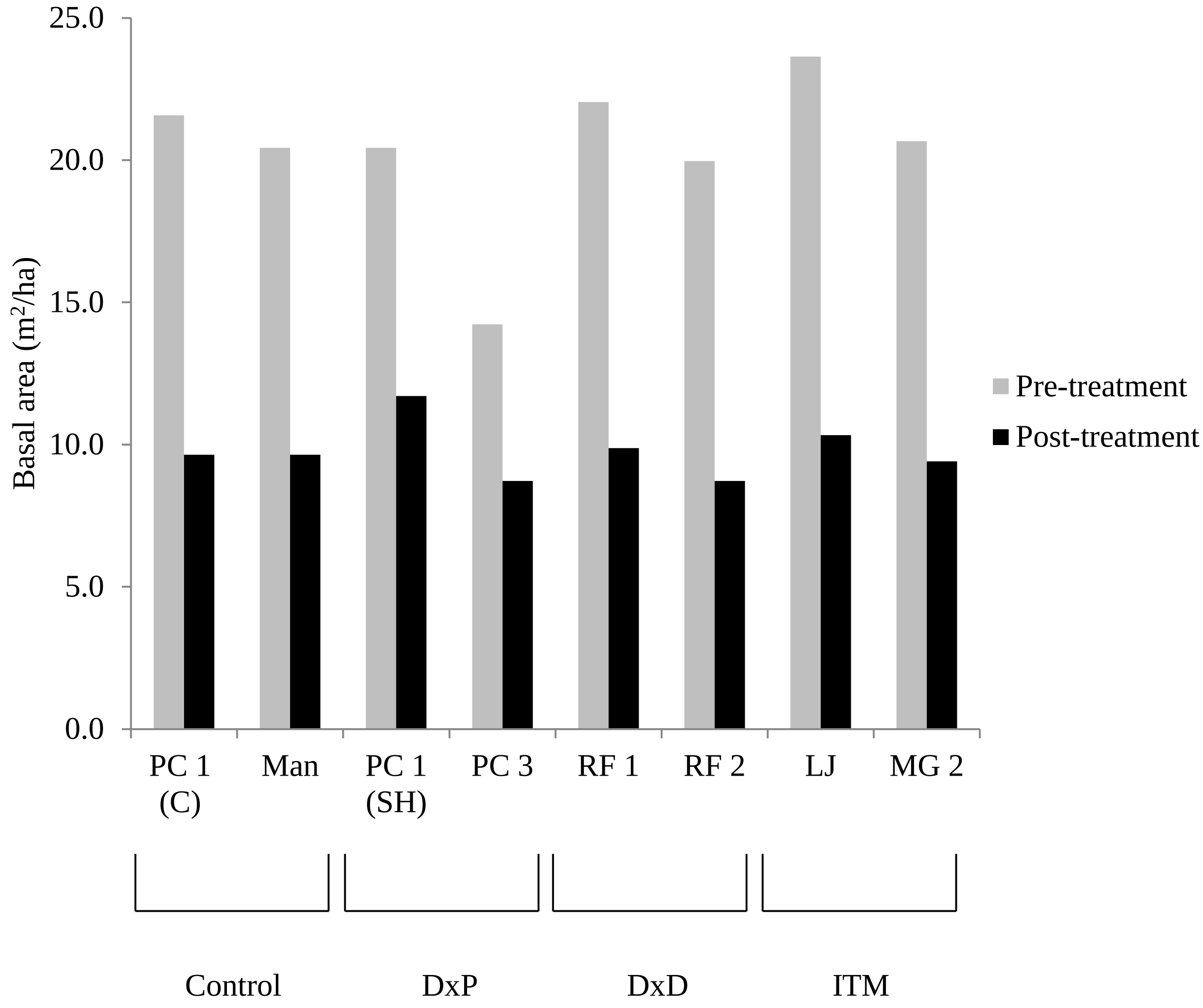

Figure 6. Mean basal areas among marking methods pre- and post-treatment. Pre-treatment and post-treatment areas did not differ among marking methods. There were two significant differences in the difference between pre- and post-treatment: DxD and DxP (*p*=0.087) along with DxP and ITM (*p*=0.066).

3. Spatially heterogeneous comparisons

The coefficients of variation of tree densities did not differ significantly among marking methods pre-treatment (*p*>0.10). These coefficients ranged from 0.37 to 0.65 before treatment (Figure 8). However, post-treatment, DxD and DxP had significantly larger coefficients of variation when compared to the control (*p*=0.099, *p*=0.056). After treatment, the range of coefficients increased to 0.53 - 1.14 (Figure 7). The difference from the post-treatment to the pre-treatment coefficients of variation did not differ significantly among the marking methods.

