Using LiDAR to Inform Silvicultural Restoration in the Crater Lake Panhandle

Final Report to National Park Service
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1. Introduction

Management of fire-adapted forests on public lands across the western United States is focused on restoration of resilience in areas that have been fire-suppressed, cut and replanted, or otherwise degraded (North et al. 2009). Typically restoration work is done through a combination of mechanical treatment and prescribed fire (Stephens et al. 2013, North et al. 2009, Stephens & Ruth 2005). Planning for restoration treatments has largely been guided by ground-based resource inventory; however, there is considerable interest in and action toward using remote sensing tools to supplement field data: this is beneficial both for defraying the high cost of field work as well as for enabling larger-scale analyses that can provide landscape context (Kane et al. 2013, 2014).

Airborne LiDAR has emerged as a key remote sensing technology (Wulder et al. 2008, Reutebuch et al. 2005) that has started to see usage in forest landscape restoration (Kane et al. 2014, Churchill et al. *in prep*). In forestry, LiDAR was initially used primarily for inventory (Parker & Evans 2009, Means et al. 2000, Næsset 1997) but it was quickly realized that the expansive high-resolution structural measurements could also be used to answer ecological questions (Kane et al. 2011, Falkowski et al. 2009, Martinuzzi et al. 2009, Hyde et al. 2005). Ecological restoration brings together forestry – inventory, silviculture, operations, and economics – with forest ecology – understanding the relationships between plant communities, wildlife, microbiota, and abiotic factors. Since each of these sub-fields of LiDAR research is relatively new, their synthesis is decidedly nascent.

In this case study we pilot the use of LiDAR for informing the silvicultural aspects of ecological forest restoration at the scale of individual treatment units. In order to work at this relatively fine scale (<100 ac; <40 ha) we process the LiDAR data using individual tree detection. This process analyzes the geometry of the LiDAR point cloud and picks out individual tree crowns. However, since many tree crowns – especially smaller trees – are hidden from aerial view by the dominant canopy layer, we consider the detected trees to be tree-approximate objects (TAOs) (Jeronimo et al. *in review*). TAOs are dominated by a single tree that was well-illuminated by the LiDAR instrument, but may also encompass a few subordinate trees that cannot be individually delineated.

We expect that using LiDAR will provide several benefits that would not otherwise be possible. Complete coverage of LiDAR data allows for an excellent overall view of stand structural conditions at a higher level of detail than is possible with only ground-based data collection. This coverage can help elucidate landscape contexts and enable understanding of the varying patterns of different conditions within and between stands. LiDAR also makes it possible to visualize simulated treatments in a spatially explicit way, so that multiple approaches can be virtually experimented with before settling on a final strategy.

The purpose of this report is to use TAOs as a basis for assigning treatment prescriptions to restoration units. We use TAOs to identify "backbone trees," representing large and old trees within the area that will serve as biological anchors for the treatment. We then look at the clumping and opening patterns of the backbone trees, along with the density of forest cover in smaller trees, to determine general treatment guidelines in terms of density and clumping pattern targets for each unit. Finally, we suggest additional fieldwork that would be required to complement the LiDAR data and develop a final prescription.

2. Methods

2.1 Study area

We carried out this study in the Annie Creek Extension (commonly known as the "Panhandle") of Crater Lake National Park (CRLA) (Figure 1). When the Panhandle was added to CRLA in 1932, one goal was to protect its old-growth mixed-conifer forests, which had been disappearing on neighboring lands. Since that time the forests of the Panhandle have been excluded from fire and have correspondingly become overly dense and laden with fuels. Under CRLA's Fire Management Plan (2012) and Resource Management Plan (1999), restoration is a high priority in the park, and the Panhandle's fire-adapted ecosystem is specifically targeted for restoration.

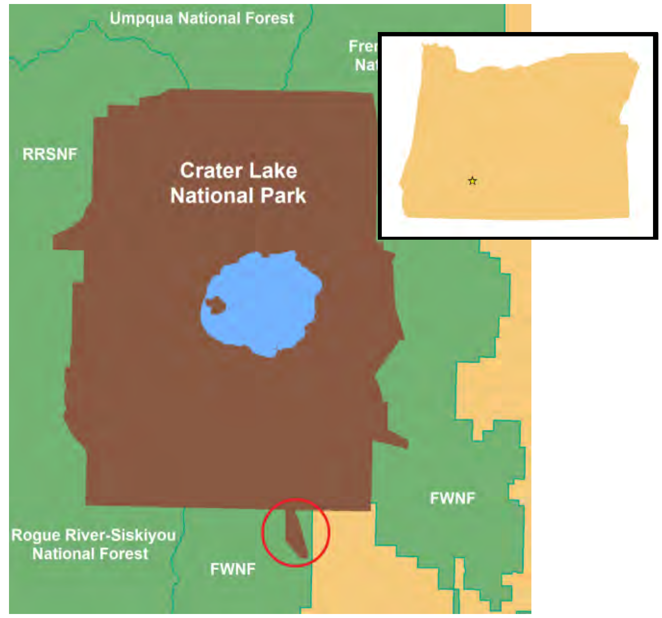


Figure 1 Crater Lake National Park, with Annie Creek Extension ("Panhandle") circled in red and location in Oregon inset.

Specific restoration objectives in the Panhandle are to improve survivorship of old, shade-intolerant trees, reduce the risk of high-severity fire, increase structural diversity, and promote regeneration of shade-intolerant, fire-tolerant conifer such as ponderosa pine (PNW Cooperative Agreement 2014).

The Panhandle lies at 4330-4820 ft (1320-1470 m) elevation and is bisected by Annie Creek, which runs north-south. The area experiences a warm-summer Mediterranean climate. During the 2001-2010 normal period, summer high temperatures were 77 F (25 C), winter lows were 22 F (-5 C), and 32.2 in. (818 mm) of precipitation fell annually, 26.2 in. (665 mm) of which fell as snow. There is a long dry period during the summer months, during which there is typically less than 2 in. (50 mm) of precipitation (ClimateWNA 2016). The soils of the Panhandle are primarily volcanic, formed of pumice and ash flows from Mt. Mazama (NRCS 2016).

2.2 LiDAR acquisition

LiDAR data were acquired on August 23-September 5, 2010 by Watershed Sciences, Inc. of Corvallis, Oregon. Data were acquired using a combination of Leica ALS60 sensors and dual-mounted Leica ALS50 Phase II sensors. These systems were flown at 2953 ft (900 m) and 4265 ft (1300 m) above ground level with scan angles of ±14° and ±13°, respectively. Both instruments were able to record up to 4 returns per pulse with pulse rates >83 kHz. Flight lines were flown with >50% sidelap yielding an average pulse density of 0.78 ft^{-2} (8.39 m^{-2}). Return location accuracy was 0.15 ft (0.05 m) RMSE. The vendor created a bare-earth ground model using TerraScan and TerraModeler software (TerraSolid Oy, Helsinki, Finland).

2.3 LiDAR data processing

LiDAR data were processed using FUSION LTK (McGaughey 2016) to create the canopy height model and delineate tree-approximate objects and using R version 3.3.2 (R Core Team 2016) to analyze tree height distributions and clumping and opening patterns.

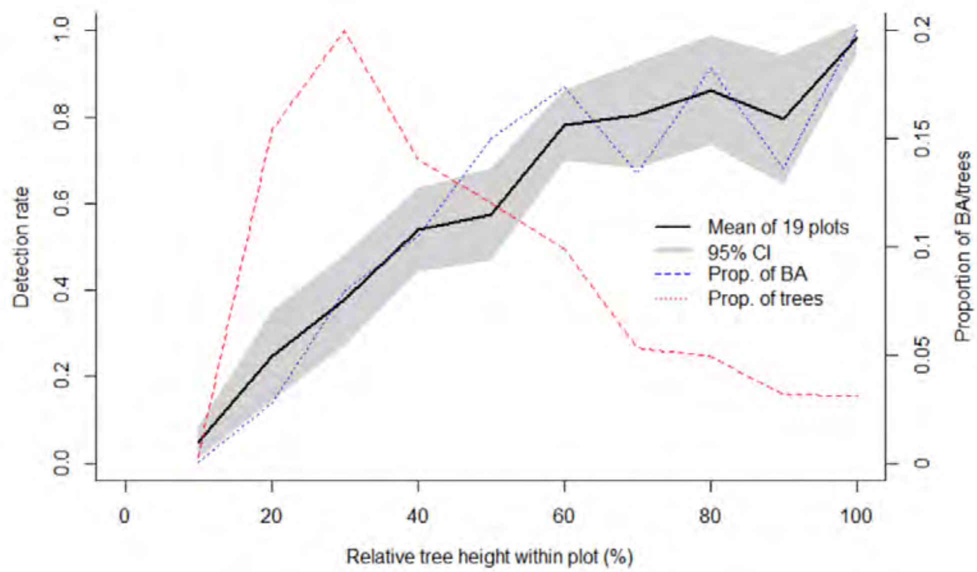


Figure 2 Accuracy of LiDAR individual tree detection by relative height. The tallest trees at any given site are much more likely to be detected than the shorter trees. Trees taller than 60% of the local maximum height have an 80% or better chance of detection. Since the larger number of trees is small, it is difficult to accurately measure overall density using individual tree detection. However, since the majority of basal area is in the larger trees this metric can be measured well.

2.3.1 Canopy height model

A canopy height model (CHM) is a 3-dimensional representation of the forest canopy surface with respect to the ground. A CHM was created for the Panhandle using the LiDAR point cloud normalized by the vendor-delivered ground model. The CHM was created as a 2.46 ft (0.75 m) resolution raster in which each cell took on the *z*-value of the highest LiDAR return in that cell. The CHM was smoothed with a 3×3 mean filter to remove noise.

2.3.2 Tree-approximate objects

Individual tree crowns were detected using the FUSION TreeSeg tool, an implementation of the watershed transform (Vincent & Soille 1991). Detected trees were taken to be tree-approximate objects (TAOs), or small groups of one or more trees including at least one canopy dominant (Jeronimo et al., *in review*). Each TAO was assigned a georeferenced *xy*-location and a height corresponding to the highest LiDAR return in the TAO's crown.

Jeronimo et al. (*in review*) examined the patterns of accuracy in LiDAR individual tree detection and concluded that most canopy dominant trees – that is, those with direct visibility from the sky – are correctly identified, while most subdominant trees are not. In particular, trees taller than 60% of the local maximum height were usually detected (Figure 2). This indicates that using TAOs to describe patterns of larger trees, or to summarize stand metrics driven by larger trees, should have good accuracy.

2.3.3 Backbone trees

Legacy trees, that is, old trees that established before significant impacts of Euro-American settlement, are typically the backbone of restoration prescriptions (Franklin et al. 2013, Agee & Skinner 2005). We set out to identify legacy trees by searching for the tallest TAOs within the LiDAR footprint. However, because of infilling by fast-growing species such as white fir (Merschel et al. 2014, Dolph et al. 1995) and because some old trees are small (Van Pelt 2008), a height cutoff is insufficient to truly identify legacy trees. Therefore, we instead focused on "backbone trees." Backbone trees represent the largest trees, which should comprise the majority of the old trees along with a few of the largest younger trees. Backbone trees will generally be retained in a restoration treatment; however, some of the younger shade-tolerant backbone trees may be removed to mitigate crown fire risks. Conversely, some small old trees that do not qualify as backbone trees will certainly be retained.

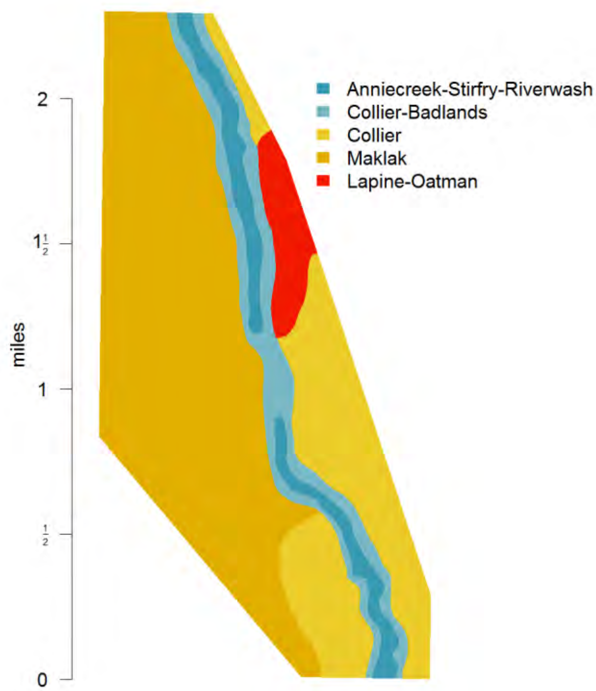


Figure 3 Soil units in the Crater Lake Panhandle (NRCS 2016).

To identify backbone TAOs we first divided the Panhandle by soil type (Figure 3), since at fine scales soil characteristics determine maximum tree height (Carmean 1968). Then we calculated the 80th percentile TAO height for each soil type and selected trees taller than that threshold to be backbone TAOs.

2.3.4 Tree clumping

We used the point pattern of the *xy*-locations associated with each TAO to determine clumping patterns across the Panhandle. Each TAO was assigned membership in a clump based on a 20 ft (6 m) limiting distance, as in Churchill et al. (2013). TAOs with no neighbors within 20 ft were considered to be individual trees. Following Churchill et al. (2013) clumps were binned into size classes: small (2-4 TAOs), medium (5-9 TAOs), large (10-14 TAOs), and super (15-30 TAOs).

2.3.5 Open space

We quantified the distribution of intertree space, that is, all open space between canopies including both large openings and small, snaky corridors. Following Churchill et al. (2013) and Lydersen et al. (2013), we used the empty space function *F(t)*. The *F(t)* transform lays a grid over the analysis area – we used a 2.46 ft (0.75 m) grid to match our CHM and other raster products – and calculates the distance from each grid cell to the nearest tree. In our case, we used TAO high points in lieu of tree positions. The distribution of these distance values gives a measure of the amount of open space in different positions in relation to the canopy. We classified the *F(t)* values into 9.84 ft (3 m) bins up to a distance of 80 ft (24 m).

2.4 Regressions

In order to translate stand structural conditions measured from TAOs into a form that would be usable for silviculturists, we estimated diameter at breast height (DBH) and basal area (BA) for the dominant member of each TAO. We created height-diameter equations based on compiled plot data from 133 Forest Service Forest Inventory and Analysis plots nearby CRLA (FIA 2016). We derived the following equation ($r^2 = 0.81$, $p < 0.0001$, $n = 4585$):

$$DBH = 0.2676 \times Height - 2.9707, \qquad \text{(Eq. 1)}$$

where DBH is diameter at breast height in inches and $Height$ is total tree height in feet (Figure 4).

Using this height-diameter relationship we predicted DBH for each TAO. It is important to note that the TAOs do not represent all trees in the stand: many smaller trees are hidden by the canopies of larger trees (Jeronimo et al., *in review*). However, since the backbone trees comprise the largest individuals they should be detected with high accuracy, and the DBH distributions for the back-bone trees should reflect the true distributions well.

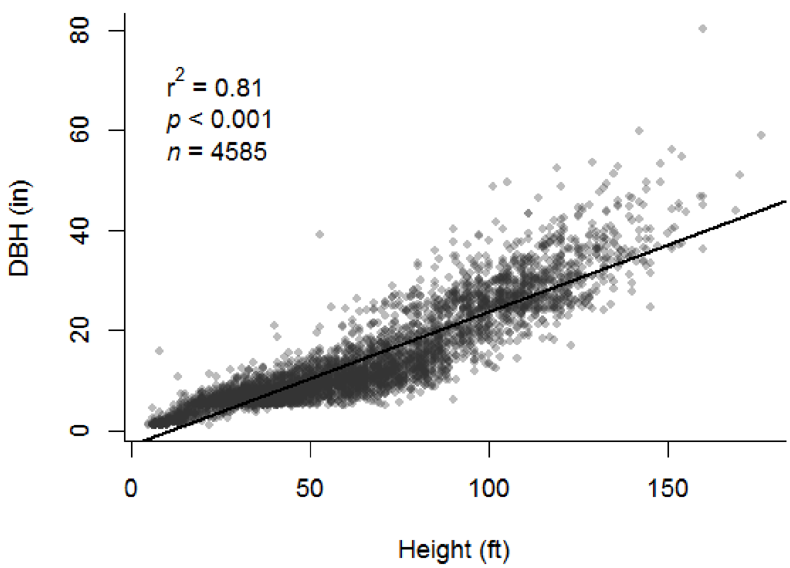


Figure 4 Linear regression relationship between height and diameter for 133 Forest Inventory and Analysis plots surrounding Crater Lake National Park (FIA 2016), including all conifer species.

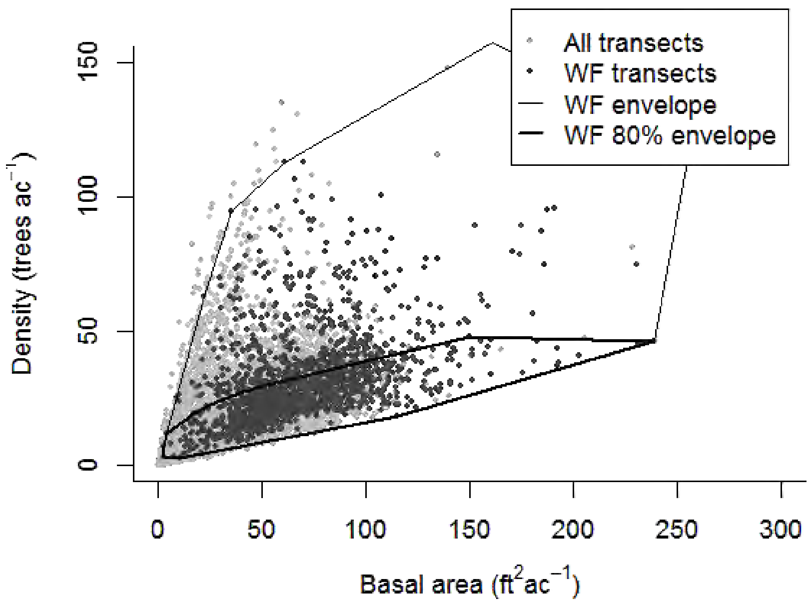


Figure 5 Reference conditions from 1920's survey of former Klamath Indian Reservation (Hagmann et al. 2013). Light gray points (All transects) represent conditions for all cruise transects. Dark gray points (WF transects) represent conditions from cruise transects containing any white fir. Light gray polygon (WF envelope) is the convex hull of the WF transects, representing the range of stocking conditions present on the historical landscape. Dark gray polygon (WF 80% envelope) is the convex hull of the 80% of the WF transects with the least residual deviance from the mean, representing the core historical envelope where most of the transects existed.

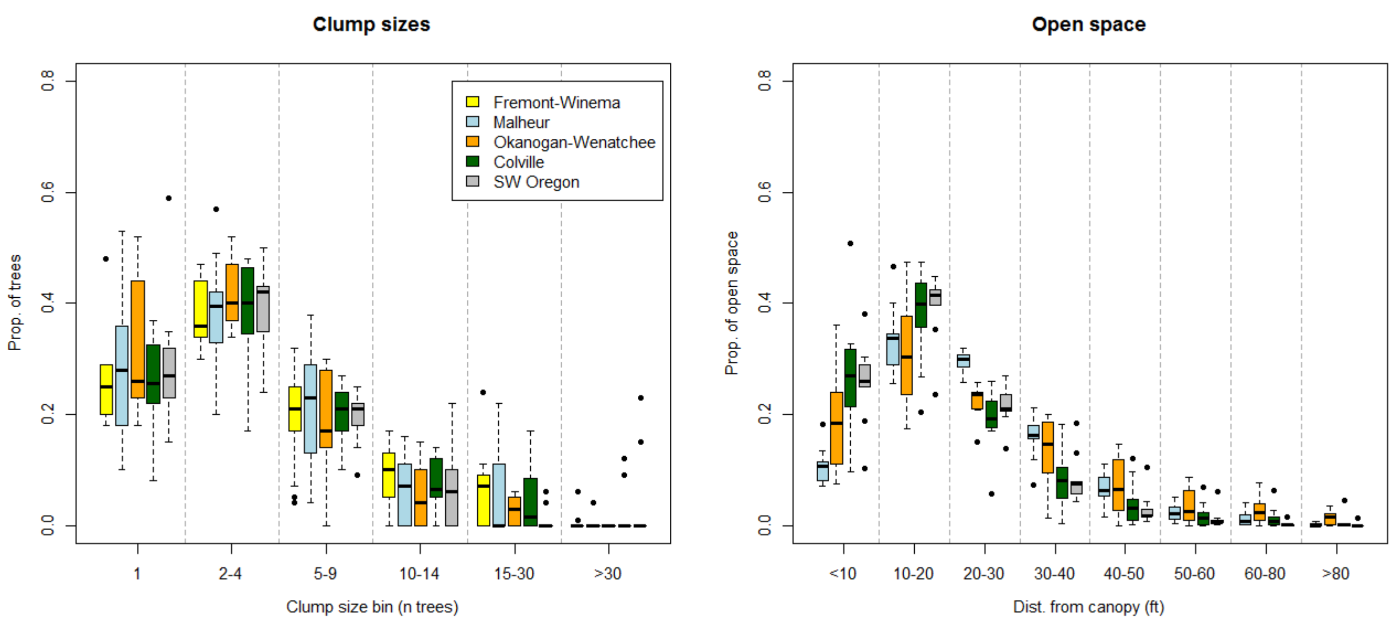


Figure 6 Reference conditions for pattern from 57 stem map plots reconstructed to the 1890's (Churchill et al., *in press*). Names in legend refer to national forests where reconstruction took place; an envelope is presented for each sampled forest. Left panel gives conditions for pattern in terms of proportions of trees in clumps of different sizes. Right panel gives conditions for open space in terms of proportion of area at various distances from the nearest tree. See Churchill et al. (2013) for interpretation details.