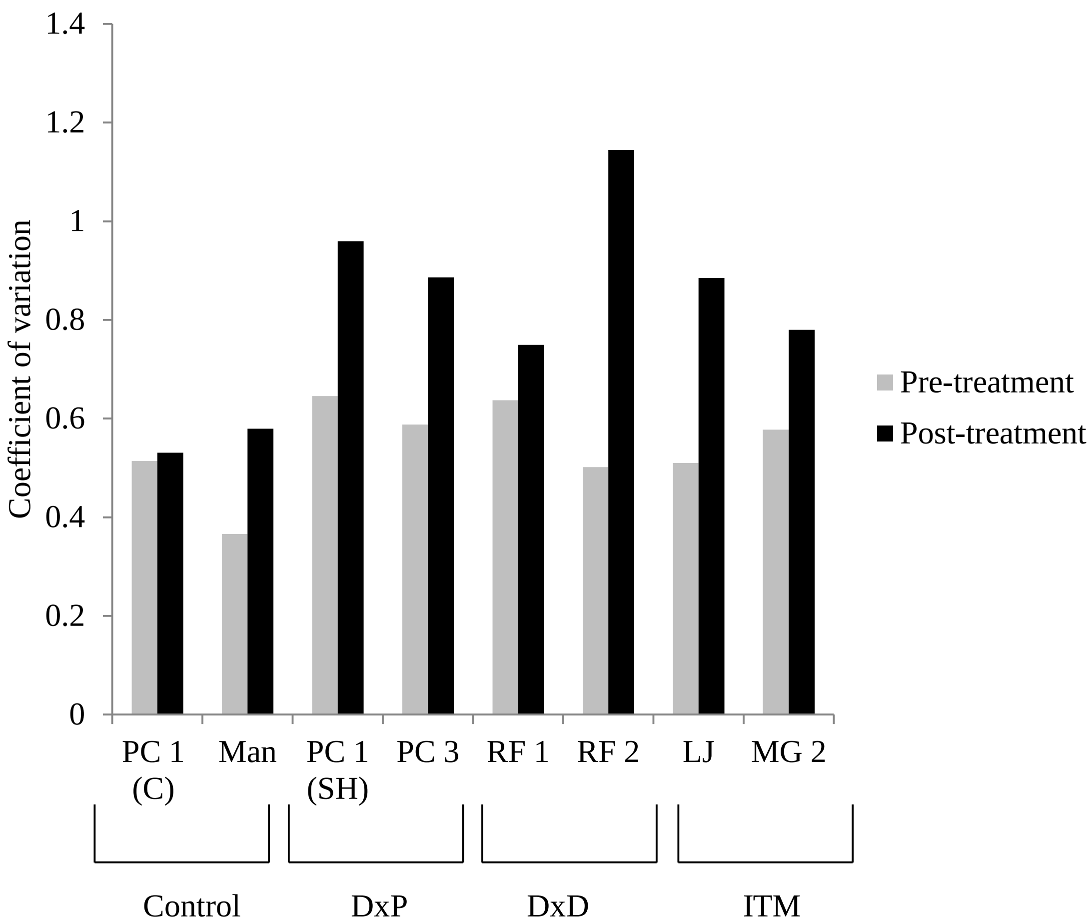

Figure 7. Coefficients of variation among tree densities by plot for each of the study sites. Pre-treatment coefficients did not differ among marking methods. Post-treatment, DxD and DxP had significantly larger coefficients of variation when compared to the control (*p*=0.099, *p*=0.056).

Control

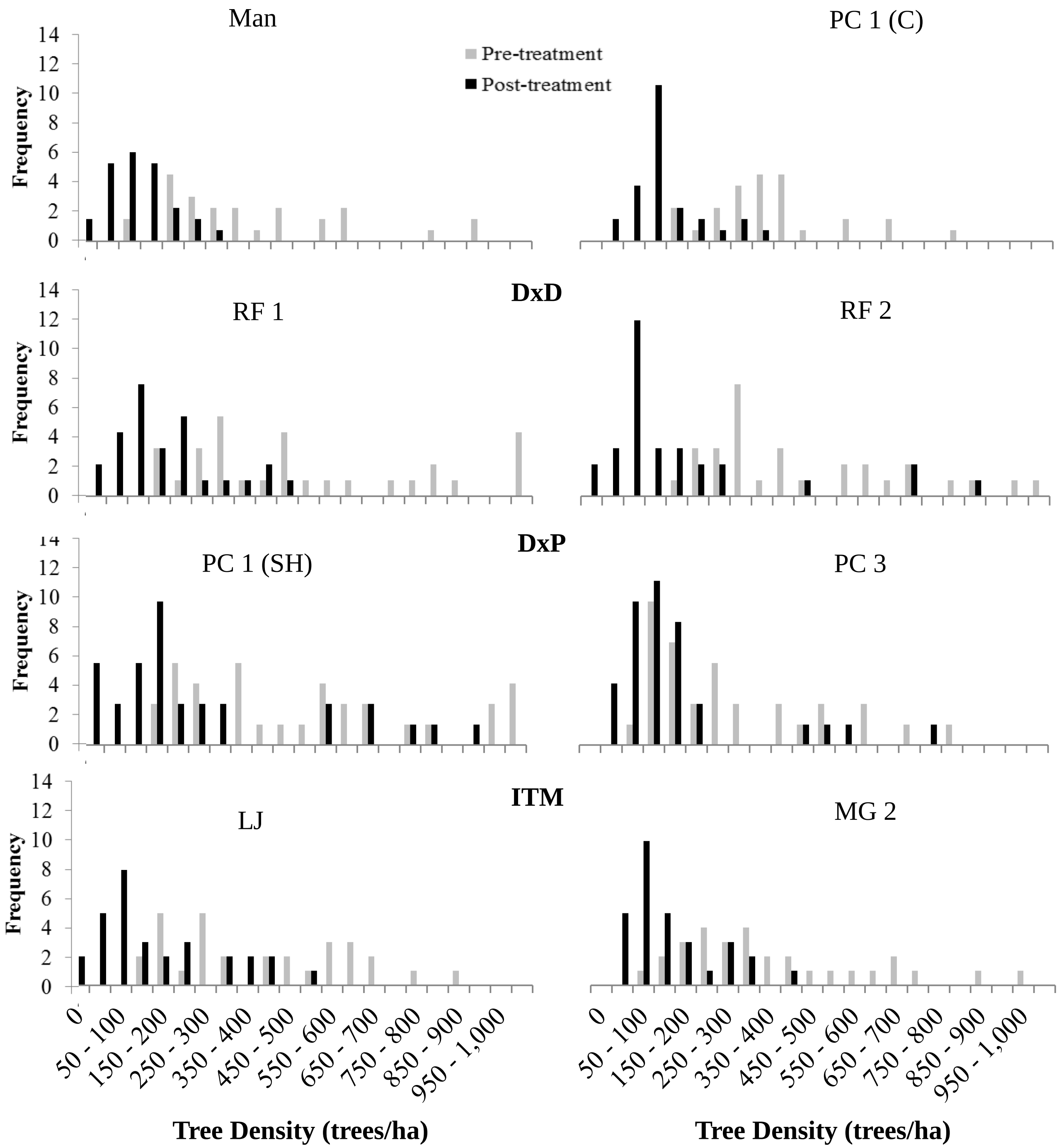
Man
PC 1 (C)
Pre-treatment
Post-treatment
DxD
RF 1
RF 2
DxP
PC 1 (SH)
PC 3
ITM
LJ
MG 2
Frequency
Tree Density (trees/ha)
0
50 - 100
150 - 200
250 - 300
350 - 400
450 - 500
550 - 600
650 - 700
750 - 800
850 - 900
950 - 1,000

Figure 8. Histogram of tree density measurements pre- and post-treatment created from plot measurements at each site.

The coefficients of variation for basal area before treatment differed among all marking methods ($p<0.10$) except between DxD and ITM. After treatment, the coefficients of variation for basal area by plot were significantly different among all marking methods ($p<0.10$). The difference from the post-treatment to the pre-treatment coefficients of variation differed significantly between: control and DxD ($p=0.015$), control and ITM ($p=0.07$), DxD and DxP ($p=0.015$), ITM and DxP ($p=0.07$). The coefficients of variation before treatment ranged from 0.15 to 0.41. This range increased to 0.31 to 0.66 after treatment (Figure 9 and 10).

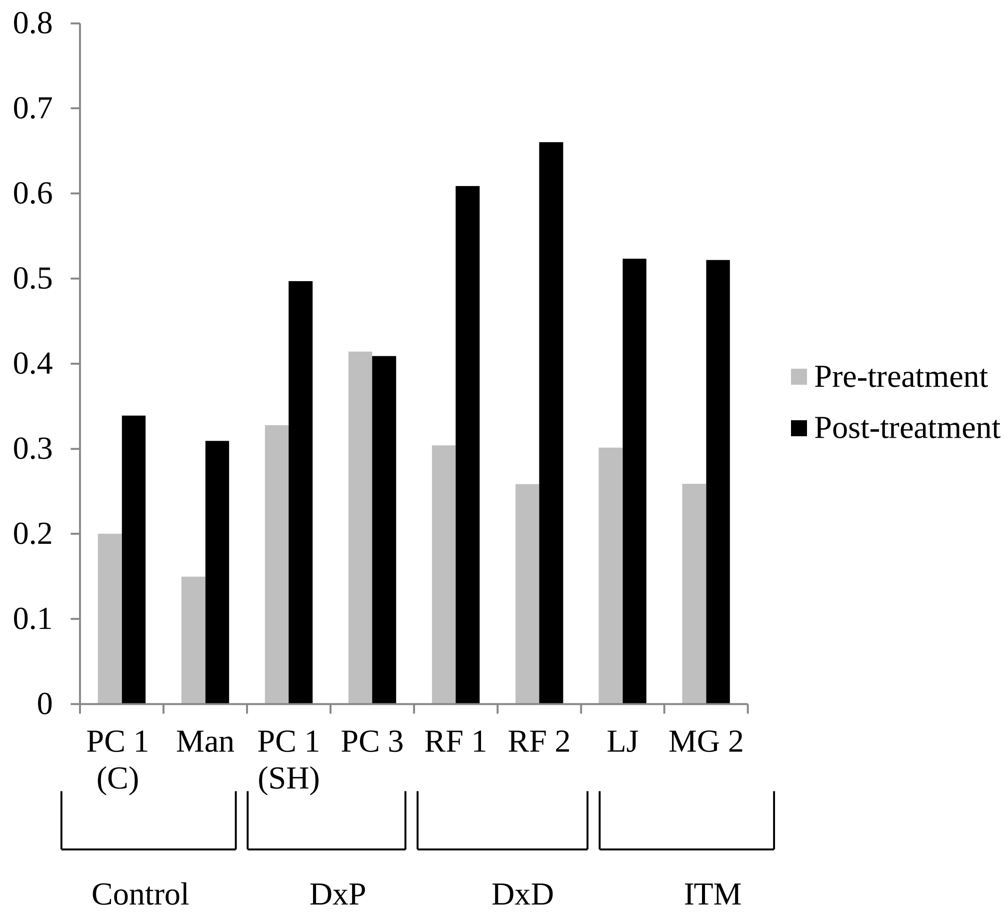

Figure 9. Coefficients of variation among basal areas by plot for each of the study sites. All pre-treatment marking methods differed signficantly except between DxD and ITM. All marking methods differed post-treatment. DxD and ITM had the largest increase in variation