2.5 Reference conditions

In order to develop ecologically appropriate targets for the restoration treatments we looked to two reference datasets describing historical conditions in similar forests in the region. First, we looked at historical ranges in density (trees per acre, TPA) and basal area (BA) using timber cruise transect data from the 1920s on the former Klamath Indian Reservation (Hagmann et al. 2013). We selected cruise transects from that dataset where white fir was present, since white fir is the climax shade-tolerant species in the Panhandle forests. We plotted TPA versus BA and took the convex hull of this scatterplot to represent the historical envelope of stocking. We then took the convex hull of the subset of the 80% of transects with the smallest residual deviance from the mean to represent the core historical envelope (Figure 5). The overall envelope delineated the realm of historical conditions while the core envelope delineated the most common conditions.

Using a second set of reference conditions, we looked at historical spatial pattern using data from reconstructed stem map plots across the dry forests of central and eastern Oregon and Washington (Churchill et al., *in press*). These data are divided into sets representing several National Forests: the Colville, Okanogan-Wenatchee, Malheur, Fremont-Winema, and Rogue-Siskiyou. We visualized the historical range of spatial patterns on each of these forests by producing box plots showing proportion of trees in each clump size and opening class for each forest (Figure 6). We interpreted the historical envelopes in light of our knowledge about the biophysical environment of the different national forests relative to that of the Panhandle.

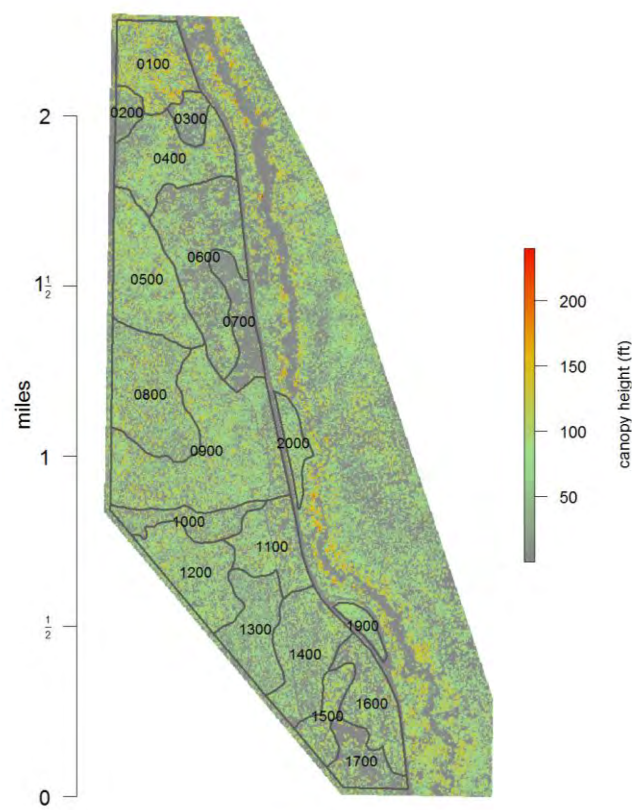


Figure 7 Treatment unit numbers and locations superimposed on a canopy height model.

2.6 Prescription recommendation development

We defined prescription recommendations on the basis of polygonal units, which were previously delineated using photo interpretation and supplied by the National Park Service (NPS) (Figure 7). Because goals for this restoration project included preserving old trees all prescriptions called for complete retention of legacy structures, and since legacy structures were present throughout the project area all treatments options were necessarily partial cuts. With the goal of increasing structural diversity, a spacing-based treatment would not have been sufficient (Churchill et al. 2013). Therefore treatment options were categorized as either (1) radial release (RR), where all most or all trees within twice the dripline distance of legacy structures are removed, or (2) variable density thin (VDT), where trees are thinned generally from below and stocking targets vary throughout the treatment unit. We also looked for opportunities to leave untreated “skip” areas and create large openings within the units to increase spatial heterogeneity and provide habitat favorable for the regeneration of fire-tolerant pines (Franklin et al. 2013).

We developed prescription recommendations from the starting point of leaving all backbone trees and removing all other trees. Supposing this canonical treatment, we calculated residual density (trees per acre, TPA), basal area (BA), clump size distribution in terms of the proportion of clumps in each size class (individual, small, medium, large, and super), and the open space distribution in terms of the distribution of $F(t)$ values in 9.8 ft (3 m) bins. We overlaid these data on the reference condition plots to visualize if and how the restoration units were departed from historical conditions. The prescription recommendation for non-backbone trees was then developed by calculating the additional TPA to retain and the target pattern for retention in order to move each unit toward or within the reference envelope. The particular values for TPA and clump targets were chosen not just to satisfy reference condition goal but also to be realistic given the current conditions in the stand and to encourage landscape-level variability.

Along with the quantitative recommendations for stocking and clumping, we also developed qualitative recommendations for openings and non-commercial treatment. We classified TAOs into three classes using a merchantability cutoff of 9 in. DBH: backbone trees, merchantable non-backbone trees, and non-merchantable trees. We mapped these trees and visually interpreted the patterns, looking for opportunities to create large openings and, in some cases, recommend pre-commercial thinning (PCT).

3. Results

3.2 Backbone trees

Height cutoffs for backbone trees were relatively consistent across soil types, except that riparian areas along Annie Creek had higher thresholds than non-riparian (Table 1). To validate these thresholds, we compared the 113 ft (34 m) cutoff used over the majority of the area to distributions of tree height by age class using plot data from Sierra Nevada mixed-conifer forests (Jeronimo et

Table 1 Soil characteristics, including height threshold used for determining backbone TAOs. AWC = available water content in the first 6 ft of the soil. Data from NRCS (2016).

Soil unit	Acres	Prop. Area	Landform	Parent material	AWC (in)	Backbone cutoff (ft)
Anniecreek-Stirfry-Riverwash	69	0.07	Stream terrace	Pumice and ash	7.2	136
Collier-Badlands	111	0.11	Ashflow	Ash and cinders	7.1	141
Collier	244	0.23	Ashflow	Ash and cinders	7.1	114
Maklak	566	0.54	Ashflow	Pumice and ash	6.2	113
Lapine-Oatman	49	0.05	Ashflow	Ash and pumice	6.2	114

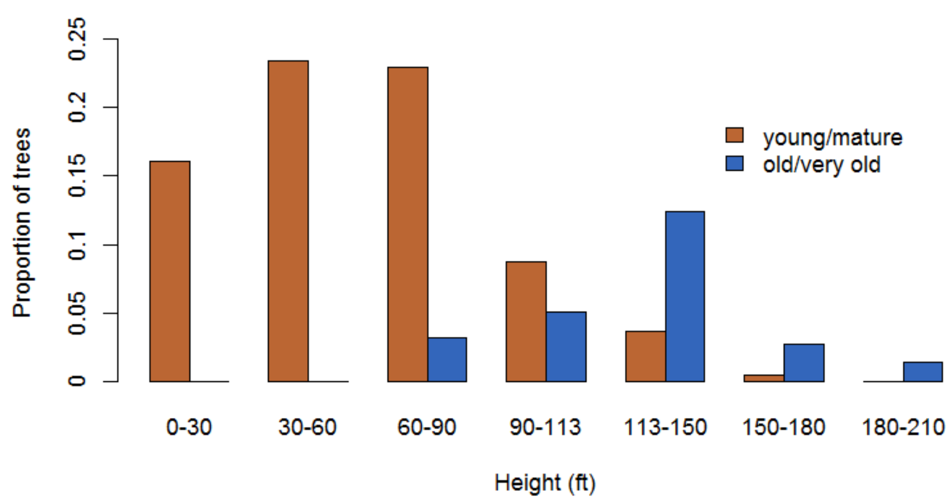


Figure 8 Distributions of tree heights by age class in a Sierra Nevada mixed-conifer forest. Young/mature refers to trees younger than 150, old/very old refers to trees older than 150. The 113 ft cutoff proposed in this study captures 66% of the old trees and 6% of the young trees in this distribution. Data from Jeronimo et al. (*in review*).

al., *in review*). Though in a different geographic area, this dataset sampled forests supporting similar species composition. These trees were measured for height and classified by age, including classes young (<80 yr), mature (80-150 yr), old (150-250 yr), and very old (>250 yr). These data support the 113 ft cutoff, suggesting that 94.5% of young and mature trees are less than 113 ft in height, while 66.7% of old and very old trees are greater than or equal to 113 ft in height (Figure 8).

3.1 Tree-approximate object metrics

TAO heights ranged from 6.56 ft (2 m) to 204.6 ft (62.4 m). Corresponding predicted DBHs ranged from 0.5 in. to 51.8 in. (1.3 to 131.6 cm). For backbone TAOs, predicted DBHs ranged from 27.4 in. to 51.8 in. (69.6 to 131.6 cm).

Because of LiDAR's difficulty with delineating small trees, we calculated unit-wise TPA for backbone TAOs separately from non-backbone TAOs, and we calculated BA only for backbone TAOs. We have high confidence in the backbone TAO metrics and lower confidence in the non-backbone TAO metrics. The non-backbone TAO metrics can still be instructive; however, they must be interpreted with care. Backbone TAO density ranged from 5.9 TPA (14.6 trees ha^{-1}) on unit 1300 to 32.5 TPA (80.3 trees ha^{-1}) on unit 0100. The range of backbone BA was 29.7 to 243.6 ft^2 ac^{-1} (6.8 to 55.9 m^2 ha^{-1}), again on units 1300 and 0100 respectively. Non-backbone TAO density ranged from 27.9 TPA (68.9 trees ha^{-1}) on unit 0100 to 90.1 (222.5 trees ha^{-1}) on unit 1300.

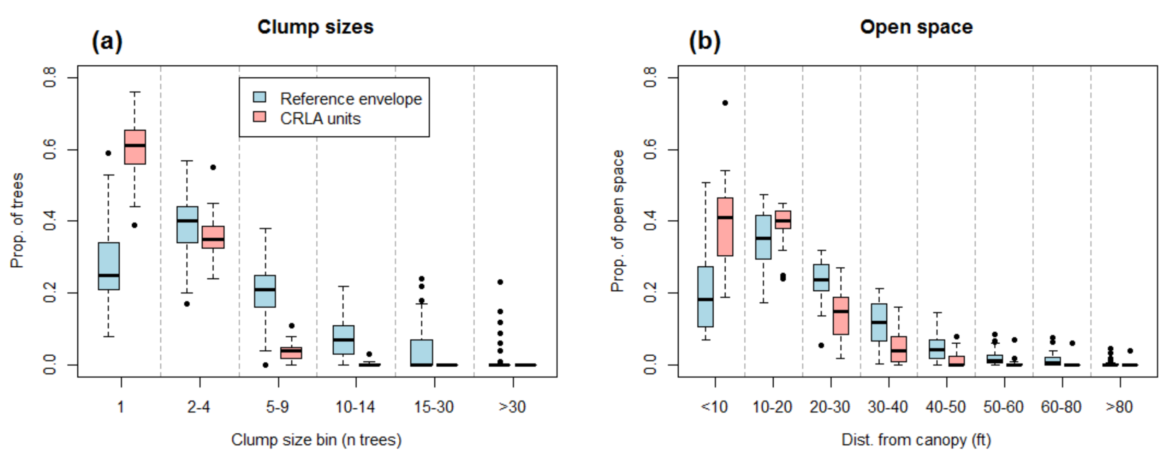


Figure 9 Comparison between spatial pattern reference envelope (pooled distribution of all 57 reconstruction plots, see Figure 6) and distribution of patterns on CRLA units supposing a canonical treatment in which all backbone trees are retained and all others are removed. Under this treatment, CRLA units would have many more individuals and many fewer medium and large clumps, along with more area in small intertree spaces and less area in large openings.

Table 1 Attributes of treatment units, including TAO metrics. Last 5 columns give proportions of backbone TAOs in different clump sizes under the canonical treatment retaining all backbone trees and removing all others. There were no super clumps under this treatment.

Unit	Acres	Backbone TPA	Backbone BA (ft^2ac^{-1})	Backbone QMD (in)	Non-back-bone TPA	Non-back-bone % mer-chantable	Prop. in-dividual	Prop. small (2-4)	Prop. medium (5-9)	Prop. large (10-14)	Prop super (15-30)
100	32.5	32.5	243.6	37.1	27.9	64	0.44	0.45	0.11	0.01	0
200	6.2	13.7	94.4	35.6	57	33.2	0.59	0.41	0	0	0
300	8.5	10.1	61.1	33.4	59	44.7	0.39	0.55	0.05	0.01	0
400	41.4	18.6	112.4	33.3	55.7	82.6	0.57	0.36	0.07	0	0
500	43.1	19.6	118.5	33.3	58.7	86.7	0.55	0.4	0.03	0.01	0
600	58.9	11.1	66.9	33.3	63.7	61.9	0.69	0.27	0.04	0	0
700	18.5	6.6	38.1	32.5	87.9	20.5	0.66	0.32	0.02	0	0
800	49.4	14.4	87.5	33.3	65	78.2	0.65	0.33	0.02	0	0
900	93	16.2	96.2	33	61.4	85.6	0.61	0.37	0.02	0	0
1000	17.8	13.9	82.5	32.9	71.8	76.4	0.61	0.34	0.05	0	0
1100	27.4	15.1	85.9	32.3	55.7	82	0.68	0.31	0.01	0	0
1200	33.6	15.5	86.4	32	68	89.3	0.63	0.33	0.04	0	0
1300	28.2	5.9	29.7	30.4	90.1	92.7	0.61	0.35	0.04	0	0
1400	38.3	10.7	57.1	31.3	62.3	78.8	0.55	0.37	0.05	0.03	0
1500	13.6	22	124.9	32.3	36.9	69.1	0.45	0.44	0.08	0.03	0
1600	27.8	11.8	66.1	32.1	41	82.5	0.62	0.34	0.05	0	0
1700	18.5	10.1	59.7	32.9	31.5	68.2	0.6	0.37	0.03	0	0
1900	5.8	6.6	38.6	32.8	60.9	94.6	0.76	0.24	0	0	0
2000	9.8	11	71.5	34.5	61.1	93.5	0.7	0.29	0.01	0	0

Of the non-backbone trees, between 20.5% and 94.6% were predicted to be of merchantable size (≥9 in. [22.9 cm] DBH), with ≥70% merchantability on 63% of the units (Table 2).

3.2 Clump-opening patterns

Under the canonical treatment (retain all backbone trees, remove all else), clumping patterns showed a majority of TAOs as individuals and members of small clumps, with less than 4% of TAOs as members of medium and large clumps (Figure 9a). At the unit scale, 39-76% of TAOs were individuals, 24-55% of TAOs were in small clumps, 0-11% of TAOs were in medium clumps, 0-3% of TAOs were in large clumps, and no TAOs were in super clumps (>30). Averaged over all units, 60% of TAOs were individuals, 36% were in small clumps, 3.8% were in medium clumps, and <1% were in large clumps. Compared to the reference distributions the average values were outside of the envelope: there were more individuals and fewer medium, large, and super clumps after the canonical treatment than on the reference sites (Figure 9a).

Under the same treatment, opening patterns showed a majority (78%) of the area as being less than 20 ft (6 m) from a TAO point. On average, 15% of the area was between 20 and 30 ft (6-9 m) away from a TAO point and just 7% of the area was farther than 30 ft (9 m). In 14 of 19 units more than 90% of the area was less than 30 ft (9 m) away from a TAO point. Compared to the reference distributions the average values were higher in the first class (0-10 ft [0-3 m]), lower in the third class (20-30 ft [6-9 m]), and slightly lower in all classes larger than 30 ft (9 m) (Figure 9b). There was somewhat less open space suitable for early-seral habitat and pine regeneration after the canonical treatment than on the reference sites.

3.3 Prescriptions

We did not prescribe any RR treatments. We found that RR typically either resulted in (1) patterns that were more evenly spaced than anything appearing in the reference envelope or (2)

Table 3 Density and clumping level targets for treatment units. Non-backbone retain TPA is the number of additional trees to be retained after accounting for backbone trees. For clumping level definitions see Table 4.

Unit	Target TPA	Non-backbone retain TPA	Clumping level
0100	40	7.5	Hi
0200	20	6.3	Low
0300	12	1.9	Low
0400	25	6.4	Med
0500	24	4.4	Med
0600	19	7.9	Low
0700	25	18.4	Low
0800	28	13.6	Med
0900	27	10.8	Hi
1000	25	11.1	Med
1100	22	6.9	Low
1200	25	9.5	Med
1300	18	12.1	Low
1400	23	12.3	Low
1500	35	13.0	Hi
1600	20	8.2	Low
1700	14	3.9	Low
1900	12	5.4	Low
2000	18	7.0	Med

Table 4 Clumping level targets defined using the reference clumping envelope (Figure 6). Each cell gives the target proportion of trees in clumps of the size given by the column for the clumping level given by the row.

	1	2-4	5-9	10-14	15-30
Low	0.35	0.45	0.18	0.02	0
Medium	0.27	0.38	0.25	0.1	0
High	0.2	0.35	0.22	0.15	0.08

densities that were much higher than anything appearing the reference envelope. In most units it was necessary to prescribe retention of backbone trees in clumps with non-backbone trees to meet the clumping targets. Units where this was not the case had low stocks of backbone trees and very high stocks of non-backbone trees, and so would have remained overly dense without a matrix thinning. Therefore, all units were prescribed VDT treatments.

The treatment guidelines start with retaining and releasing all backbone trees, then retaining an appropriate number of TPA to move the unit within or reasonably near the stocking reference envelope. Target densities ranged from 12-40 TPA (30-99 trees ha^{-1}) (Table 3). Based on the pattern reference envelope, we defined low, medium, and high clumping level targets (Table 4) and assigned a clumping level to each unit (Table 3). Of the 19 units 10 were given low clumping targets, 6 were given medium clumping targets, and 3 were given high clumping targets. Clumping targets were then translated to per-acre numbers of clumps to add in each bin, for example, one prescription called for adding 2 small clumps per acre and 1 medium clump per 2 acres (Appendix A).

For openings two kinds of guidelines were given: general guidelines on where the opportunities exist in each unit to create functioning open space and specific guidelines describing the numbers and configurations of openings to create. The general guidelines indicated one of the following: (1) backbone trees are very evenly spaced throughout the unit and there is simply not much opportunity for creating open space, (2) there is some opportunity for creating open space if careful, so leave retention clumps in loosely associated patches rather than scattered throughout the stand, (3) there is adequate space in openings or non-merchantable tree cover, so any implementation of the clumping targets will probably achieve open space targets, or (4) the unit could be too open after harvest, so be sure to retain clumps in a way that splits excessively large openings to break up sighting distances. In case (2), specific guidelines were given as to how many openings to create of what sizes.

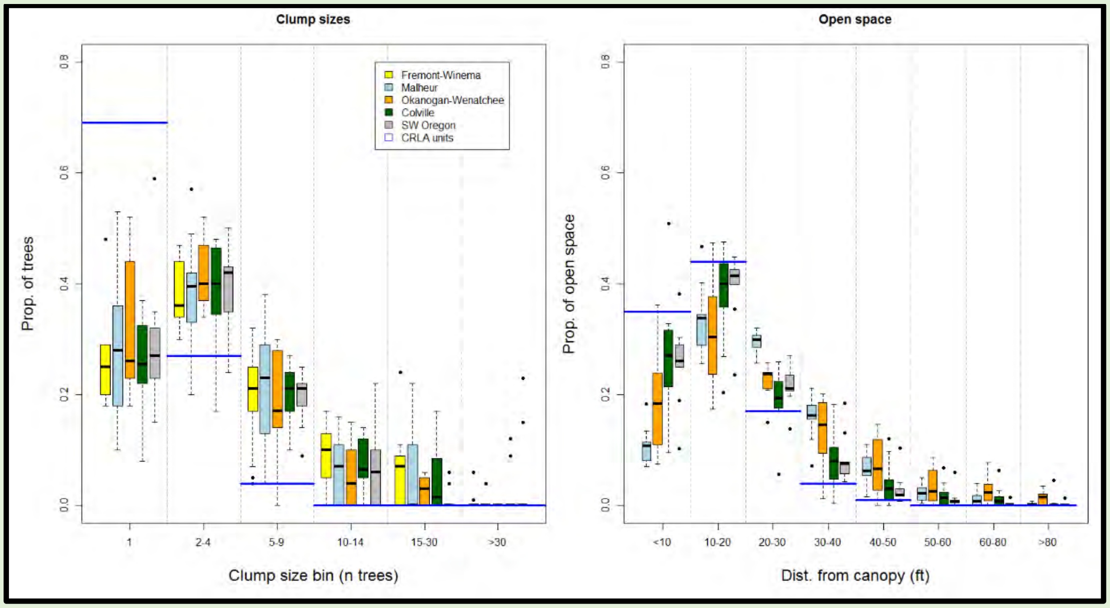
For non-merchantable trees we chose one of three general treatment types depending on the size and amount of openings and non-merchantable patches throughout the unit. (1) In units with small amounts of open space we recommended complete or near-complete removal of non-merchantable trees as a way to maximize the effect of the small openings that were there. (2) In units with abundant open space but small patches of non-merchantable trees we recommended clearing most non-merchantable trees but retaining scattered patches of pine regeneration. (3) In units with abundant open space filled with large patches of non-merchantable trees we recommended a PCT focused on retaining larger pines of good form and vigor. In some units high canopy cover in large trees obscured the mid- and understories so that there was not enough information to make a judgment about non-commercial treatment.