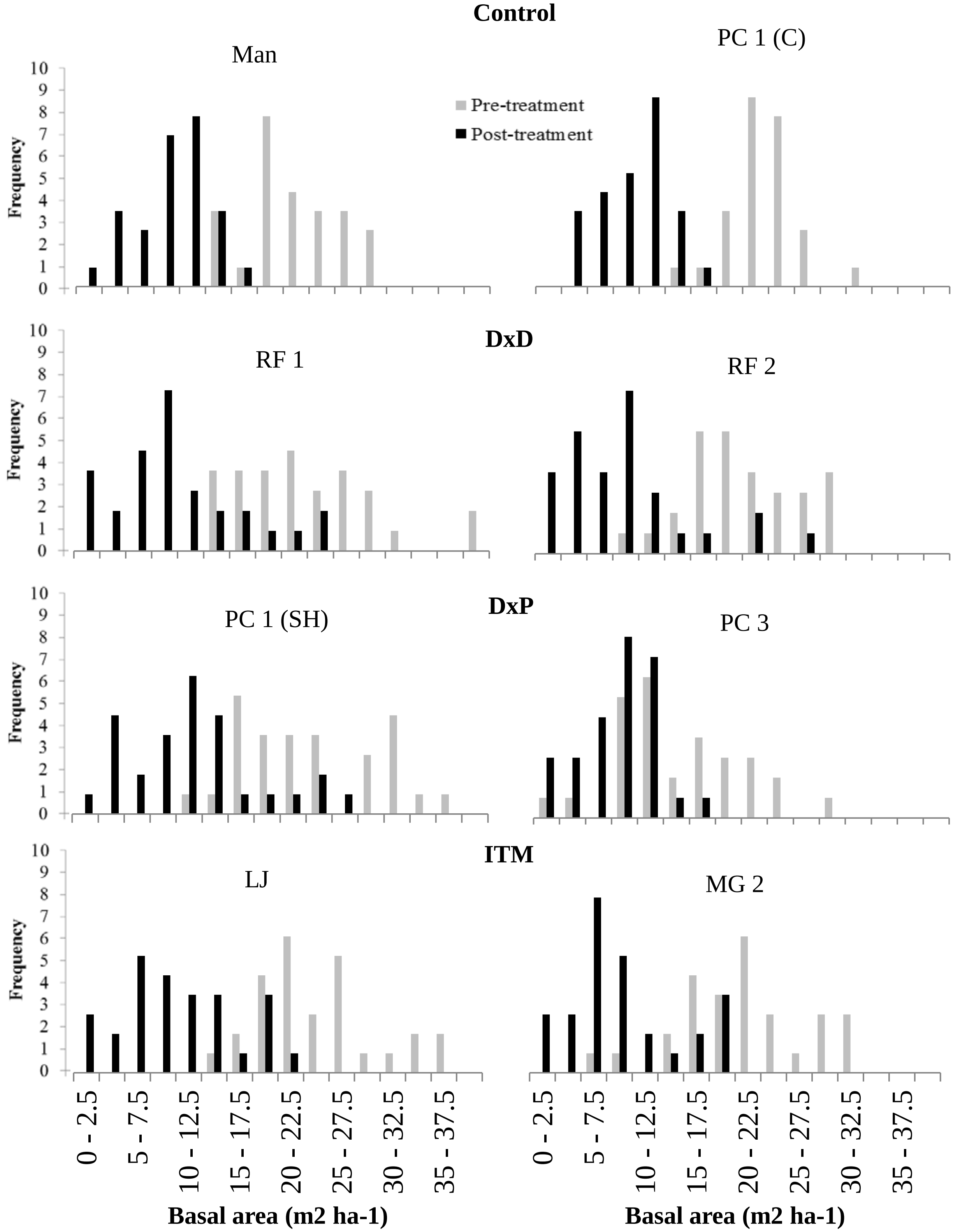

Figure 10. Histogram of basal area measurements pre- and post-treatment created from plot measurements for each site.

Prior to treatment, Pielou's index of nonrandomness indicated that all sites had aggregated spatial patterns. These sites did not significantly differ from one another (Figure 11, p=0.581). In contrast, the post-treatment values indicated that all sites had regular spatial patterns. The post-treatment index values for the control sites were significantly less than both the DxP (p=0.048) and ITM (p=0.079) marking methods. The pre-treatment values for Pielou's index of non-randomness ranged from 1.6 to 3.9 Post-treatment these values ranged from 0.2 to 0.6.

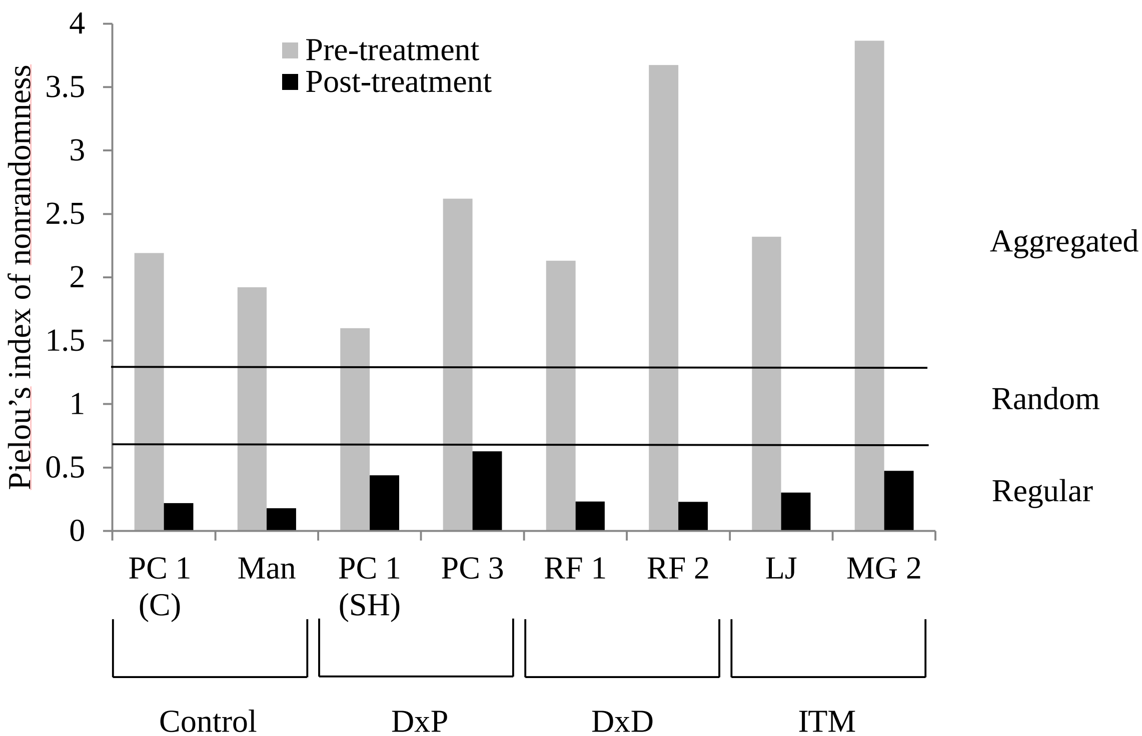

Figure 11. Pielou's index of non-randomness among sites. The right hand classifications represent the 95 % confidence interval (0.675-1.388) for a random spatial pattern. All pre-treatment marking methods had indices above the confidence interval for a random pattern,

which indicates aggregation. All post-treatment methods fell below the interval, indicating a regular pattern.

3.2 Qualitative results

1. Stakeholder analysis: conflicts and tradeoffs

The study design was utilized to identify conflicts and tradeoffs that occur among stakeholder groups for the various marking methods. Common themes were identified and analyzed among marking methods to identify how the marking methods differ among the stakeholders (Table 2). Overall, there are tradeoffs and conflicts that occur among all of the marking methods for each stakeholder.

Table 2. Main conclusions from the stakeholder analysis among marking methods. Main themes were identified from this table to further analyze with axial coding.

	DxP	DxD	ITM
Silviculturist	+ Treat more area - Lower expectations of end result - No monitoring between marking and tratment - Uncertainty in final structure	+ Treat more area +/- More certainty in end product - No monitoring between marking and tratment - Diameter and spacing limitations	+ Higher expectations for tree selection + Highest certainty in end product + Monitoring between marking and cutting - Longer timeframe for contract completion - Treat less area
Sales Preparation	+ Less work + Lower cost + Less time	+ Less work + Lower cost + Less time	- More work - Higher cost - Added paint cost - More time
Sales Administration	- More frequent site inspections - Higher cost - More time	- More frequent site inspections - Higher cost - More time	+ Less frequent site inspections + Lower cost + Less time
Contractor	- Limited visibility for tree selection - Tree selection is time consuming - Slower productivity - Uncomfortable creating openings	+ Selection based on tree condition creates shorter tree selection time - Limited visibility for tree selection - Slower productivity - Uncomfortable creating openings	+ No uncertainty in tree selection + Maximum productivity + Openings already created

One main theme that was consistent among stakeholders was that with the addition of restoration objectives that specify heterogeneous structures, the duty of tree selection becomes more complex. This complexity is illustrated below:

> "With going from your standard prescription, the thin from below, our objectives for these have always been fuels. Until more recently when we started getting into restoration. And so you're trying to capture multiple objectives, and the more objectives you have with any prescription, the more complex it's going to be."
>
> –Sales preparation

2. Tree selection complexity

Looking further into the theme of tree selection complexity, two main components were found to dictate the complexity: opening requirements and the structure of the stand before treatment. When selecting trees to create openings, it can be difficult to decide where to select the opening. This quote exemplifies the difficulty that sales administrators have during DxP and DxD marking methods with selecting an area for an opening:

> "For me to put anything larger than about an acre cutting on the contractor gets a little scary. If I give him the authority to cut anything larger than an acre today, I don't know what I'll find the next day. I might come out there and he's like, there ya go, I decided to take this whole 20 acre hillside…What?! That's not quite what I was looking for."
>
> – Sales administration

Opening selection can be either aided or hindered by the horizontal structure of the stand before treatment. This quote illustrates that stands that are spatially heterogeneous before treatment make tree selection easier to increase spatial heterogeneity:

> "Ya know there are some stands that actually lend themselves to clumpiness. Messenger Gulch, Well that was kind of clumpy by nature. So when you have a stand like that, it's easier. Something that's already clumpy, is going to be much

> easier for the logger, 'Oh okay so I just go pick out these trees in between here and I'm good to go'."
>
> –Sales administration

3. Tree selection tradeoff

The duty of tree selection falls on different stakeholders depending on the marking method being used. In ITM treatments, the responsibility of tree selection falls on the sales preparation employees who physically mark trees to be either cut or left. The sales administration employees are only responsible for ensuring the marked trees are cut for ITM treatments. On the other hand, in DxP and DxD treatments, the responsibility of tree selection falls on the sales administrators and contractors, while the sales preparation employees do not have the responsibility of selecting cut or leave trees. This shift in responsibilities is displayed in Figure 12 with the size of the rectangle being related to the amount of work being carried out for the marking method.

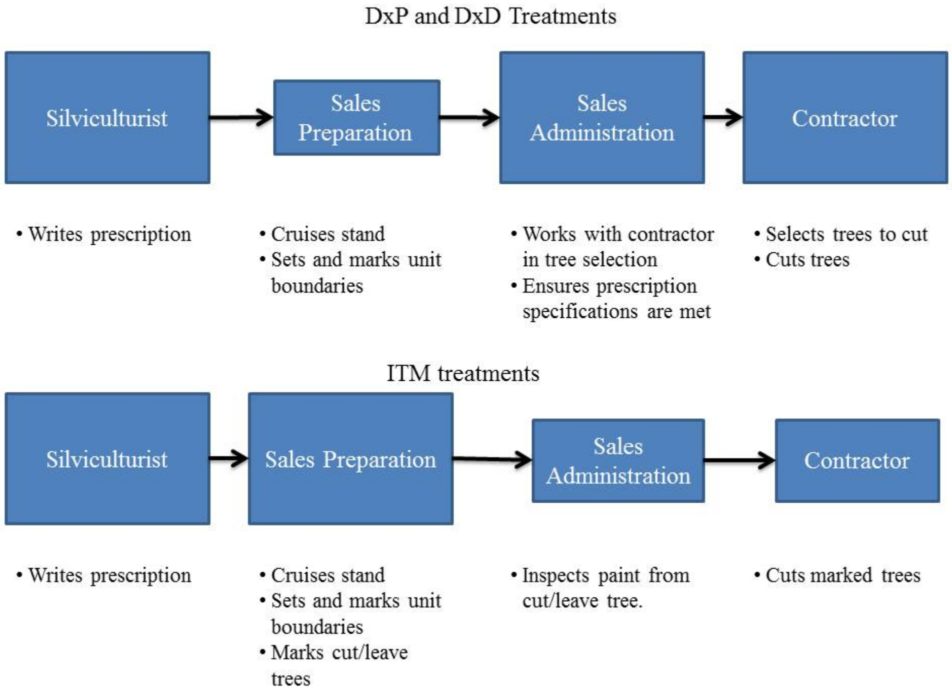

Figure 12. Stakeholder responsibilities among marking methods. The size of the rectangle relates to the amount of effort required for the marking method. DxP and DxD are grouped into the same flow diagram because the stakeholder responsibilities are similar to eachother.