An example prescription recommendation appears in Box 1, a set of simulated treatment visualizations appear in Appendix A, and all prescription recommendations appear in Appendix B.

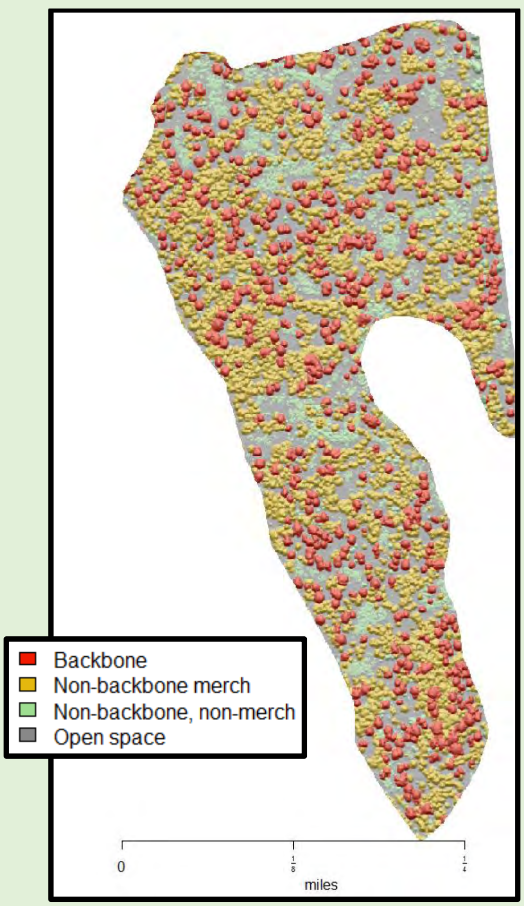
Box 1 Example prescription recommendation and simulated treatments.

Unit 0600

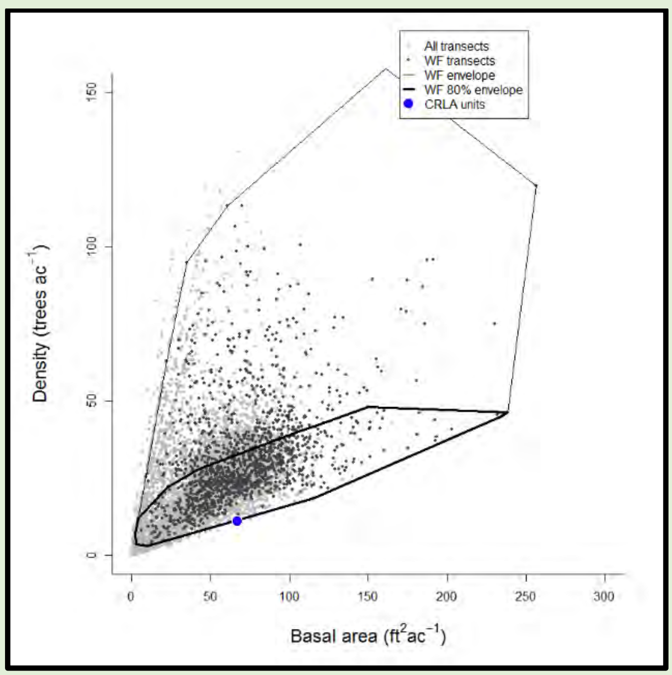
Acres: 58.9
Backbone TPA: 11.1
Backbone BA: 66.9
Non-backbone merch TPA: 39.4
Non-backbone, non-merch TPA: 24.3



Spatial patterns of backbone trees compared to reference conditions



Map of TAOs in unit



Density and basal area of backbone trees plotted on historical envelopes

Box 1, continued

Prescription Recommendations

Target TPA: 19

Justification: At a BA of 70-80, the reference TPA ranges from 18-35. Since this stand has good open space characteristics around the backbone trees we would like to be at the lower end of the density envelope.

Non-backbone retain TPA: 7.9

Justification: Target TPA - Backbone TPA = 7.9

Clumping level: Low

Justification: At the low prescribed density it would be difficult to create a lot of very large clumps.

Clumping targets:

- Bring 2 individuals per acre into small and medium clumps
- Add 1 small clump per acre
- Add 1 medium clump per 2 acres

Justification: These are the numbers of clumps necessary to move from the current clump size distribution to the targeted clumping level at the target TPA. The directive "Bring X individuals per acre into small and medium clumps" refers to leaving non-backbone trees in clumps with backbone trees to make larger clumps. Non-backbone trees can also be used to connect two clumps of backbone trees and make a larger clump. Usually it is best to select larger non-backbone trees with relatively clear lower boles to avoid leaving ladder fuels into backbone tree crowns.

Opening targets:

- Removing most of the non-merchantable trees will provide sufficient open space

Justification: The open space distribution matches the reference conditions well.

Non-commercial treatment: Save scattered pine regen patches, remove all else

Justification: The open space in the unit is arranged in frequent small open patches rather than a few very large patches. In this configuration clearing out most of the non-merchantable trees will help maximize light coming into the openings, while saving scattered advance regen patches will make use of the abundant light.

In Appendix A, the preceding figures and recommendations are made for each unit. Justifications are not given for every unit but the logic for selecting targets follows that given here. ■

4. Discussion

4.1 What is and is not captured with this method

Measurements using LiDAR individual tree detection were able to provide a good deal of insight into the structural conditions of pre- and post-treatment units, including density, basal area, clumping and opening patterns, and some understory conditions. However, there are several remaining points of uncertainty that cannot yet be fully assessed using only LiDAR data. These include the inexact equivalency of backbone trees and legacy trees; incomplete knowledge of trees in subordinate canopy positions; lack of knowledge about species composition; and the omission of data about aspen clones, small wetland areas, and other biological hotspots.

The backbone trees identified in this study were selected with a height threshold that varied by soil type. However, restoration treatments are, in practice, anchored around old trees, not just large trees (Franklin et al. 2013, Franklin & Johnson 2012). Old trees, even when small, provide several desirable characteristics that large young trees do not, including unique and functionally valuable crown structures (Ishii & McDowell 2002), lower sapwood-to-heartwood ratios and correspondingly higher water use efficiency (Moore et al. 2004), lower mortality rates (Larson et al. 2015), higher fire resistance (Taylor 2010), and a higher number of high-quality habitat-providing cavities (Lindenmayer et al. 2012). In light of this, it is always important to distinguish between old trees and large trees; correspondingly, age class characteristics should be included in forest inventory.

The inability to fully characterize subordinate trees and other understory vegetation is a consistent issue in LiDAR application (Richardson & Moskal 2011, Martinuzzi et al. 2009; but see Wing et al. 2012). This issue is more pronounced in areas where high canopy cover in large trees obscures LiDAR's view of understory structure (Falkowski et al. 2008). For the purposes of this study some questions remain open as to the amount of commercial volume that would be removed under various treatments as well as the amount of work that would be necessary to thin or remove non-merchantable trees. This is not a major issue when it comes to defining the desired conditions since those conditions are driven by the larger trees in the stand; however, it is an issue in terms of assessing economic viability of the restoration treatments at both unit and project area scales.

Species composition is an important element of forest restoration that has not been accounted for in this work (Franklin & Johnson 2012). Typically, fire-suppressed mixed-conifer forests have shifted from historical dominance by fire-tolerant pines with some Douglas-fir to contemporary dominance by fire-intolerant young Douglas-fir and true firs (Johnston et al. 2016; Hagmann et al. 2013, 2014; Merschel et al. 2014). Although some work has been done using LiDAR to differentiate species based on crown morphology (Heinzel & Koch 2011; Brandtberg 2007) the results have not been particularly strong and, more importantly, there is a dim prospect of successfully identifying species of trees in subordinate canopy positions using this type of approach.

Lastly, forest restoration typically includes the goal of maintaining unique micro-environments that may occur across a landscape. Examples of these include aspen clones, moist swales supporting different vegetation than the surrounding matrix, rock outcrops and other areas of unique geologic or pedologic significance, and patches of snags or decadent wildlife trees (Franklin et al. 2013). There also may be forest health issues to address, such as pockets of infection by root rots, mistletoe, or insect activity. There is evidence that some of these micro-environments can be detected with LiDAR (Barbosa et al. 2016, Wing et al. 2015), but identifying these locations remains largely outside of the scope of LiDAR analysis.

Filling these data gaps and developing a final prescription would clearly require additional fieldwork. In particular, the actual density and stocking of legacy trees (as compared to backbone trees) should be evaluated to verify the appropriateness of the recommended treatments. Some inventory or cruise data must be gathered to estimate the volume and grade of material to be removed, as well as to ensure that there are enough non-legacy trees of desirable species to meet the prescribed residual density and clumping targets. Each unit should be evaluated to determine specific non-commercial treatments of understory trees and fine fuels and estimate costs associated with these treatments. Lastly, a qualified silviculturist should identify locations for small retention patches focused on different biological hotspots along with areas to focus on improvement of forest health.

4.2 How this method compares to the traditional approach

For forest restoration projects carried out to date, planning activities have been approached using the tools of traditional forestry. This includes delineating stands using aerial photos and ground truth surveys, timber and resource inventories on a grid of plots, a silvicultural assessment based on field surveys, and presale layout. The methods applied in this study augment the traditional approach. Using TAOs to estimate certain attributes of forest structure and spatial pattern, as well as to visualize patterns and potential treatment options, provides an additional level of knowledge before groundwork for a project even begins. The traditional steps of stand delineation, timber inventory, silvicultural assessment, and layout can all be made more efficient and effective using TAOs. For stand delineation, densities and clump/opening patterns of backbone trees can be taken into account along with aerial photos in order to better define units with homogeneous prescriptions. Timber inventory designs can be guided by pre-existing knowledge of forest structure, for example: sampling effort in different stands can be scaled proportionally to structural variability; sampling can potentially be foregone or modified in large patches of pre-forest or non-commercial trees; and specific locations of rare and unique features – which may be missed in a typical gridded inventory – can be identified and visited. As demonstrated in this report, the structural data provided by TAOs can be used to outline much of a prescription for each treatment unit, leaving only a few details to be filled in using ground observations and inventory data. Finally, layout can be approved using TAO maps to pre-identify locations for openings and potentially skips, which can also inform placement of landings and yarding corridors.

Along with supplementing traditional approaches, the methods in this study make a new level of sophistication available to silviculturists and other restoration planners. Since wall-to-wall LiDAR data can provide total coverage of project areas and their surrounding landscapes LiDAR tools can enable analyses that are not otherwise possible. For example, inventory plots are not large enough to capture patterns of tree clumps and openings, since these patterns are structured at a scale of 1-10 acres (Churchill et al. 2013, North et al. 2007). The large footprint of LiDAR data allows for spatially explicit assessment of clump and opening pattern that would not otherwise be feasible.

4.3 Recommendations for use of LiDAR in future projects

In the future, the methods applied in this study could be built upon to improve accuracy of legacy tree detection, incorporate new remote sensing technologies for identifying tree species, and use reference conditions that are more methodologically compatible.

Legacy tree detection could be improved by installing a set of plots relating tree height to tree age to localize the relationship, or by including a tree age or age class estimate in the standard timber inventory. Another improvement could come from using tree height and crown size (which can be measured from TAOs) together in a logistic regression model to predict legacy tree status. This approach would make more complete use of the available TAO measurements.

For species identification, a promising lead is the developing technology of co-acquisition of LiDAR and high-resolution hyperspectral orthophotos. Alonzo et al. (2014) demonstrated using these data to identify the species of individual street trees in Santa Barbara, CA with better than 80% accuracy. Although forest conditions are much more difficult than the urban environment, hyperspectral imaging nevertheless shows promise as the best option for mapping species at the TAO scale.

The reference condition datasets used in this study, while relevant, are not in the best possible format for comparison with LiDAR data. In particular, it would be preferable to compare LiDAR-derived metrics to LiDAR-derived metrics, rather than ground-based metrics. Using the same methods for reference condition definition and departed condition assessment would be a more straightforward and more certain comparison. There is, then, a case for defining reference conditions using LiDAR data collected over contemporarily restored landscapes, such as the Aspen and Illillouette Valleys in Yosemite National Park, CA and the Sugarloaf Valley in Sequoia National Park, CA, where the legacy of fire suppression has begun to be reversed by the reestablishment of frequent, low-intensity fire regimes (Collins et al. 2016, Lydersen et al. 2014, North et al. 2007).

5. Conclusions

Tree-approximate objects derived from LiDAR individual tree detection can be used to assess density, stocking, clumping, and opening patterns in a way that is sufficient to assign restoration prescriptions to treatment units. TAOs provide an excellent means of understanding the largest trees in a stand, which are the biological anchors guiding ecological restoration. This approach can also provide some information about smaller trees, sometimes enough to outline non-commercial treatments. Restoration prescriptions still require ground-based reconnaissance and inventory; however, the speed and efficiency of this fieldwork can be much improved with the foreknowledge that TAO analysis can provide.

LiDAR does not currently provide solutions for mapping every bio-environmental feature of interest, including species composition, small trees, disease pockets, and more; however, these items are the feature of much current research. Embracing LiDAR tools as a part of the silvicultural process will pave the way for more efficient and effective forest restoration.

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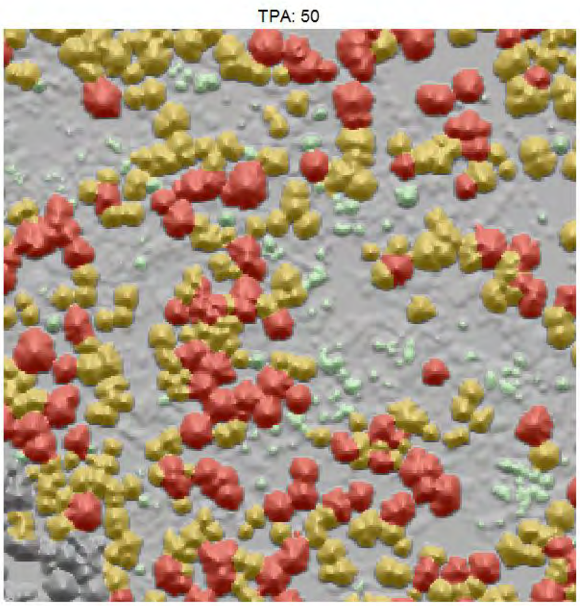
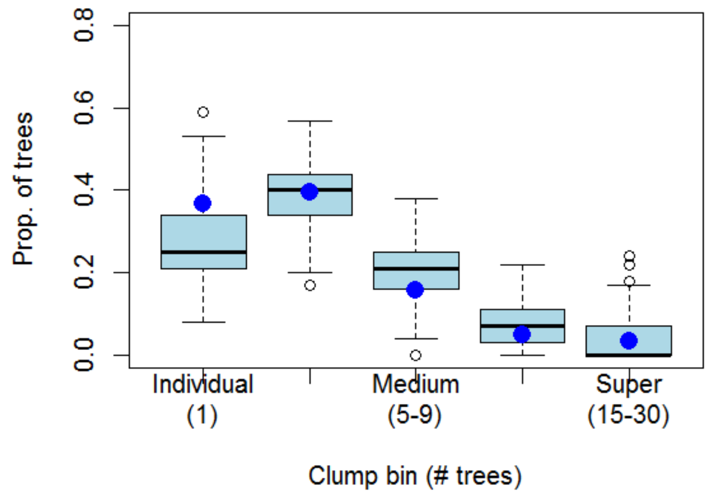
Append A: Treatment visualizations

In this appendix we have prepared a set of graphics showing the results of simulated treatments at different residual densities and clumping targets for three 10 acre areas with different structural characteristics. These visualizations are intended to provide an idea of what some treatment options might look like in order to facilitate prescription writing.

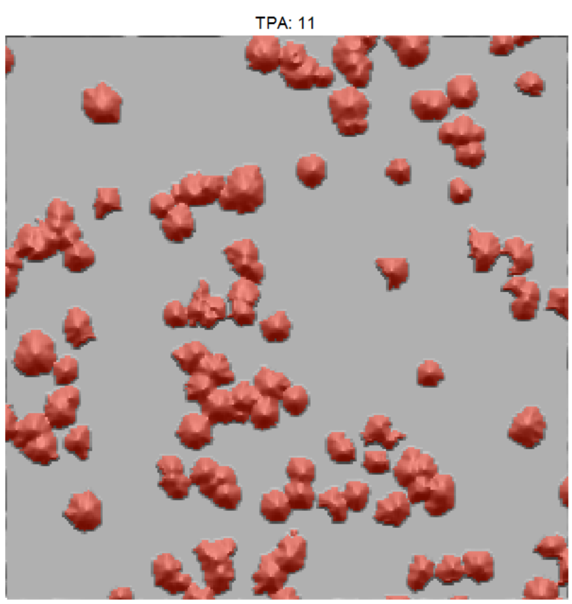
1. Open Forest Conditions

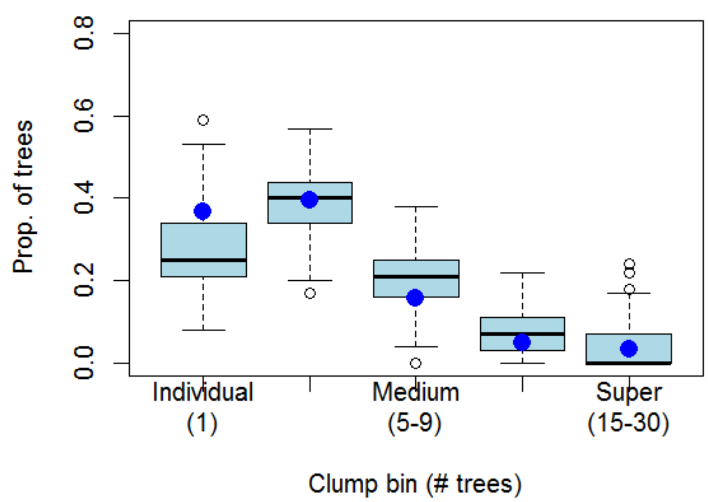




Clump distribution for this treatment compared to reference

No treatment



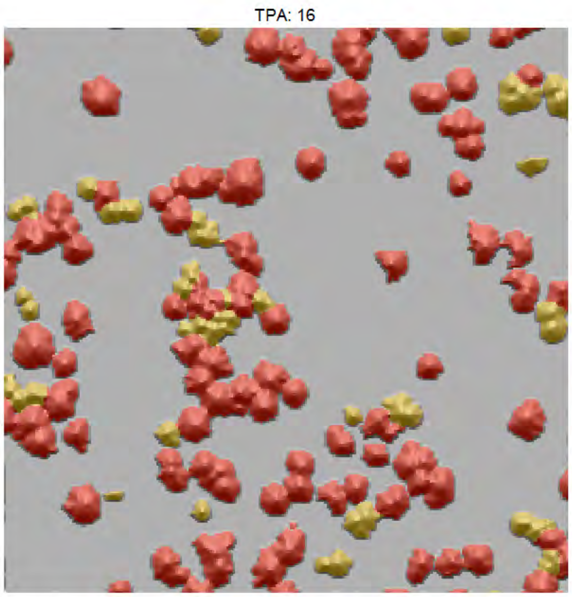


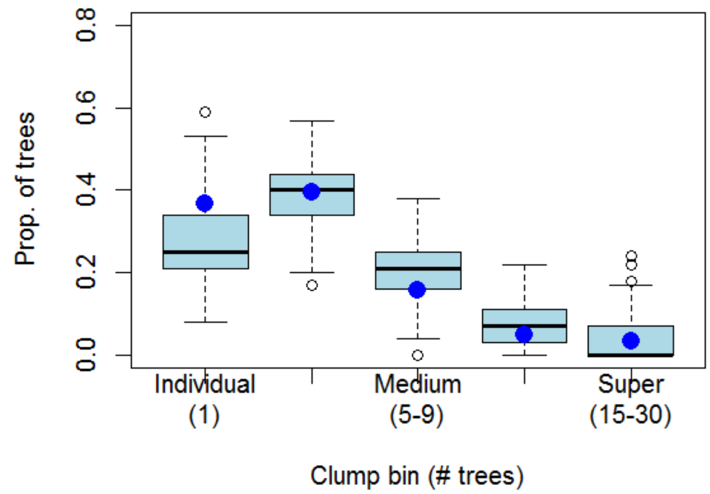
Clump distribution for this treatment compared to reference

Reference envelope
This clip

Retain only backbone trees

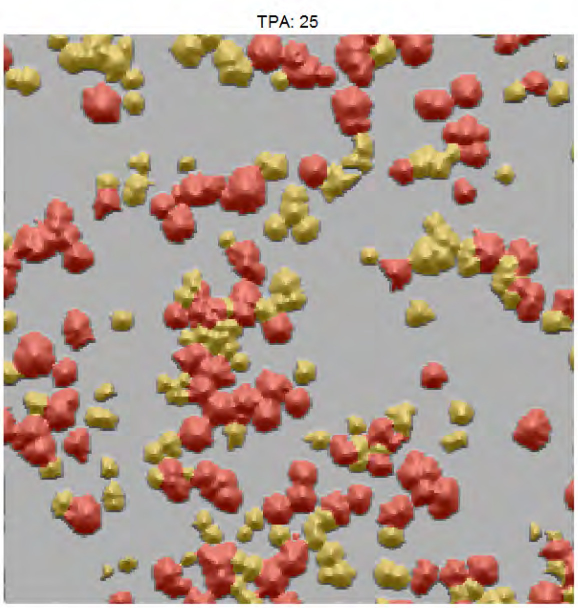
Backbone
Non-backbone merch
Non-backbone, non-merch
Open space