Chapter 4: Discussion

4.1 All marking methods result in greater spatial heterogeneity than the traditional fuels treatments

Stand average values for basal area and tree density were analyzed to compare site densities before treatment, after treatment and to detect any differences in removal densities. The results indicated that all sites and treatments are similar in density and removal, however the change in horizontal structure is different among the marking methods and the control (traditional fuels treatments).

When analyzing the horizontal structure, the marking method that created the most heterogeneity depended on the metric being analyzed. This can be explained by the scale at which each metric quantifies heterogeneity. The scale at which heterogeneity is measured influences the degree of heterogeneity that is detected. For example, if a measurement quantifies heterogeneity within an area of 1,000 hectares, another measurement quantifying heterogeneity of a 100 hectare unit may classify the horizontal structure differently.

The coefficients of variation for both tree density and basal area were looking at the variation that occurred from plot to plot within the 25 hectare sample area. This created a more coarse scale compared to Pielou’s index of non-randomness, which is a nearest neighbor measurement. Pielou’s scale is smaller than both of the coefficient of variation scales. This metric measures heterogeneity of smaller opening and groups compared to the other metrics that quantify the heterogeneity of larger openings and groups.

Although the tree density and basal area analyses both measured heterogeneity at the same scale, these analyses indicated that different marking methods created more heterogeneity. The coefficients of variation of tree density indicated that DxD and DxP created the largest amount of post-treatment variation. However, the coefficients of variation of basal area indicated that DxD and ITM created the largest amount of variation in treatments. This difference can be explained by the differences in the range of values that occur between tree density and basal area measurements. Since the tree density calculation results in a larger range of values than the basal area calculation, the coefficient of variation of tree density results in larger values. These larger coefficients mean that heterogeneity is detected with less variation compared to the basal area coefficients which have a smaller range and take more variation on the landscape to detect heterogeneity.

When moving down to the finer scale, Pielou's index indicated that all sites were aggregated pre-treatment and shifted to a regular pattern post-treatment. This shift behaves opposite of the tree density variation and the basal area variation shifts. This can be explained by the scale at which the index measures spatial structure. This index is calculated from both the average distance and average density. Using average measurements can create bias when looking at large areas. For this index, the scale of the area should be taken into account. At this scale, these treatments are failing to achieve a more heterogeneous structure post-treatment. It should also be noted that DxP and ITM had significantly larger post-treatment values compared to the control which indicates that these marking methods are closer to being classified as a random spatial structure.

In conclusion, the quantitative results indicate that all three marking methods are capable of creating spatial heterogeneity depending on the scale of the measurement. As such, forest managers should keep all three marking methods as an option depending on the scale that they are looking to create spatial heterogeneity. If heterogeneity is desired on a moderate to larger scale, DxD and ITM methods created the largest degree of heterogeneity. On the other hand, if heterogeneity is desired at a smaller scale, DxD and DxP methods created the largest degree of heterogeneity. When choosing a marking method, managers should clearly define the scale at which they are trying to achieve heterogeneity at, and also indicate the monitoring method by which they plan to measure it by. The efficiency of the implementation should also be considered when choosing a marking method.

4.2 Marking method selection criteria

When selecting a marking method, it is important to define criteria to select the most efficient marking method. Since conflicts and tradeoffs exist among all marking methods, selection should be carefully considered. Main tradeoffs that should be considered when selecting a marking method include the experience level of the stakeholders involved, marking vs designation, tree selection complexity, and DxP vs DxD.

Experience of stakeholders

All stakeholder groups recognized that experience influences the efficiency of the marking methods when creating heterogeneous structures. This efficiency is crucial for the stakeholders responsible for tree selection. Referring back to Figure 13, the responsibility of selecting trees to create heterogeneity shifts from sales preparation in ITM treatments to sales administration and contractors in DxP and DxD treatments. The following quotes display how experience affects sales preparation employees in spatially heterogeneous ITM treatments and how experience affects sales administrators and contractors in spatially heterogeneous DxP treatments:

> "You need to see the end product and it takes a lot of experience and time and good people around you to actually be able to do that. It took me a long time to be honest with you. But you go out and do it and see the diversity in the open pockets and the final product."
>
> –Sales preparation
>
> "another downfall of the dxp is both contractor turnover and forest service personnel turnover. It is not something, in my opinion, that you can just go out and readily train an individual on, throw them in the woods, they go do it. I think you need someone who has been there for a while, been on a lot of different landscapes throughout the forest and has a better feel for end results."
>
> –Sales administration

Since experience affects all stakeholder groups, the experience level of the stakeholders involved with tree selection should be considered when deciding on a marking method. Therefore, using ITM is inappropriate where sales preparation staff lack experience with heterogeneous restoration treatments. Furhtermore, it would be inappropriate to use DxP or DxD where the sales administrators and contractors are inexperienced.

Marking vs. Designation

The tradeoff of whether to physically mark trees or to designate desirable outcomes in the prescription (e.g. DxP, DxD) should be considered carefully. When deciding on which type of marking method to implement, it should be recalled that the process of marking trees in ITM treatments creates an extra step in the process. The tradeoff that occurs when skipping this step and using designation is that tree selection can create confusion and decreases productivity for the sales administrators and contractors. This quote from a sales preparation employee illustrates this.

> "if you don't have to go out there and physically mark trees, there's a benefit to preparation time. So less cost for preparation. On the converse side of that, it puts more of a burden on administration and operations. But certainly, just strictly benefits. Umm ya just don't have to visit every tree."
>
> –Sales preparation

From the silviculturists perspective, using ITM allows for inspection of the marking before treatment occurs. This allows the silviculturist to monitor the marking to ensure that the horizontal structure that has been marked for treatment is what the silviculturist had in mind. This sales administrator exemplifies that marking is more likely to result in a desired structure.

> "So far, in my opinion, marking is the only way to assure that we're going to get what we want out there on the ground, as of today, with the way the stands are. Marking is the only way to really get what we want, so far."
>
> –Sales administration

DxP vs. DxD

If designation is decided to be the preferred option, some consideration should be given whether to use DxP or DxD. DxD is only an option when the use of attributes that are verifiable post-treatment will result in the desired horizontal structure. An example of this would be a stand that was previously attacked by the mountain pine beetle (*Dendroctonus ponderosae*). The beetles select host trees that are within proximity of their previous host tree which creates groups of dead trees (Logan et al. 1998). The verifiable attribute post-treatment would be the stump having remnants of blue stain. This sales preparation employee exemplifies the ease of this in the field.

> "The other thing that's a little different for us, is our mountain pine beetle epidemic. Our openings are really keyed to where the mortality is. And so it

> makes it simple to do a DxD for your openings because you just say cut out the dead, there's your opening and so everything else is either a leave clump or thinning. And so that kind of makes it simpler for us to do the dxd in that aspect. In areas where we don't have that, ya know I think it would be a little more difficult on how we would do that."
>
> –Sales preparation

Hybrid marking methods

Although DxD seems to be limited to certain situations, if individual tree marking were to be used in conjunction with DxD, spatial heterogeneity could still be achieved. An example of this that could result in a spatially heterogeneous structure would be thin all trees under a certain stem diameter class, and then mark the trees above those diameter classes to create the groups and openings desired.

A DxP hybrid could be used when larger openings are desired in the post-treatment structure. This quote from a silviculturist exemplifies how this hybrid could be utilized when larger openings are desired.

> "In general, I think the operators have been able to continue to be uncomfortable with locating clear cuts on their own, or patch cuts, or large groups. Just because of the potential for controversy, and I'm glad that they're responding that way. I think the forest service has responsibility to do the delineation and the designation and having ownership of that. So yeah, I think a hybrid is ultimately where we're going to end up."
>
> -Silviculturist

Future research directions

Additional research could build on these findings by exploring the efficiency of each of the marking methods. It was clear from the qualitative analysis that the efficiency of each marking method differed for each of the stakeholders. A work-time study could be utilized to gain a better understanding of how the finances breakdown between the USFS and the contractors among the marking methods.

Conclusion

Outcomes of horizontal structure measurements were found to be sensitive to the scale at which the metric was taken at. Our data showed that all three marking methods were able to create more heterogeneity than traditional fuels treatments. With this, it is important to consider other factors in marking method selection that contribute to the outcome of restoration treatments. These factors include the scale at which heterogeneity is desired, the experience of the stakeholders involved, whether monitoring is necessary for a desired structure, and what will be the most efficient way to implement treatment. Forest managers should consider these factors when choosing a marking method.

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Appendix 1

Interview Questions

Foresters

What aspects (i.e. spacing, species preference, residual BA, residual diameter classes, etc.) do you focus on when writing a designation by prescription/designation by description prescription for forest restoration (groupy/clumpy treatments)?

What is your opinion on the final structure of designation by prescription/designation by description restoration treatments (groupy/clumpy)?

Have you modified designation by prescription/designation by description restoration treatment descriptions based on past treatment results? If so, how?

What do you view as the major benefits from using cut tree/leave tree marking protocols over other marking methods?

What do you view as the major constraints of using cut tree/leave tree marking protocols over other marking methods?

What do you view as the major benefits from using designation by prescription/designation by description marking protocols over other marking methods?

What do you view as the major constraints of using designation by prescription/designation by description marking protocols over other marking methods?

How does writing the prescription for spatially heterogeneous (aka "groupy-clumpy") restoration treatments differ from writing prescriptions for traditional hazardous fuels mitigation treatments?

Do you have a preference as to which type of treatment you would rather be involved with?

Tree Markers

What methods do you use to select trees for spatially heterogeneous (aka "groupy-clumpy") restoration prescriptions?

Is there a difference between marking cut tree and leave tree treatments in terms of efficiency?

Do you think that the efficiency and effectiveness of marking spatially heterogeneous (aka "groupy-clumpy") restoration treatments has improved over time, with more experience?

How does tree marking the spatially heterogeneous (aka "groupy-clumpy") prescription differ from marking more uniform prescriptions like hazard fuels reductions?

Do you have a preference as to which prescription, restoration or fuels treatment, you would rather mark?

Sales Administration

How do the different types of marking (designation by description, designation by prescription, cut tree marking, and leave tree marking) affect administering the sales contract?

Do the different marking protocols affect monitoring compliance with the contracts, and the outcomes? If so, how?

How does administering sales contracts for spatially heterogeneous (aka "groupy-clumpy") restoration prescriptions differ from sales contracts involving more uniform prescriptions?

Do you have a preference as to which prescription you would rather be involved with?

Contractors

How long does it normally take you/your crew to get an understanding of the desired forest structure in designation by prescription/description treatments? What do you find most difficult about interpreting the descriptions/prescriptions?