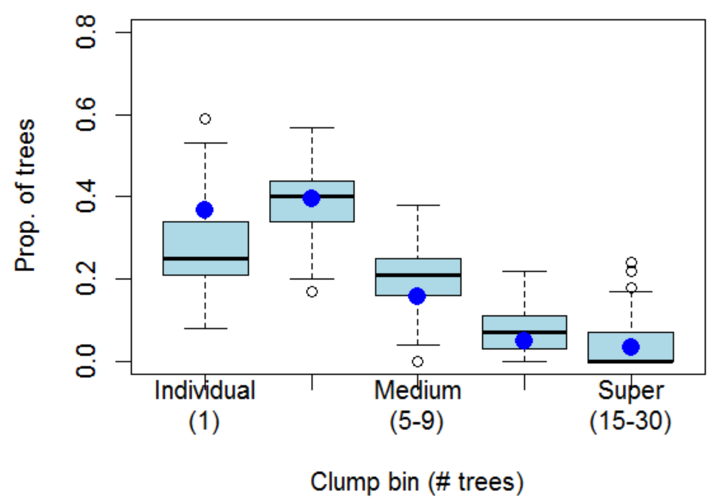




Clump distribution for this treatment compared to reference

Retain backbone trees plus 5 TPA, medium clumping level





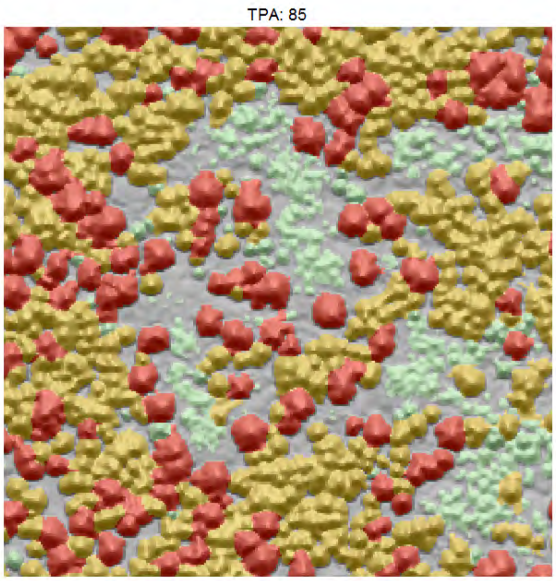
Clump distribution for this treament compared to reference

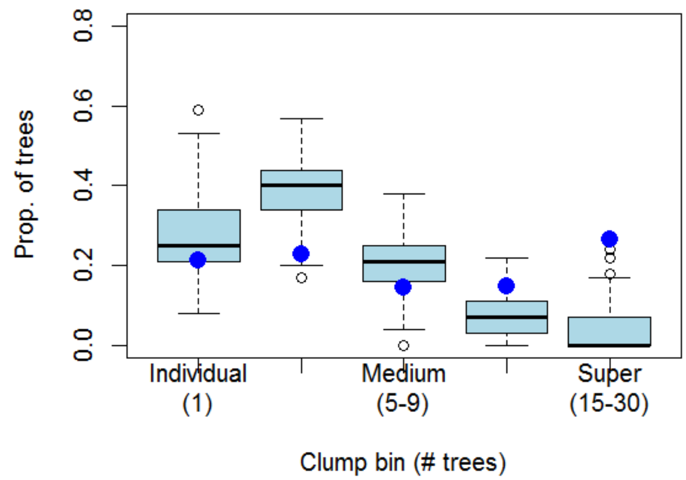
Reference envelope
This clip

Retain backbone trees plus 14 TPA, medium clumping level

Backbone
Non-backbone merch
Non-backbone, non-merch
Open space

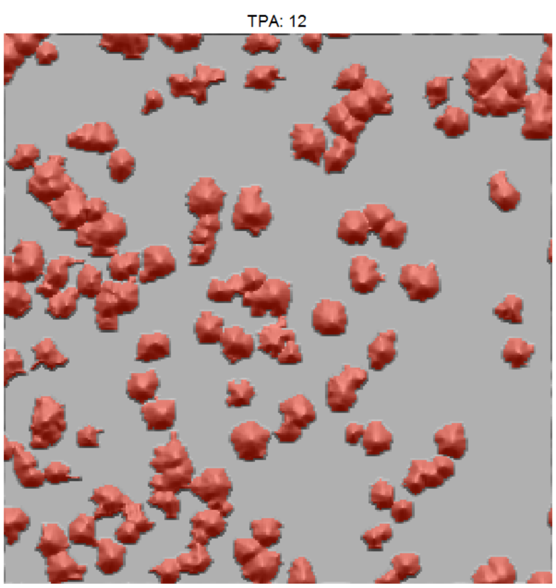
2. Mixed Conditions

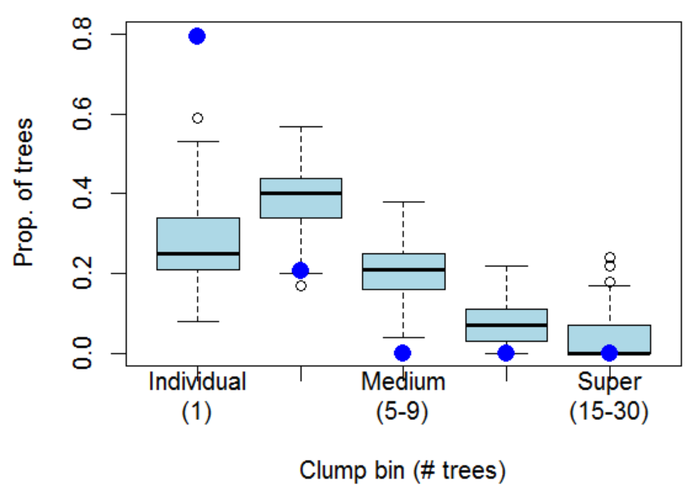




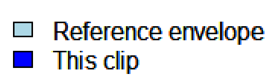
Clump distribution for this treatment compared to reference

No treatment

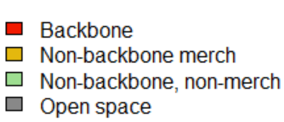


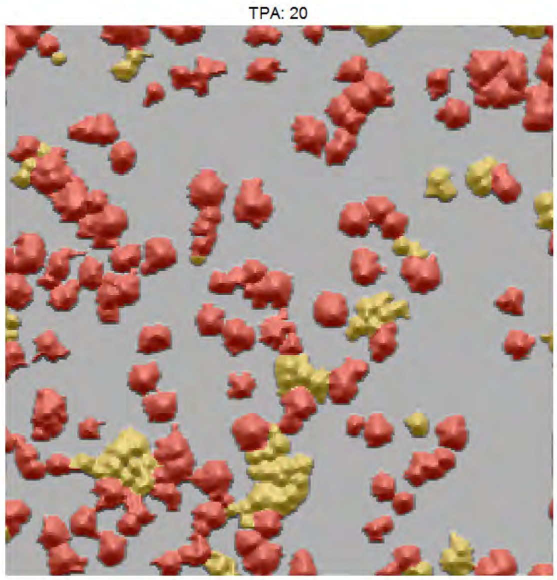


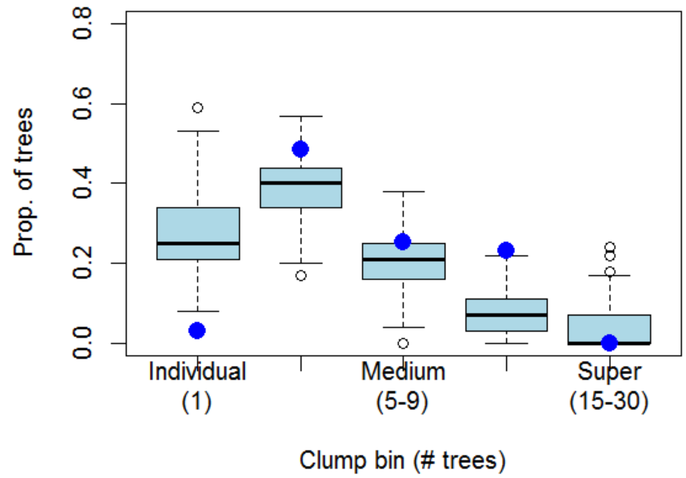
Clump distribution for this treatment compared to reference



Retain only backbone trees

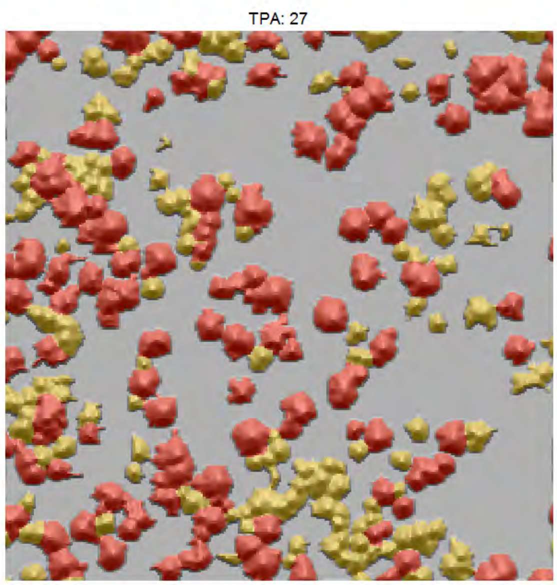


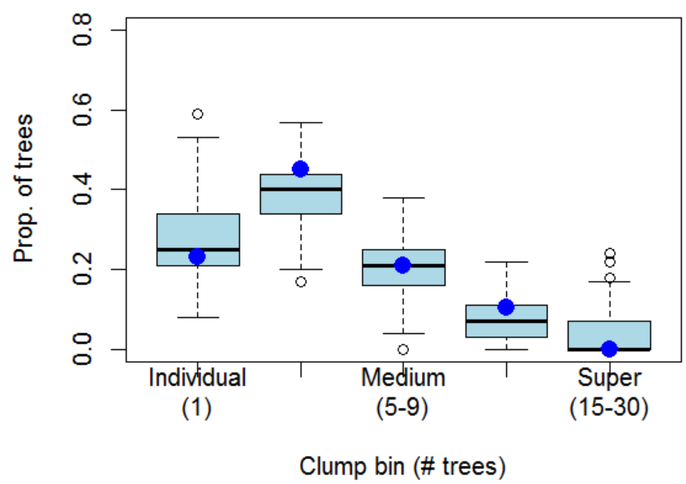




Clump distribution for this treatment compared to reference

Retain backbone trees plus 8 TPA, medium clumping level



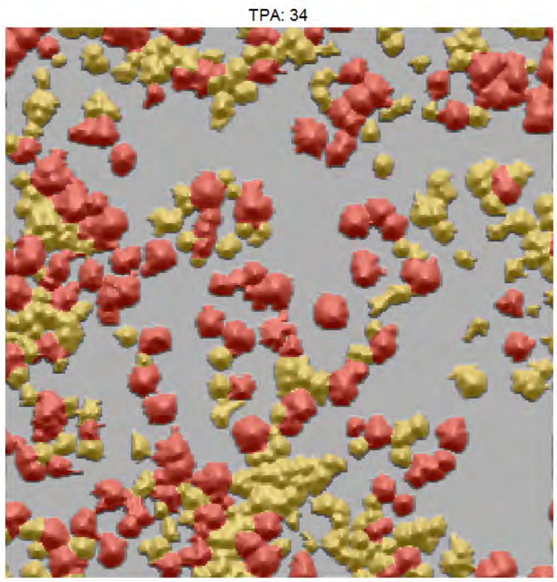


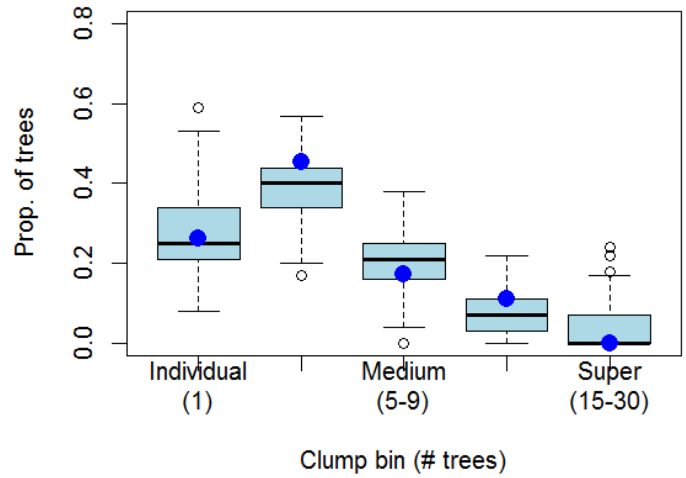
Clump distribution for this treatment compared to reference

Reference envelope
This clip

Retain backbone trees plus 15 TPA, medium clumping level

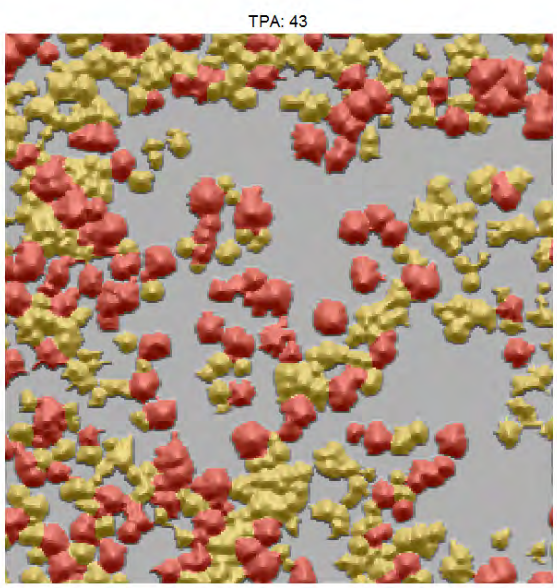
Backbone
Non-backbone merch
Non-backbone, non-merch
Open space

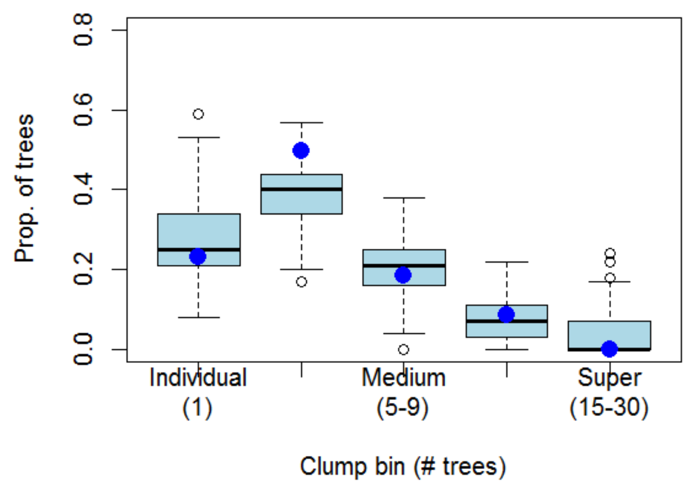




Clump distribution for this treatment compared to reference

Retain backbone trees plus 22 TPA, medium clumping level





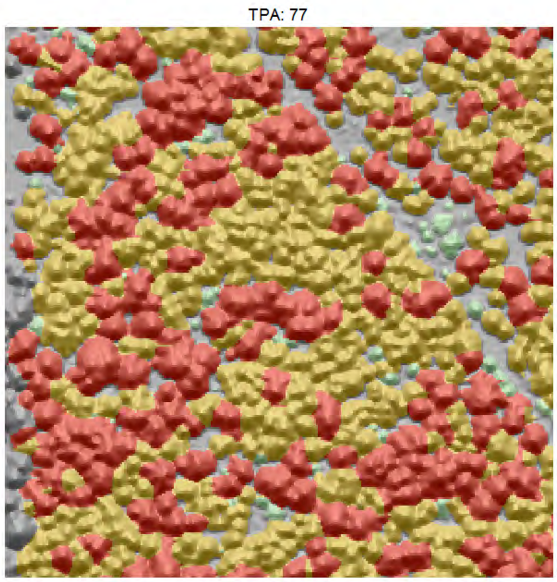
Clump distribution for this treatment compared to reference

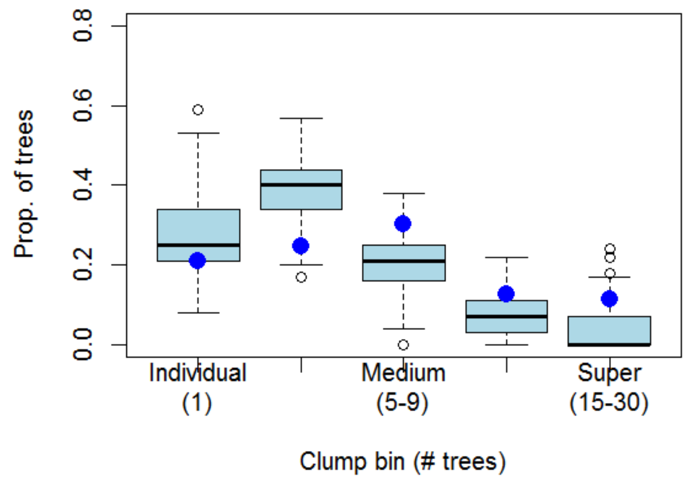
Reference envelope
This clip

Retain backbone trees plus 31 TPA, medium clumping level

Backbone
Non-backbone merch
Non-backbone, non-merch
Open space

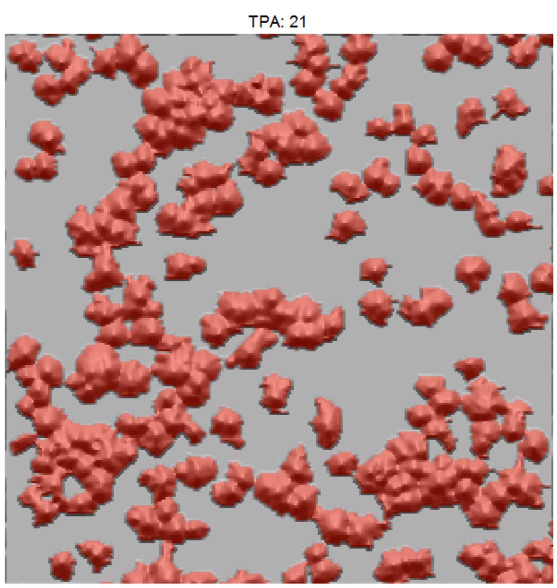
3. Closed Forest Conditions

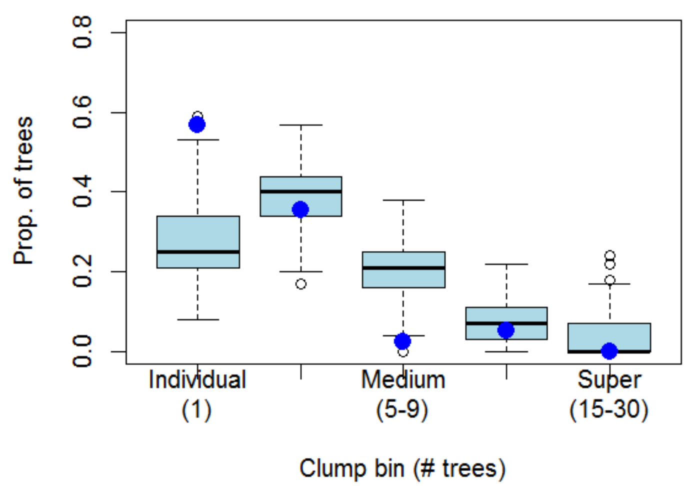




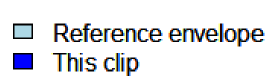
Clump distribution for this treatment compared to reference

No treatment

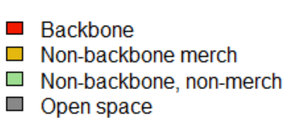


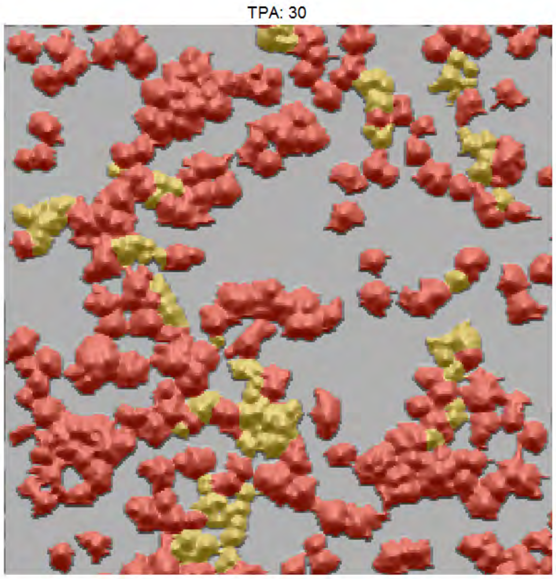


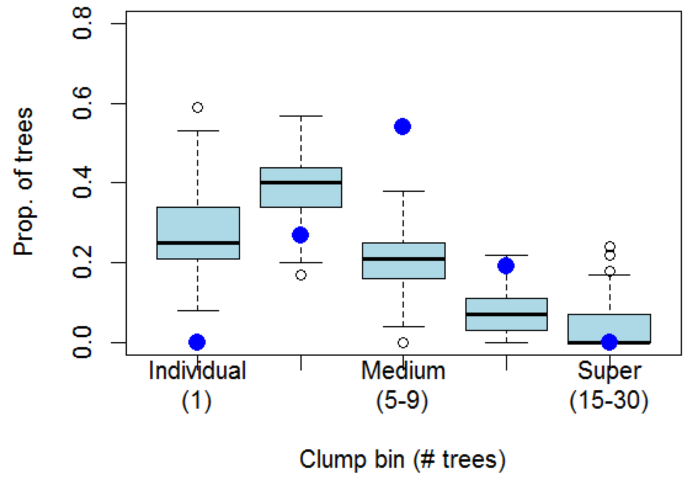
Clump distribution for this treatment compared to reference



Retain only backbone trees

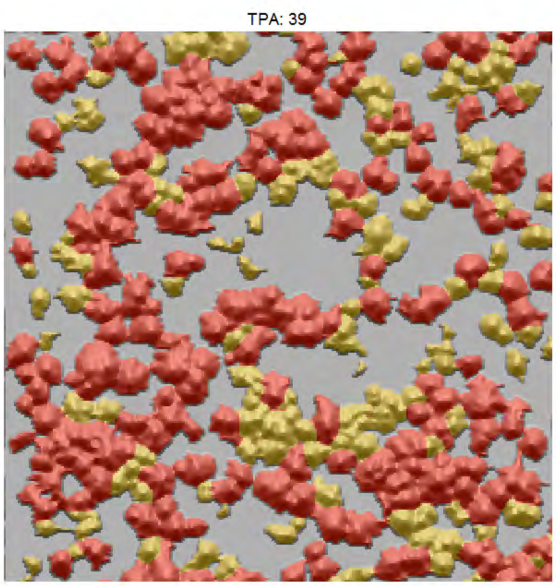


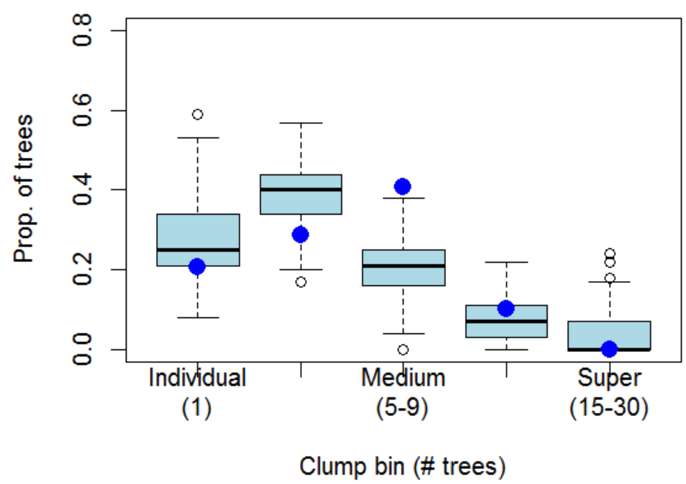




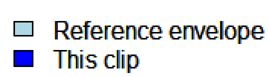
Clump distribution for this treatment compared to reference

Retain backbone trees plus 9 TPA, medium clumping level

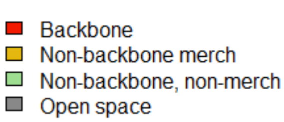


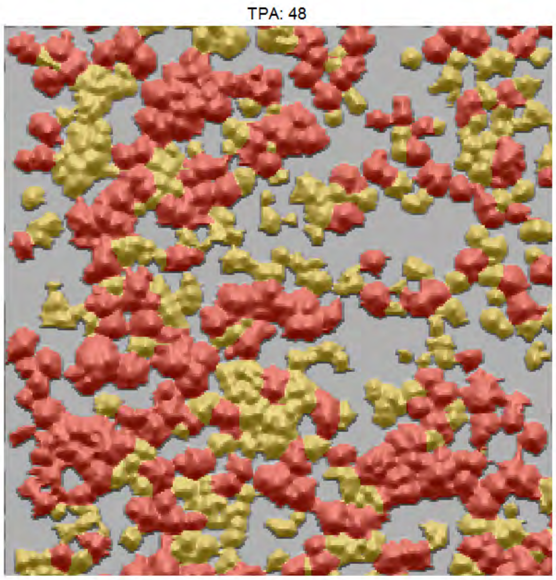


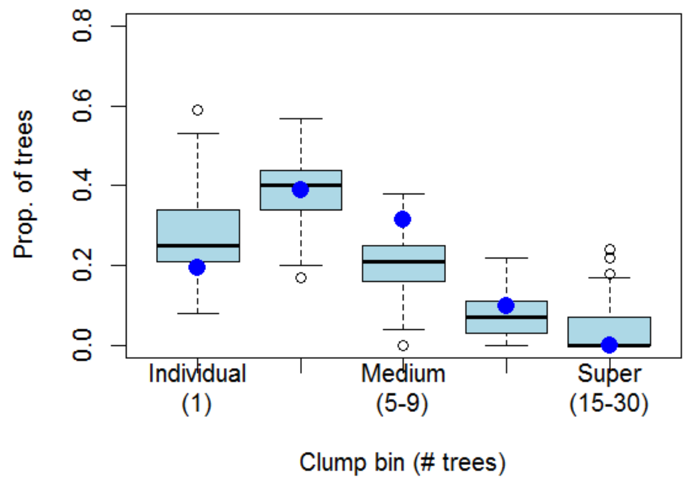
Clump distribution for tis treatment compared to reference



Retain backbone trees plus 18 TPA, medium clumping level

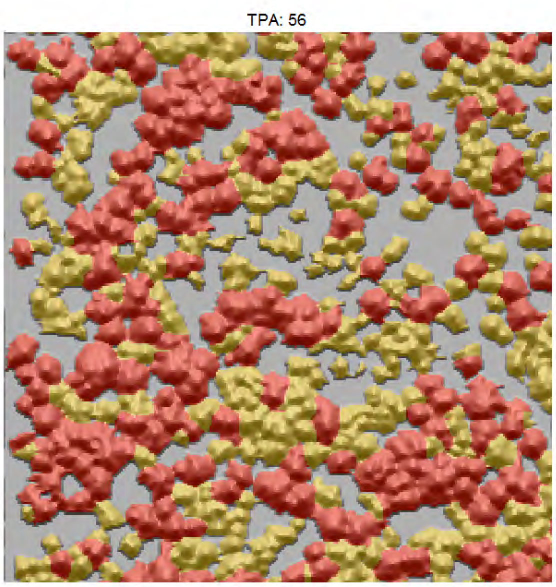


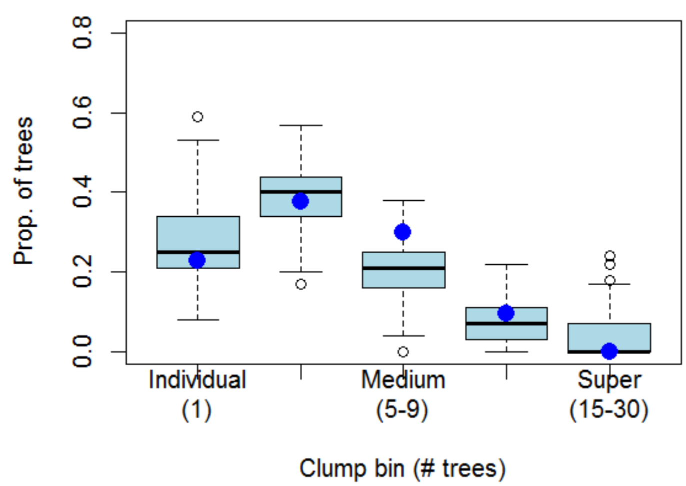




Clump distribution for this treatment compared to reference

Retain backbone trees plus 27 TPA, medium clumping level



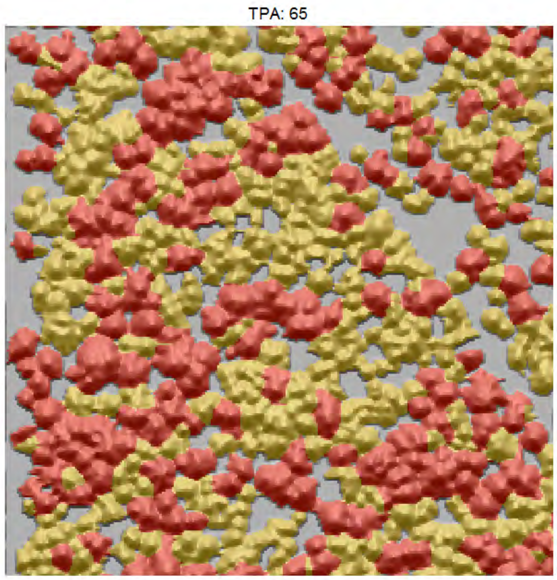


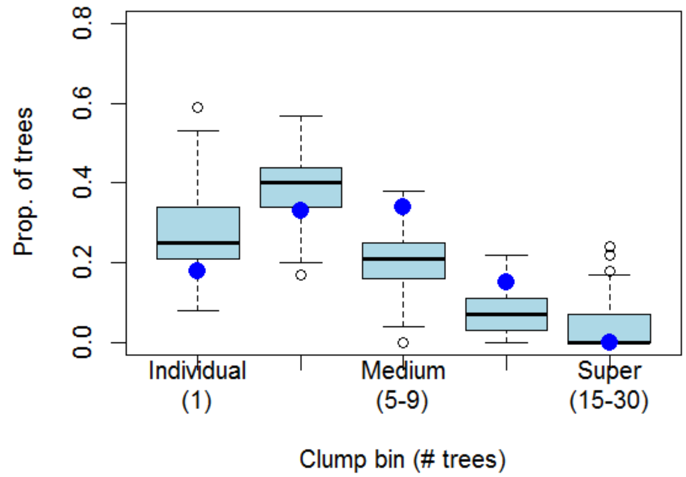
Clump distribution for this treatment compared to reference

Reference envelope
This clip

Retain backbone trees plus 35 TPA, medium clumping level

Backbone
Non-backbone merch
Non-backbone, non-merch
Open space





Clump distribution for this treatment compared to reference

- Reference envelope
- This clip

Retain backbone trees plus 44 TPA, medium clumping level

- Backbone
- Non-backbone merch
- Non-backbone, non-merch
- Open space

Appendix B: Prescription Recommendations

In this appendix we provide a graphical assessment of each treatment unit with respect to the reference conditions for stocking, clumping, and open space, along with a quantitative report of unit acreage, backbone tree density and basal area, and non-backbone density divided up by merch/non-merch.

Given these summary data, we have developed recommendations for treatment objectives. These recommendations are based solely on information from LiDAR data, and we duly recognize – and urge the reader to recognize – that there is additional work to be done to verify the parameters of these prescriptions and flesh out the details. The purpose of the data presented herein is to (1) provide the first-pass version of a prescription that should be workable, and (2) demonstrate the kinds of data that can be expected from LiDAR.

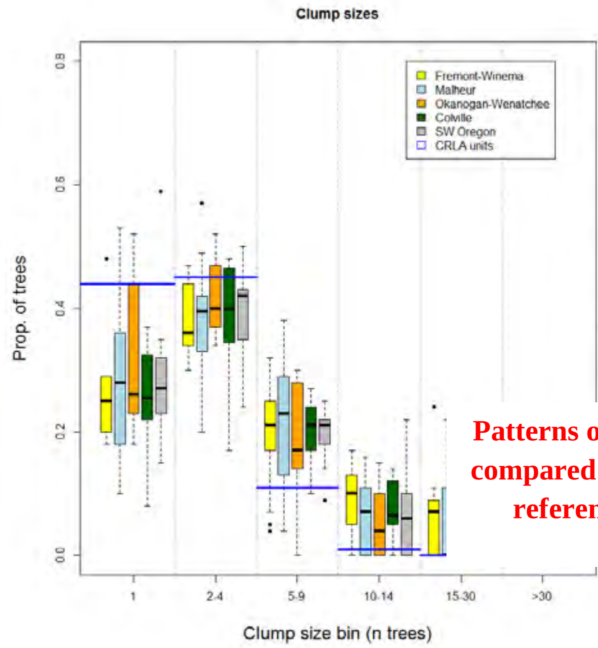
On the following page we give the summary for unit 0100, marked up to explain some of the different figures. For the remainder of the document the figures do not have captions, so refer to the following page if there are any questions as to interpretation.

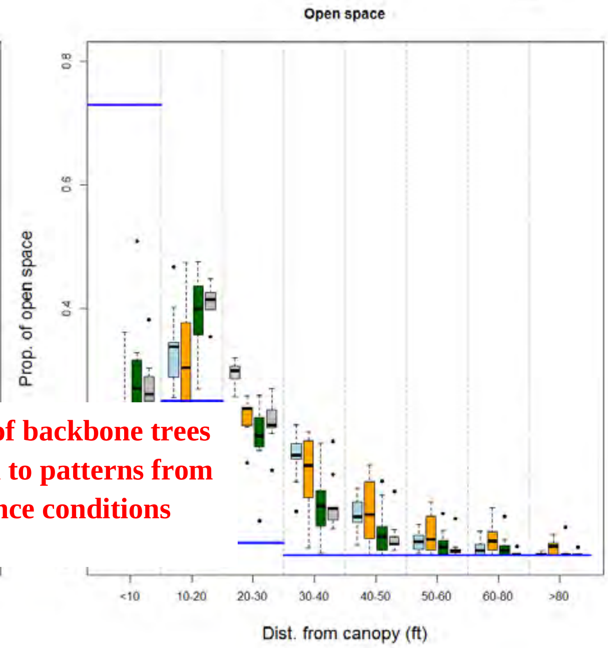
Unit 0100

Acres: 32.5
Backbone TPA: 32.5
Backbone BA: 243.6
Non-backbone merch TPA: 17.9
Non-backbone, non-merch TPA: 10

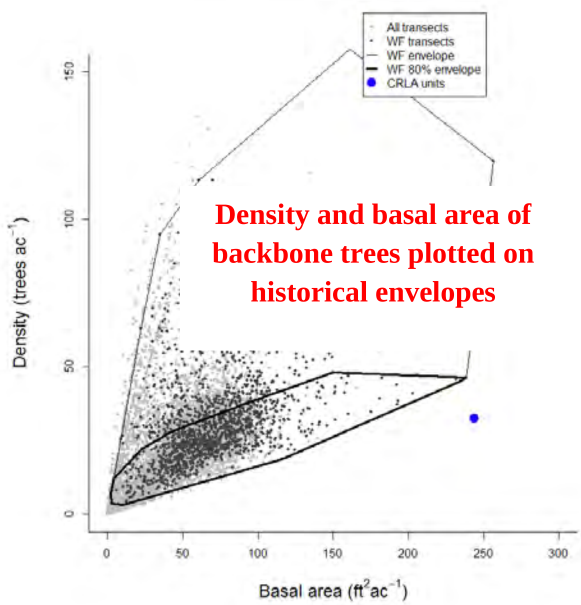
Current condition summary

Location of unit within Panhandle

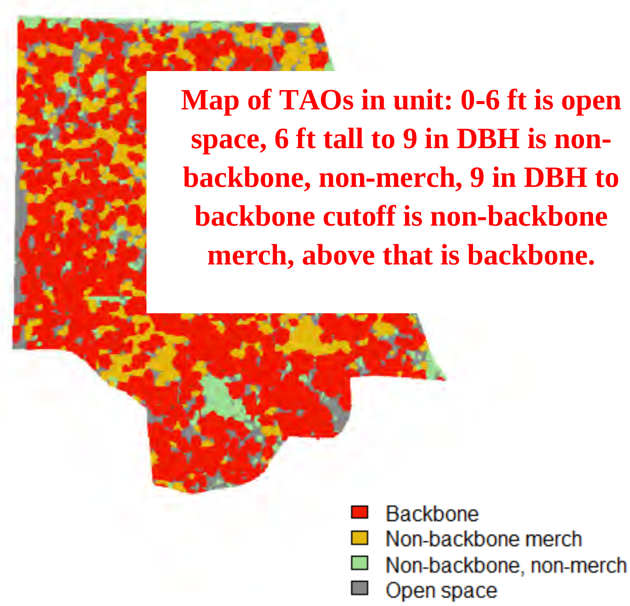




Patterns of backbone trees compared to patterns from reference conditions



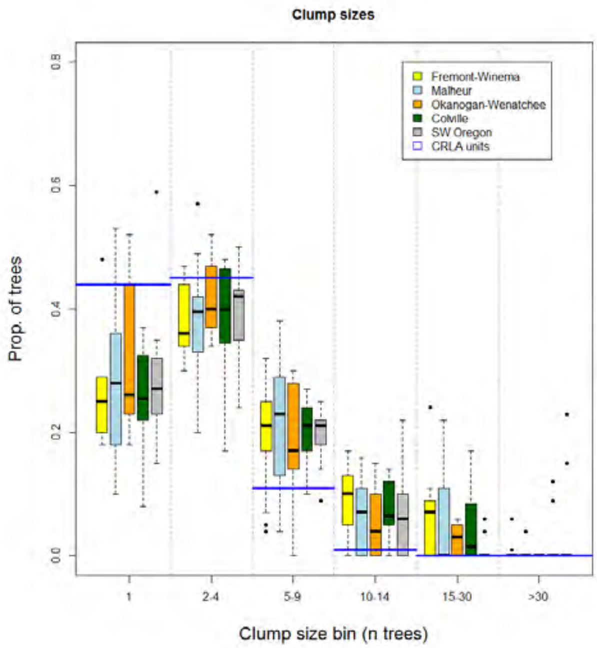
Density and basal area of backbone trees plotted on historical envelopes

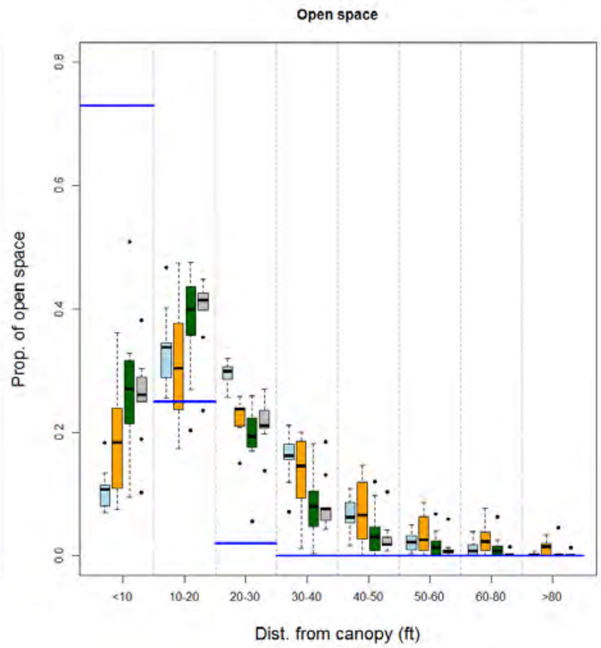


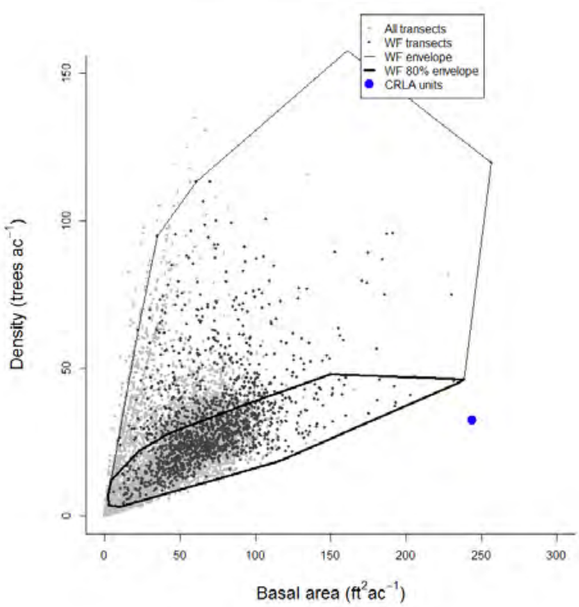
Map of TAOs in unit: 0-6 ft is open space, 6 ft tall to 9 in DBH is non-backbone, non-merch, 9 in DBH to backbone cutoff is non-backbone merch, above that is backbone.