Do you think that the efficiently and effectiveness of marking spatially heterogeneous (aka "groupy-clumpy") restoration treatments has improved over time, with more experience? Does this differ between the marking methods (designation by description, designation by prescription, cut tree marking and leave tree marking)?

What parts of the designation by prescription/description prescription help facilitate the efficiency of the treatment?

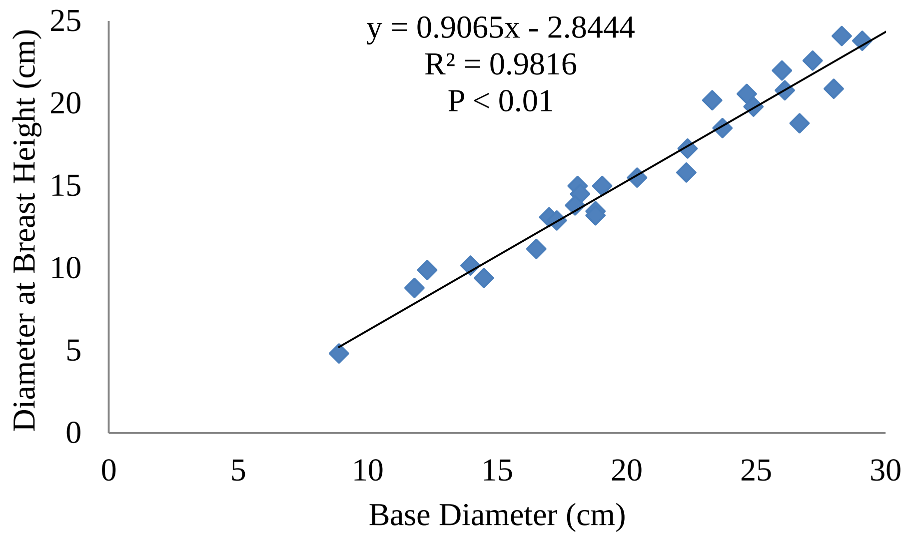
What parts of the designation by prescription/description prescription detract from the efficiency of the treatment?

How does interaction with the USFS sales administration team facilitate or hinder the efficiency or effectiveness of spatially heterogeneous (aka "groupy-clumpy") treatments?

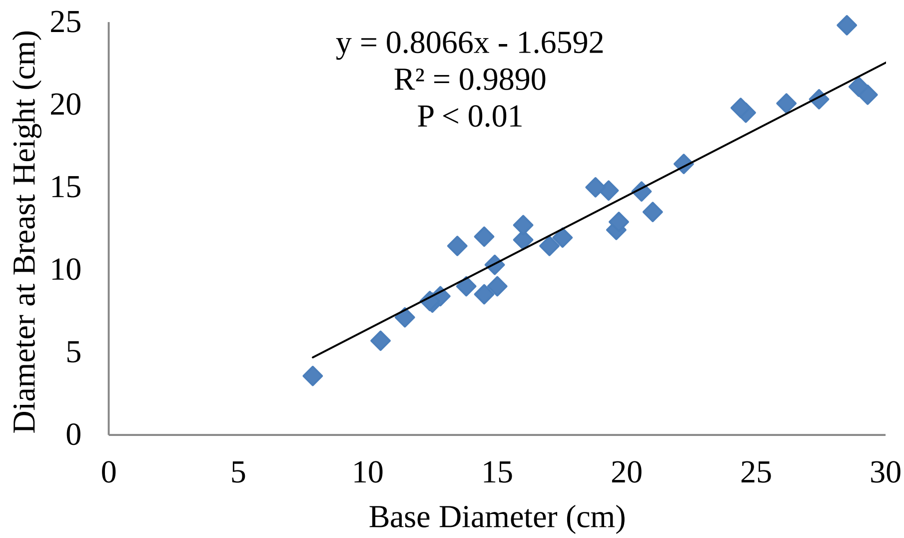
How does cutting trees for spatially heterogeneous (aka "groupy-clumpy") restoration treatments differ from cutting trees in traditional hazardous fuels reduction treatments?

Do you have a preference as to which prescription you would rather be involved with?

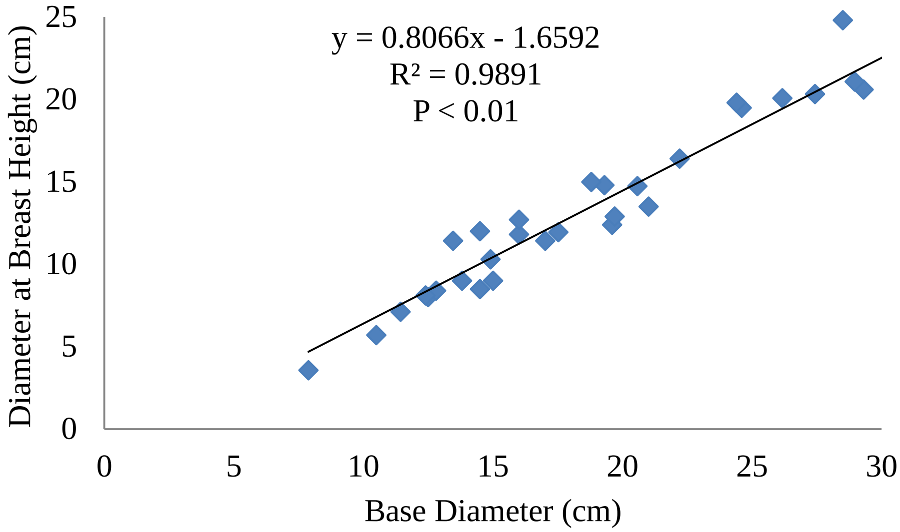
Appendix 2



Ponderosa



Douglas-fir


y = 0.8066x - 1.6592
R² = 0.9891
P < 0.01
Diameter at Breast Height (cm)
25
20
15
10
5
0
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10
15
20
25
30
Base Diameter (cm)

Blue spruce