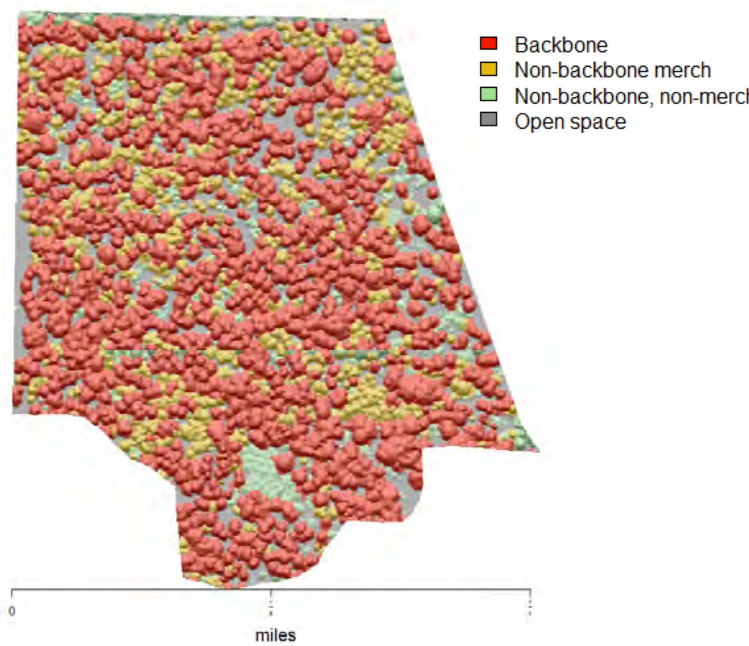
Unit 0100

Acres: 32.5
Backbone TPA: 32.5
Backbone BA: 243.6
Non-backbone merch TPA: 17.9
Non-backbone, non-merch TPA: 10









Prescription Recommendations

Target TPA: 40

Non-backbone retain TPA: 7.5

Clumping level: High

Clumping targets:

- Bring 6 individual trees per acre into small or medium clumps
- Add 0.7 medium clumps per acre
- Add 1 large clump per 2 acres
- Add 1 super clump per 5 acres

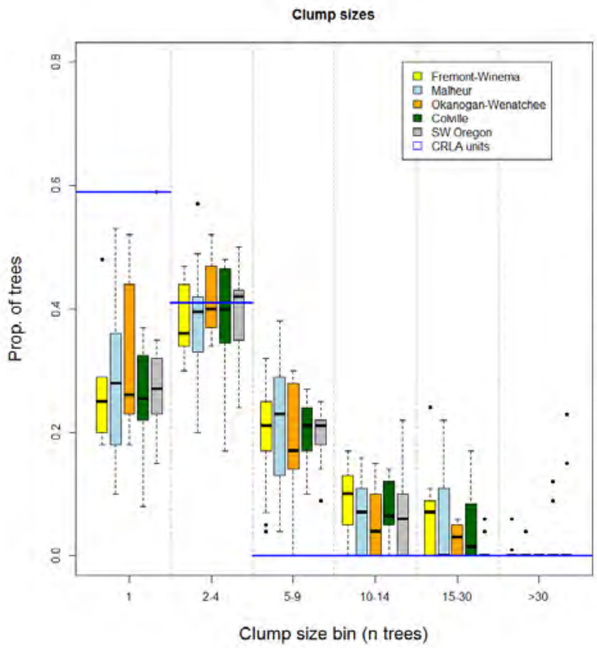
Opening targets:

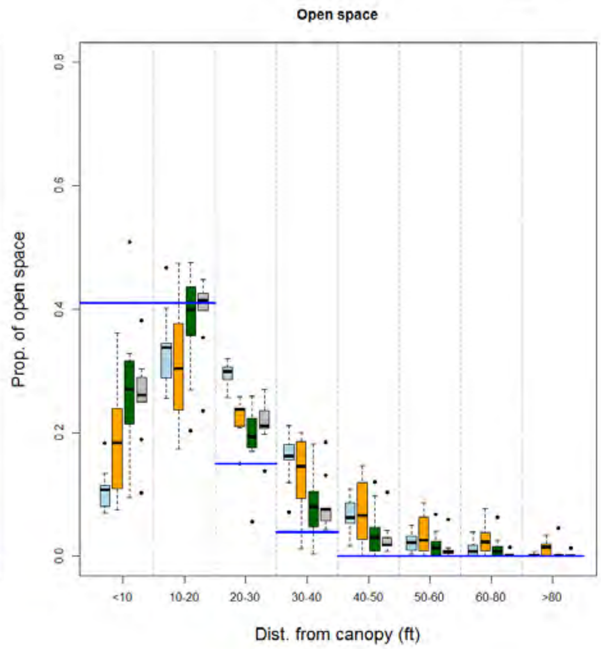
- Leave retention clumps in patches rather than dispersing them
- Leave at least 1 large opening, 0.1-0.25 acres in size, per 8 acres

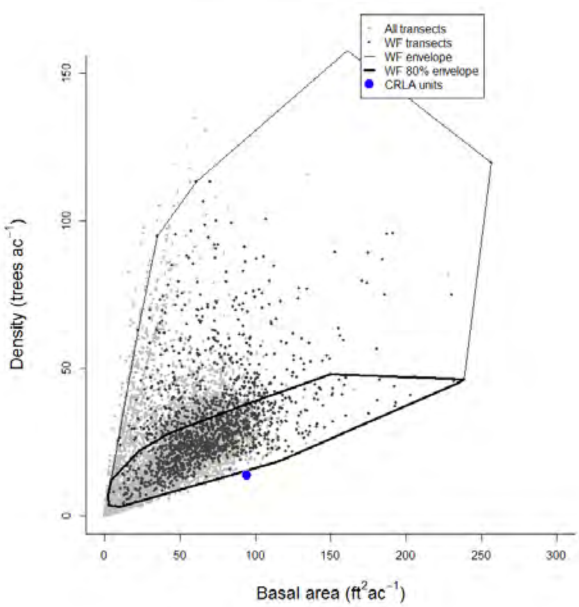
Non-commercial treatment: Not enough information due to high large-tree canopy cover

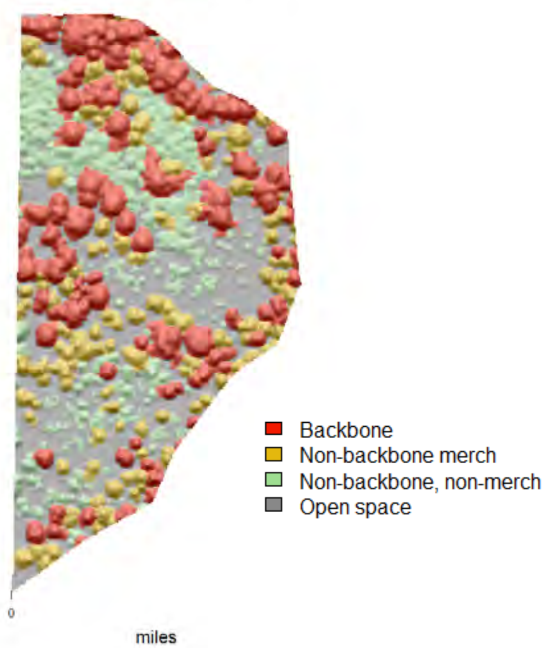
Unit 0200

Acres: 6.2
Backbone TPA: 13.7
Backbone BA: 94.4
Non-backbone merch TPA: 18.9
Non-backbone, non-merch TPA: 38.1









Prescription Recommendations

Target TPA: 20

Non-backbone retain TPA: 6.3

Clumping level: Low

Clumping targets:

- Bring 1 individual tree per acre into small or medium clumps
- Add 1 small clump per acre
- Add 1 medium clump per 2 acres

Opening targets:

- Leave retention clumps in patches rather than dispersing them
- Maintain the two larger openings in central and southern parts of unit

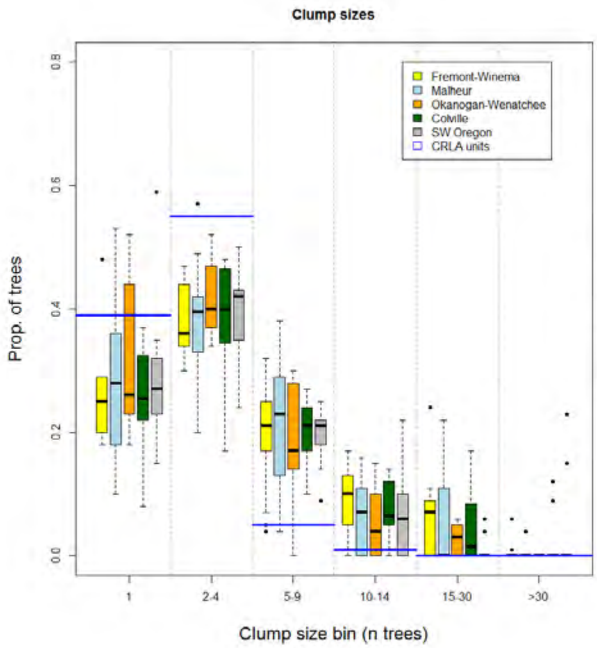
Non-commercial treatment:

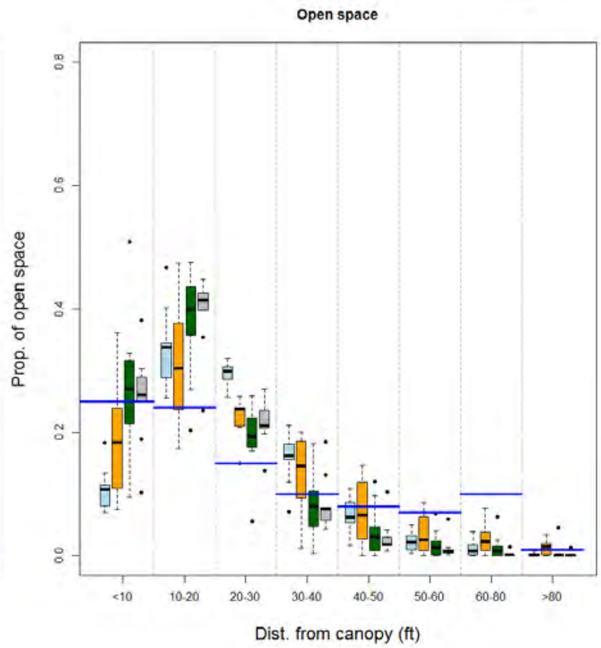
In southern portion: clear non-merchantable trees to promote large openings

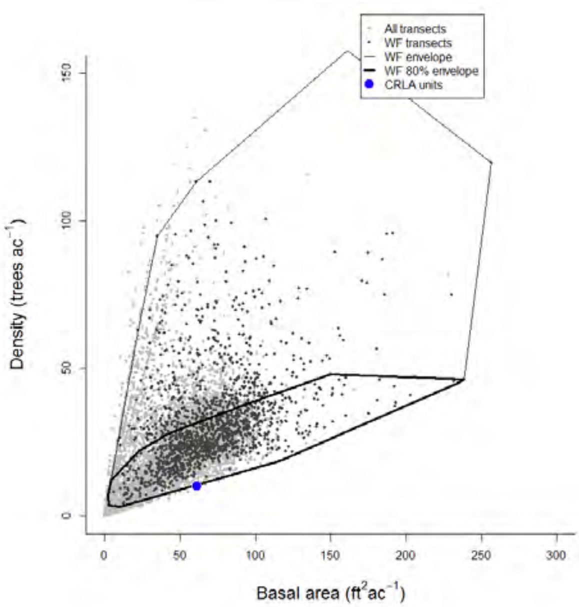
In northern portion: PCT, retaining larger pines with good form and vigor

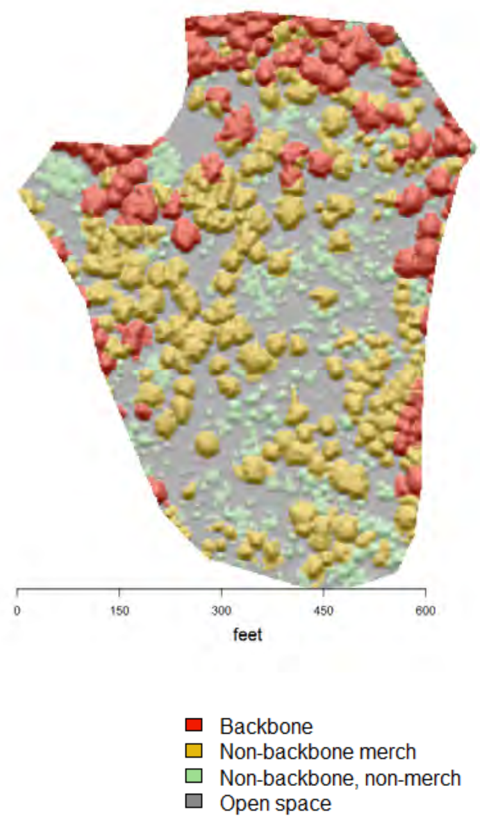
Unit 0300

Acres: 8.5
Backbone TPA: 10.1
Backbone BA: 61.1
Non-backbone merch TPA: 26.4
Non-backbone, non-merch TPA: 32.6









Prescription Recommendations

Target TPA: 12

Non-backbone retain TPA: 1.9

Clumping level: Low

Clumping targets:

- Add 1 individual tree per 3 acres
- Add 1 medium clump per 5 acres

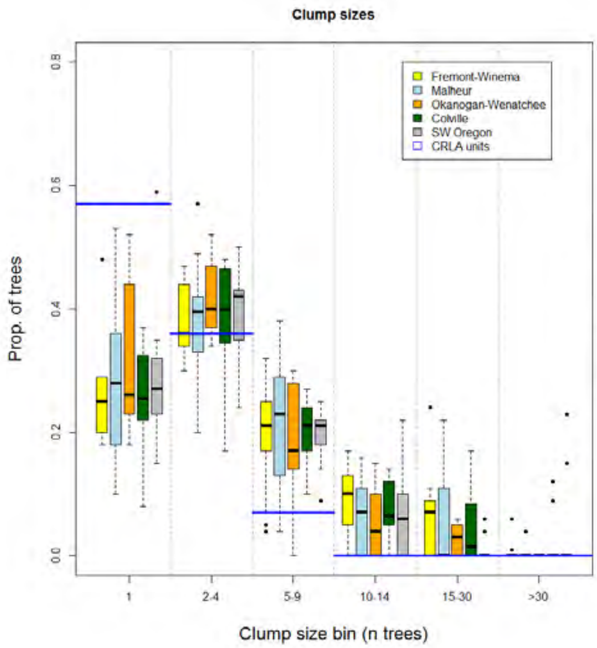
Opening targets:

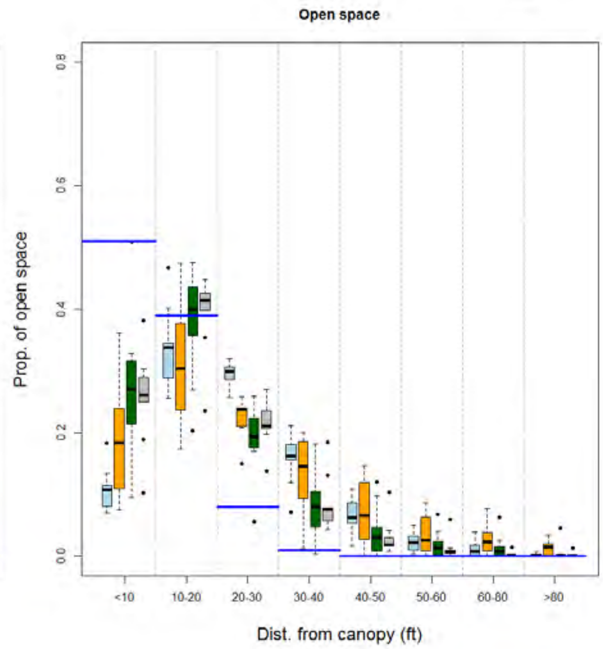
- Retain clumps in a way that splits excessively large openings to break up sighting distances

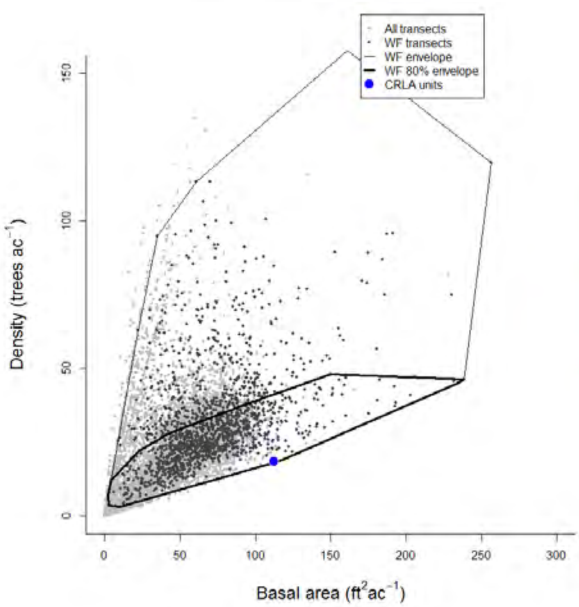
Non-commercial treatment: PCT, retaining larger pines with good form and vigor

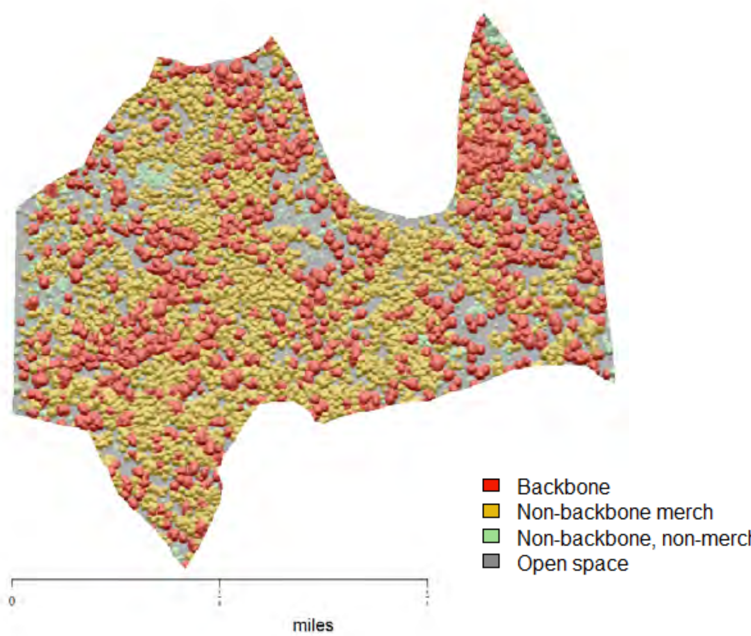
Unit 0400

Acres: 41.4
Backbone TPA: 18.6
Backbone BA: 112.4
Non-backbone merch TPA: 46
Non-backbone, non-merch TPA: 9.7









Prescription Recommendations

Target TPA: 25

Non-backbone retain TPA: 6.4

Clumping level: Medium

Clumping targets:

- Bring 4 individuals per acre into small or medium clumps
- Add 1 small clump per acre
- Add 2 medium clumps per 3 acres
- Add 1 large clump per 5 acres

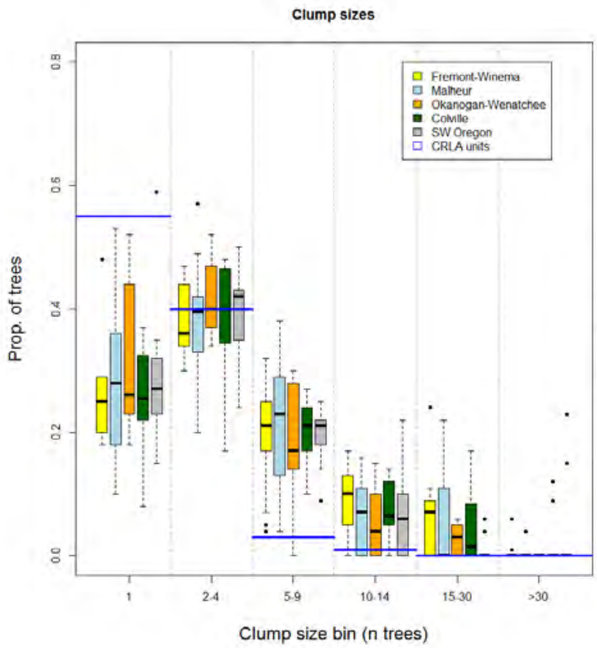
Opening targets:

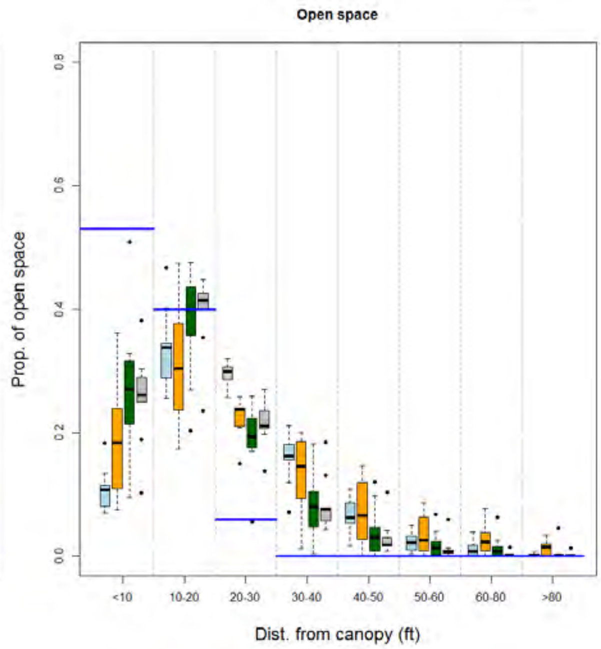
- Leave retention clumps in patches rather than dispersing them
- Create 1 large opening, 0.1-0.25 acres in size, per 5 acres

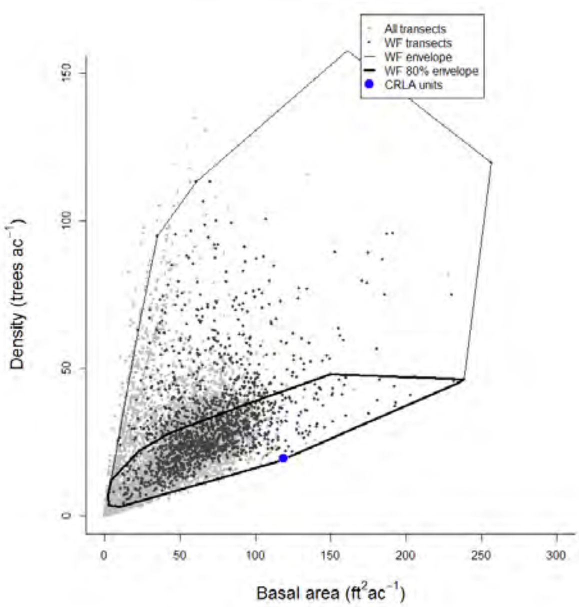
Non-commercial treatment: Not enough information due to high large-tree canopy cover

Unit 0500

Acres: 43.1
Backbone TPA: 19.6
Backbone BA: 118.5
Non-backbone merch TPA: 50.9
Non-backbone, non-merch TPA: 7.8







Prescription Recommendations

Target TPA: 24

Non-backbone retain TPA: 4.4

Clumping level: Medium

Clumping targets:

- Bring 4 individuals per acre into small and medium clumps
- Add 1 small clump per 2 acres
- Add 1 medium clump per acre
- Add 1 large clump per 5 acres

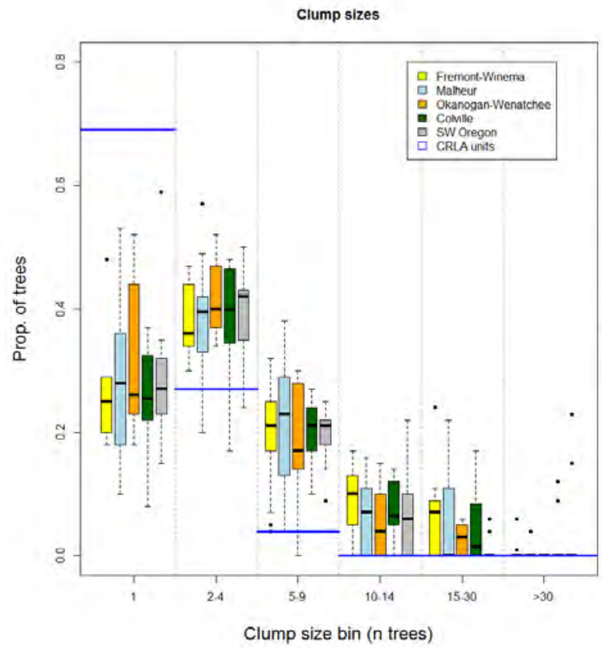
Opening targets:

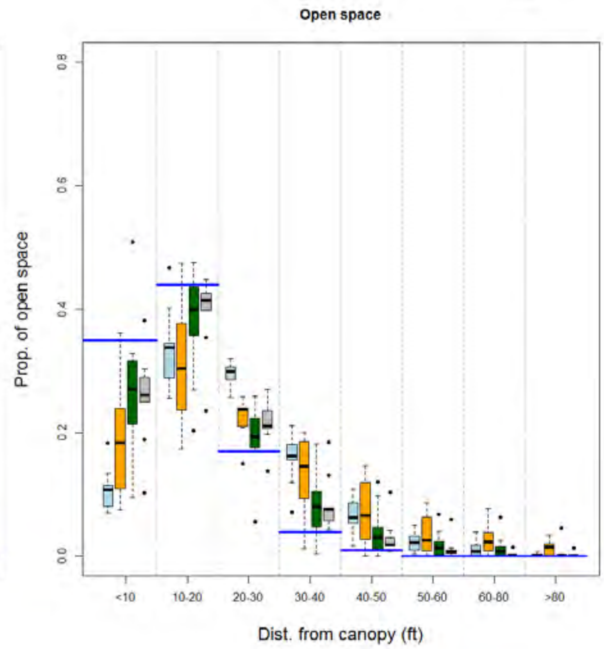
- Backbone trees are very evenly spaced throughout the unit; there is little opportunity to create open space

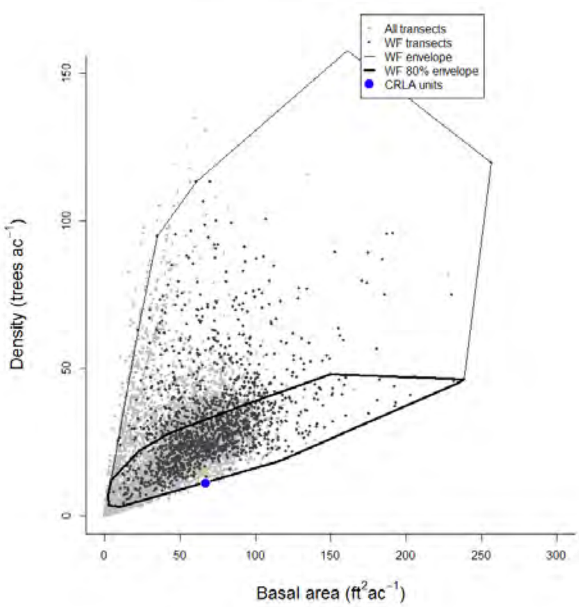
Non-commercial treatment: Not enough information due to high large-tree canopy cover

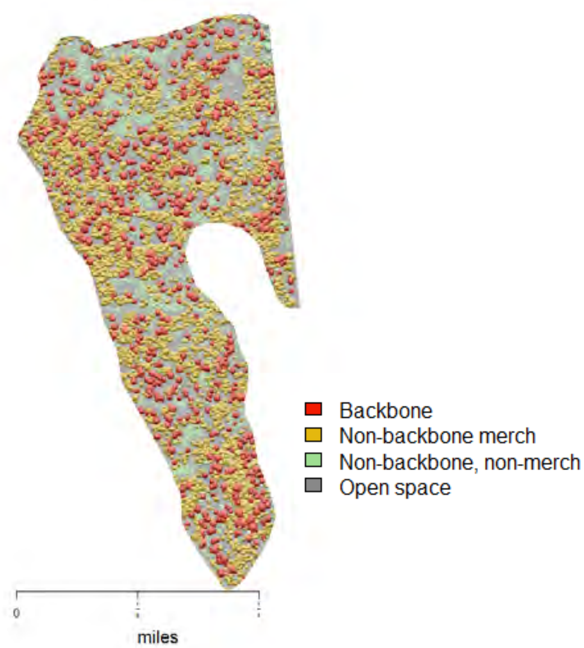
Unit 0600

Acres: 58.9
Backbone TPA: 11.1
Backbone BA: 66.9
Non-backbone merch TPA: 39.4
Non-backbone, non-merch TPA: 24.3









Prescription Recommendations

Target TPA: 19

Non-backbone retain TPA: 7.9

Clumping level: Low

Clumping targets:

- Bring 1 individual per acre into small and medium clumps
- Add 2 small clumps per acre
- Add 1 medium clump per 2 acres

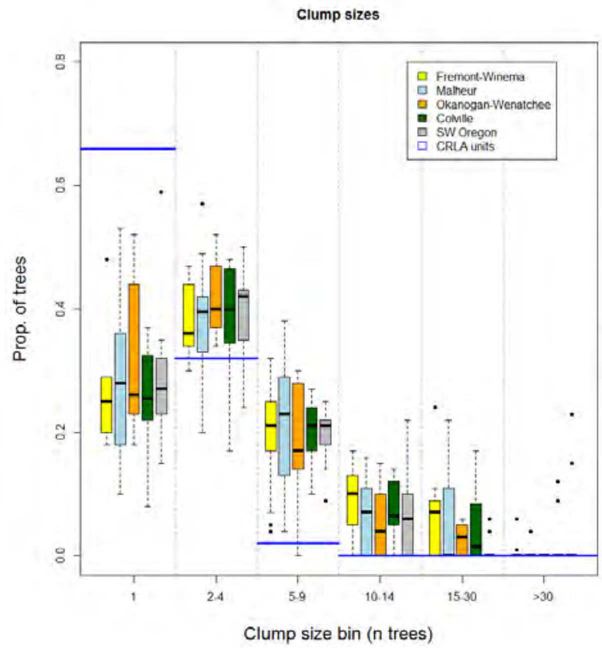
Opening targets:

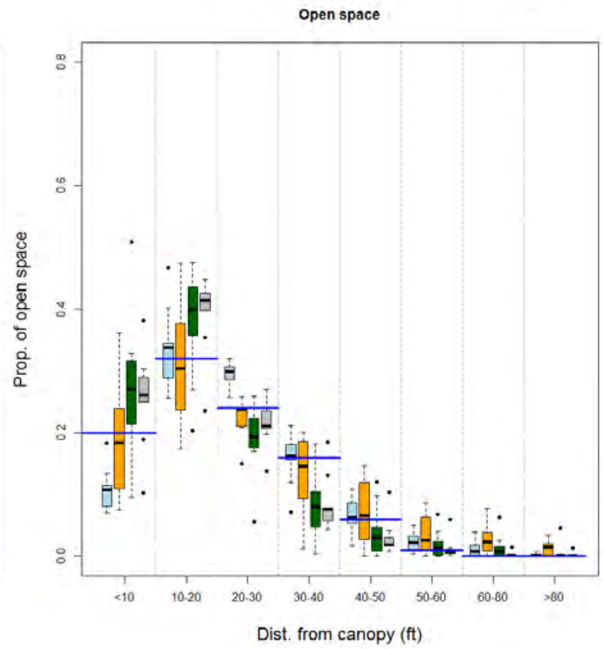
- Removing most of the non-merchantable trees will provide plenty of open space

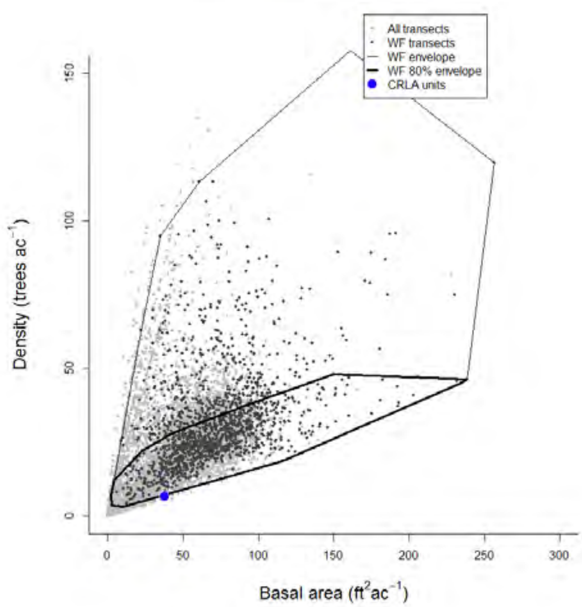
Non-commercial treatment: Save scattered pine regen patches, remove all else

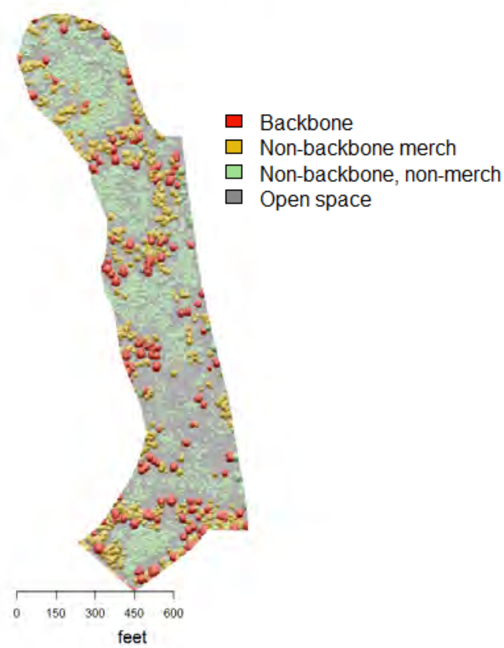
Unit 0700

Acres: 18.5
Backbone TPA: 6.6
Backbone BA: 38.1
Non-backbone merch TPA: 18
Non-backbone, non-merch TPA: 69.9









Prescription Recommendations

Target TPA: 25

Non-backbone retain TPA: 18.4

Clumping level: Low

Clumping targets:

- Add 4-5 individuals per acre
- Add 3 small clumps per acre
- Add 1 medium clump per 2 acres

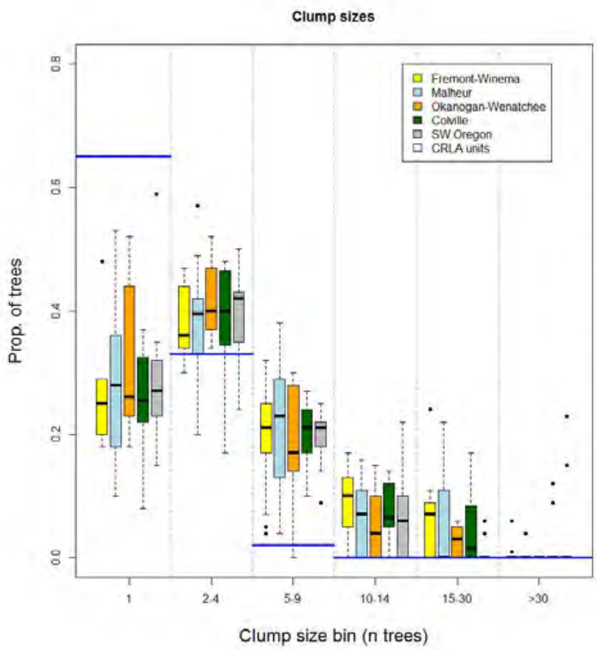
Opening targets:

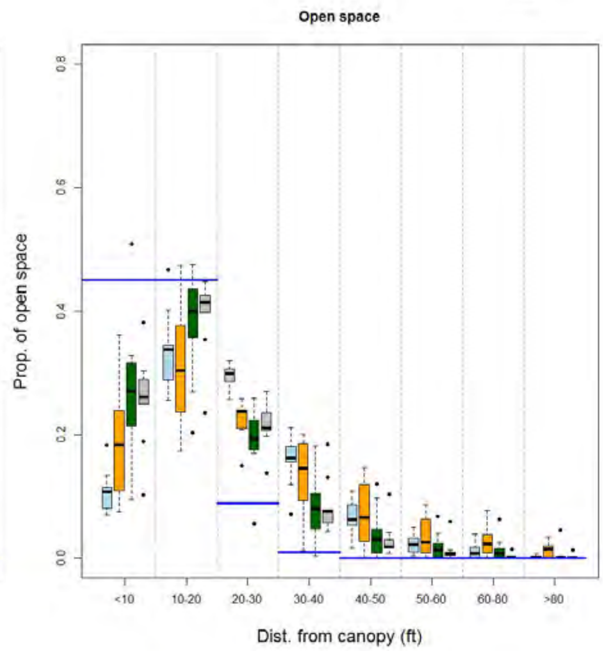
- Removing most of the non-merchantable trees will provide plenty of open space

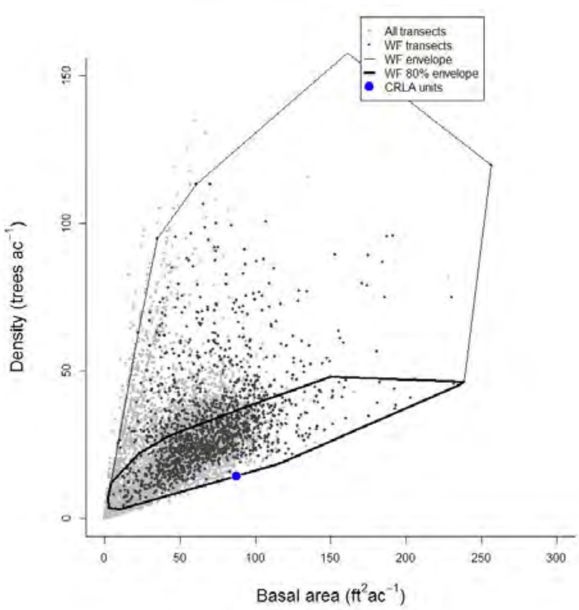
Non-commercial treatment: Save scattered pine regen patches, remove all else

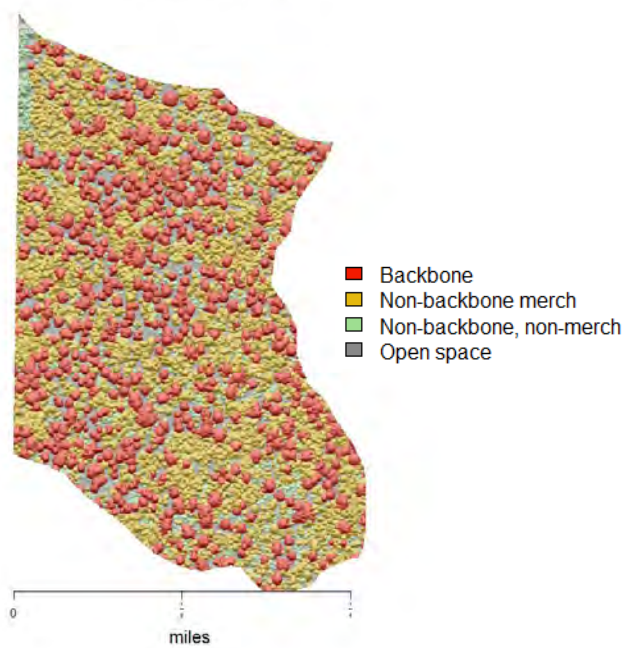
Unit 0800

Acres: 49.4
Backbone TPA: 14.4
Backbone BA: 87.5
Non-backbone merch TPA: 50.8
Non-backbone, non-merch TPA: 14.2









Prescription Recommendations

Target TPA: 28

Non-backbone retain TPA: 13.6

Clumping level: Medium

Clumping targets:

- Bring 2 individuals per acre into small or medium clumps
- Add 2 small clumps per acre
- Add 1 medium clump per acre
- Add 1 large clump per 5 acres

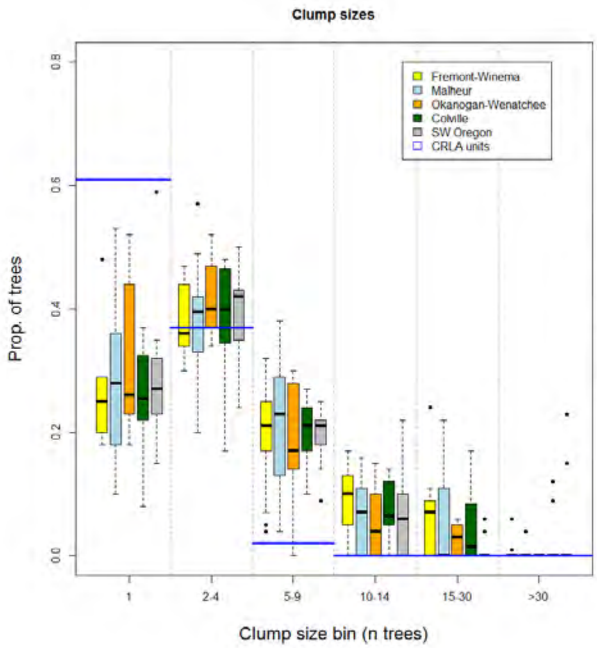
Opening targets:

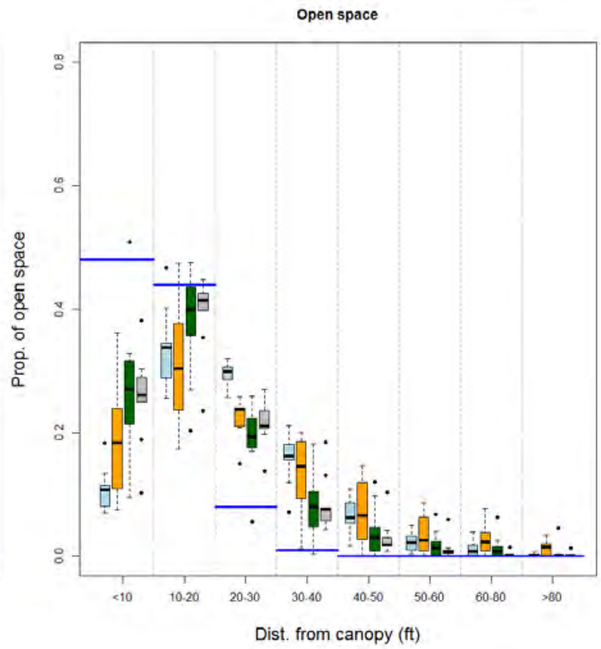
- Backbone trees are very evenly spaced throughout the unit; there is little opportunity to create open space

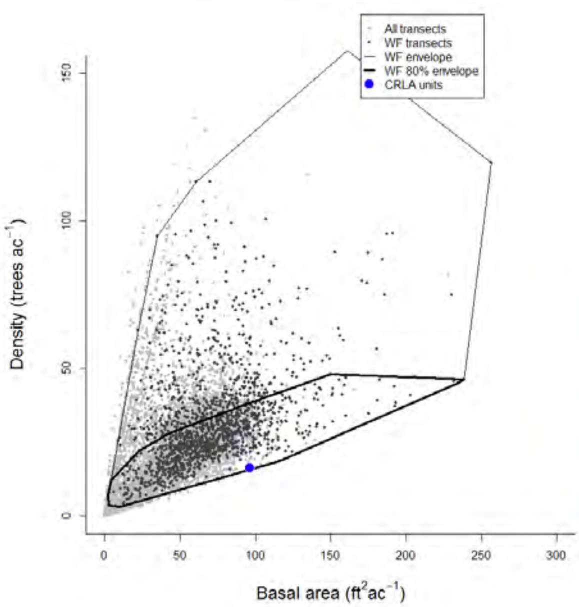
Non-commercial treatment: Not enough information due to high large-tree canopy cover

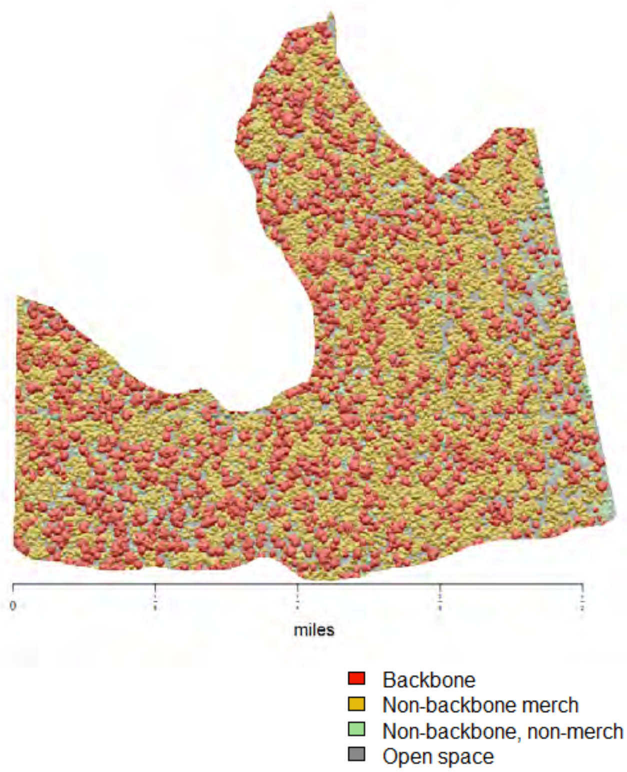
Unit 0900

Acres: 93
Backbone TPA: 16.2
Backbone BA: 96.2
Non-backbone merch TPA: 52.6
Non-backbone, non-merch TPA: 8.8









Prescription Recommendations

Target TPA: 29

Non-backbone retain TPA: 18.8

Clumping level: High

Clumping targets:

- Bring 5 individuals per acre into small or medium clumps
- Add 1 small clump per acre
- Add 1 medium clump per acre
- Add 1 large clump per 3 acres
- Add 1 super clump per 10 acres

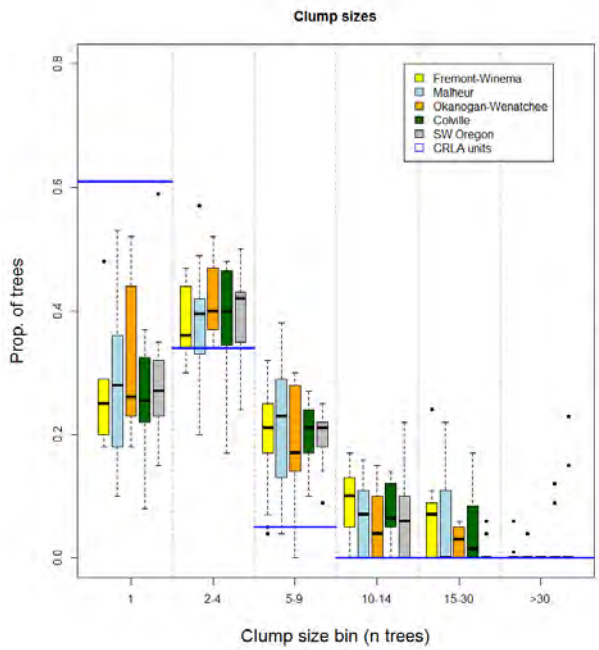
Opening targets:

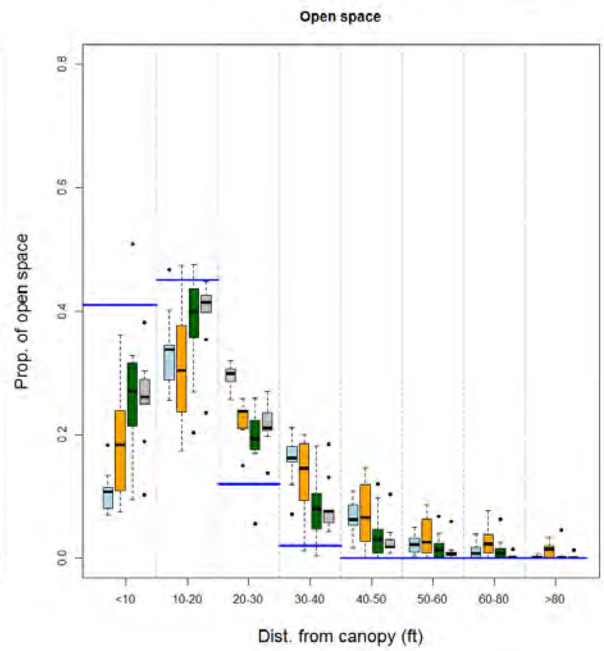
- Backbone trees are very evenly spaced throughout the unit; there is little opportunity to create open space

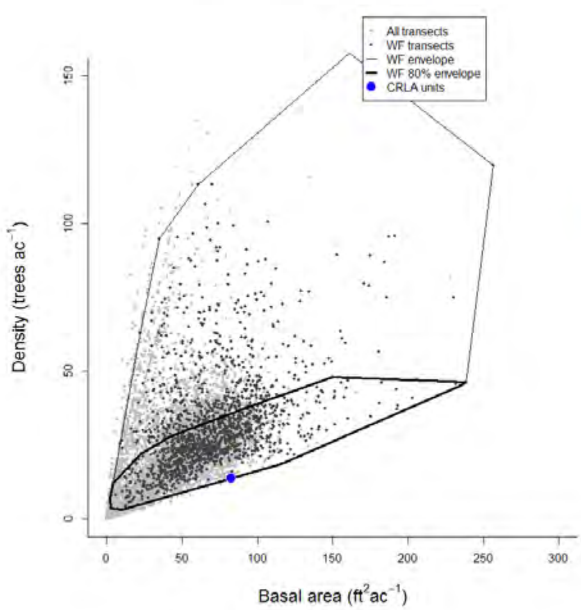
Non-commercial treatment: Not enough information due to high large-tree canopy cover

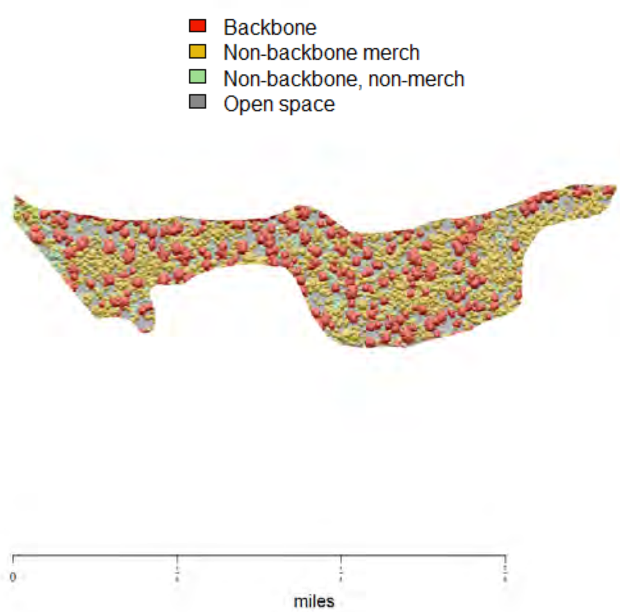
Unit 1000

Acres: 17.8
Backbone TPA: 13.9
Backbone BA: 82.5
Non-backbone merch TPA: 54.9
Non-backbone, non-merch TPA: 16.9









Prescription Recommendations

Target TPA: 25

Non-backbone retain TPA: 11.1

Clumping level: Medium

Clumping targets:

- Bring 1-2 individuals per acre into small or medium clumps
- Add 1 small clump per acre
- Add 1 medium clump per acre
- Add 1 large clump per 5 acres

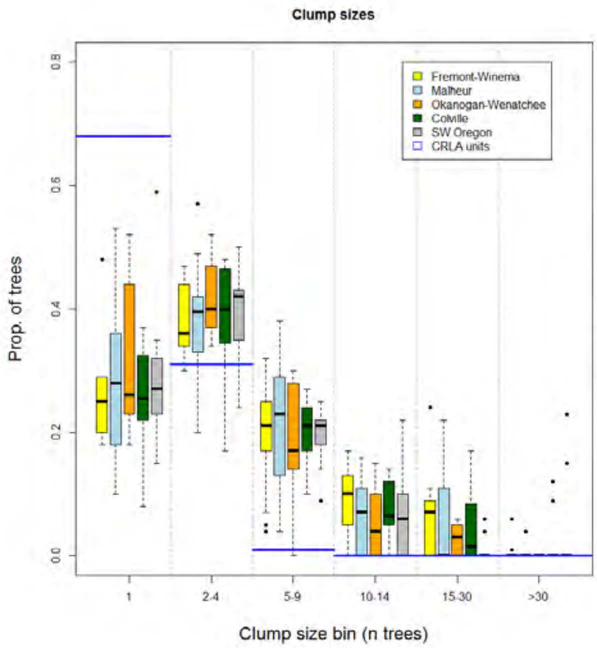
Opening targets:

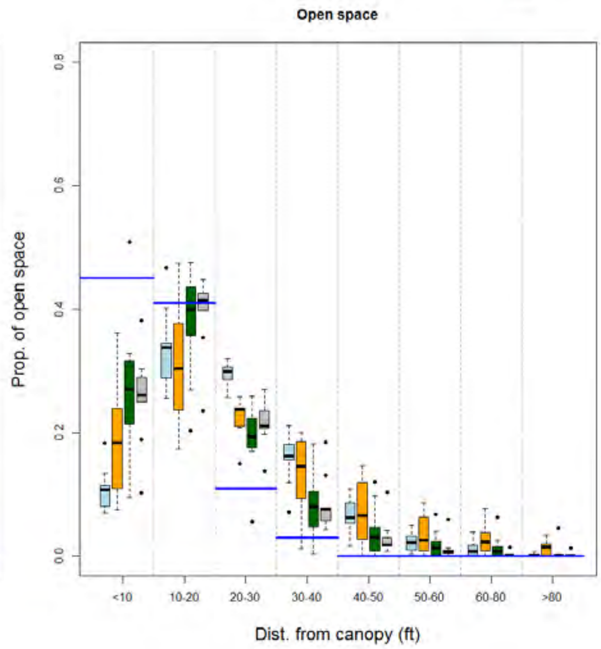
- Leave retention clumps in patches rather than dispersing them
- Leave at least 1 large opening, 0.1-0.25 acres in size, per 8 acres

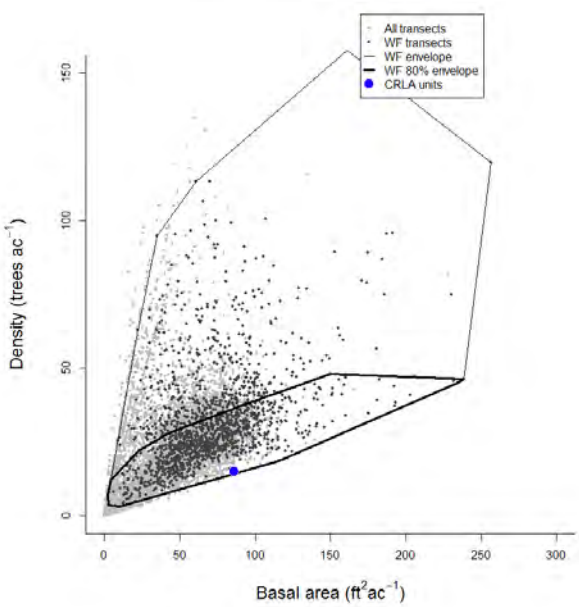
Non-commercial treatment: Not enough information due to high large-tree canopy cover

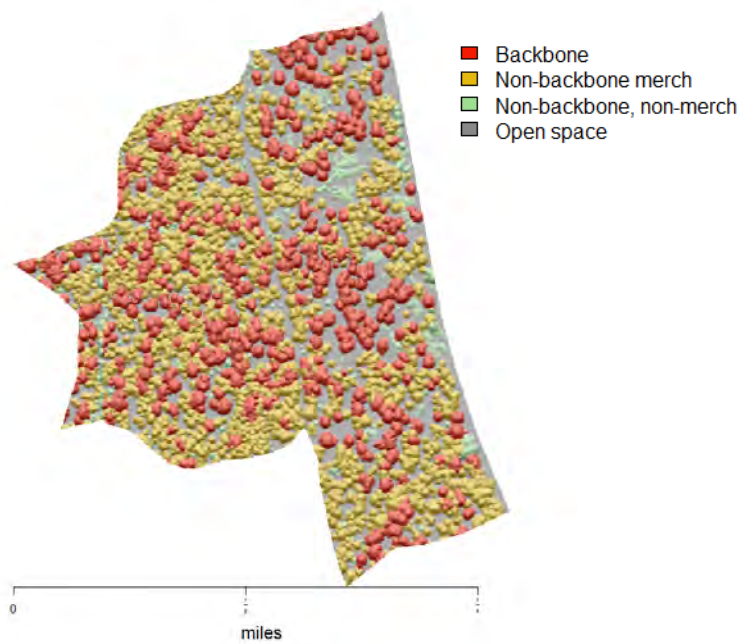
Unit 1100

Acres: 27.4
Backbone TPA: 15.1
Backbone BA: 85.9
Non-backbone merch TPA: 45.7
Non-backbone, non-merch TPA: 10









Prescription Recommendations

Target TPA: 22

Non-backbone retain TPA: 6.9

Clumping level: Low

Clumping targets:

- Bring 2-3 individuals per acre into small or medium clumps
- Add 2 small clumps per acre
- Add 1 medium clump per 2 acres

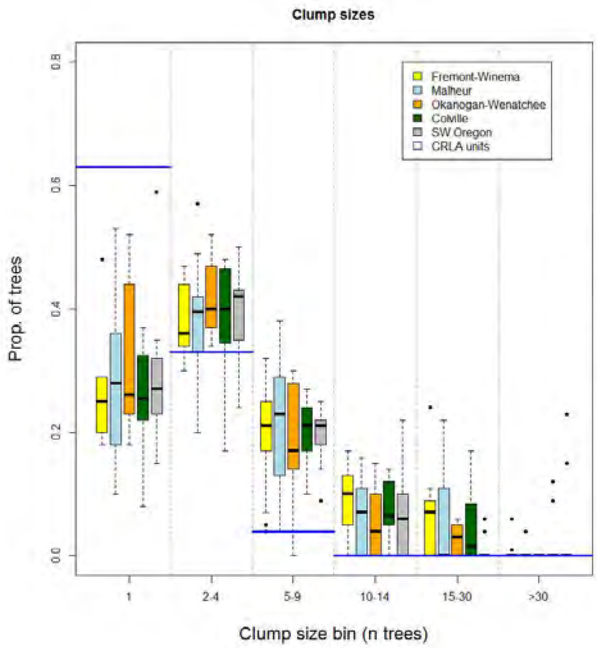
Opening targets:

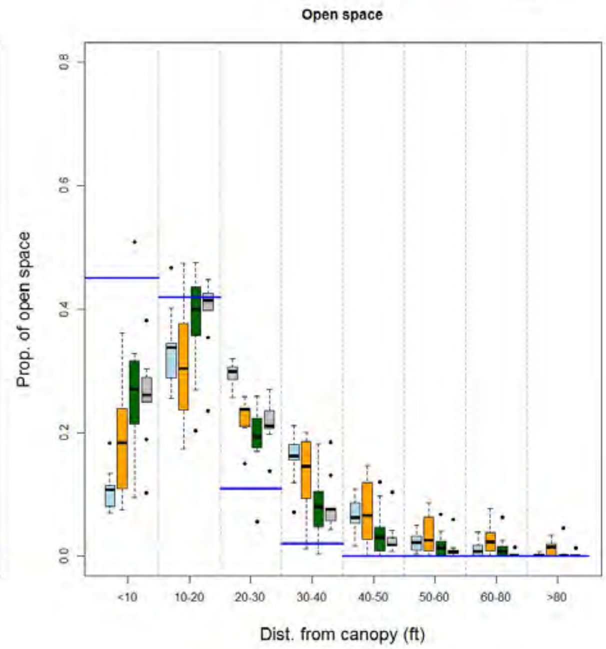
- Leave retention clumps in patches rather than dispersing them
- Leave at least 1 large opening, 0.1-0.25 acres in size, per 7 acres

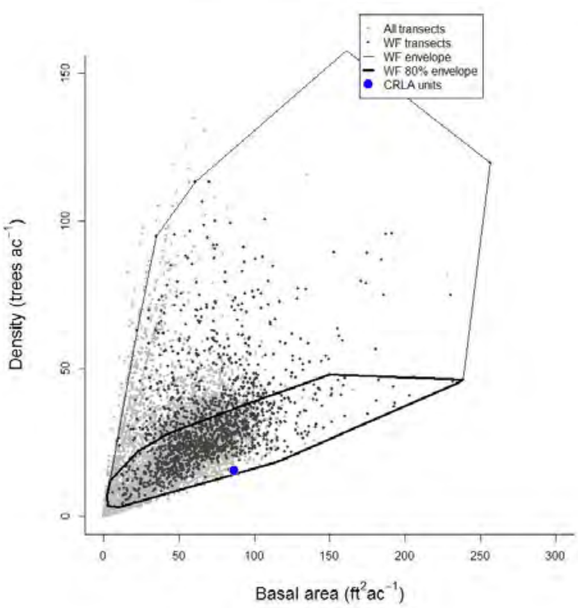
Non-commercial treatment: Clear non-merchantable trees to promote large openings

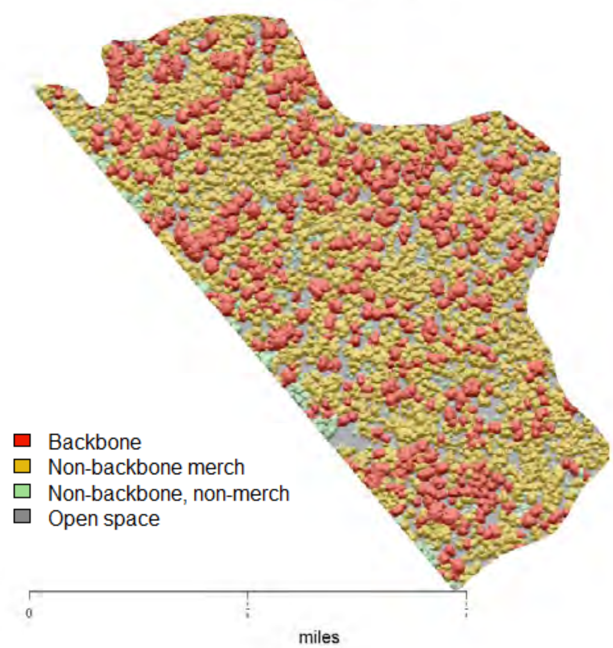
Unit 1200

Acres: 33.6
Backbone TPA: 15.5
Backbone BA: 86.4
Non-backbone merch TPA: 60.7
Non-backbone, non-merch TPA: 7.3









Prescription Recommendations

Target TPA: 25

Non-backbone retain TPA: 9.5

Clumping level: Medium

Clumping targets:

- Bring 3 individuals per acre into small or medium clumps
- Add 1 medium clump per acre
- Add 1 large clump per 5 acres

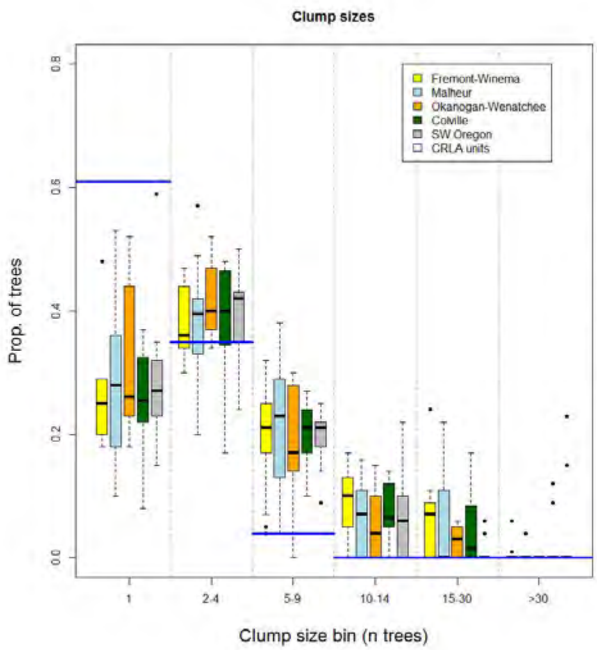
Opening targets:

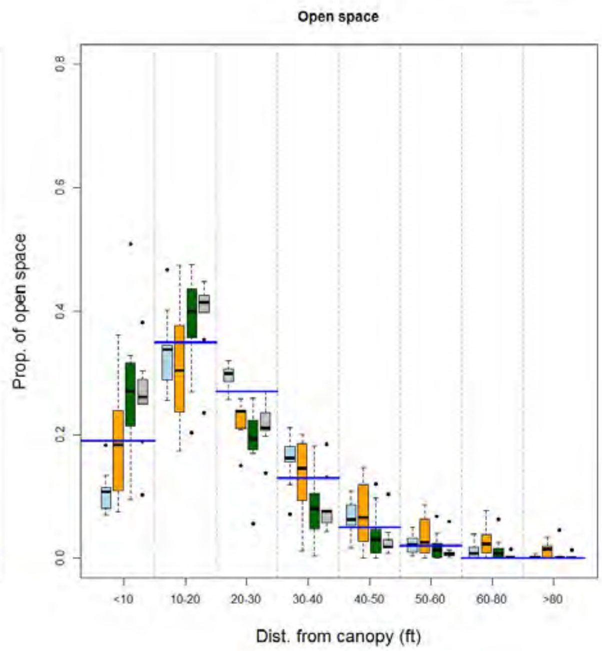
- Leave retention clumps in patches rather than dispersing them
- Leave at least 1 large opening, 0.1-0.25 acres in size, per 6 acres

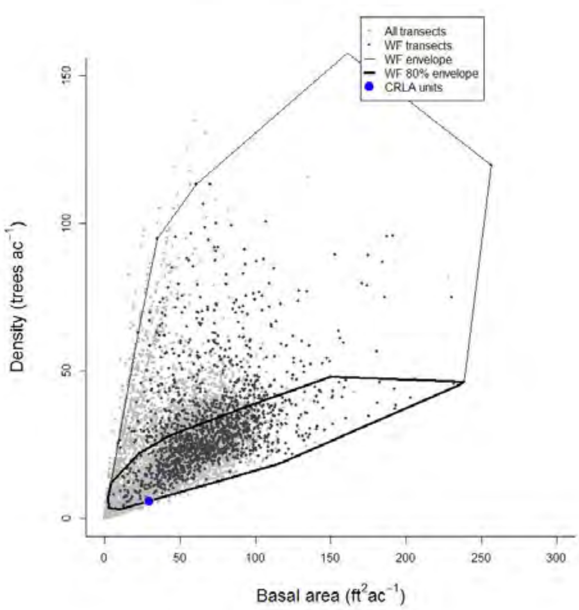
Non-commercial treatment: Not enough information due to high large-tree canopy cover

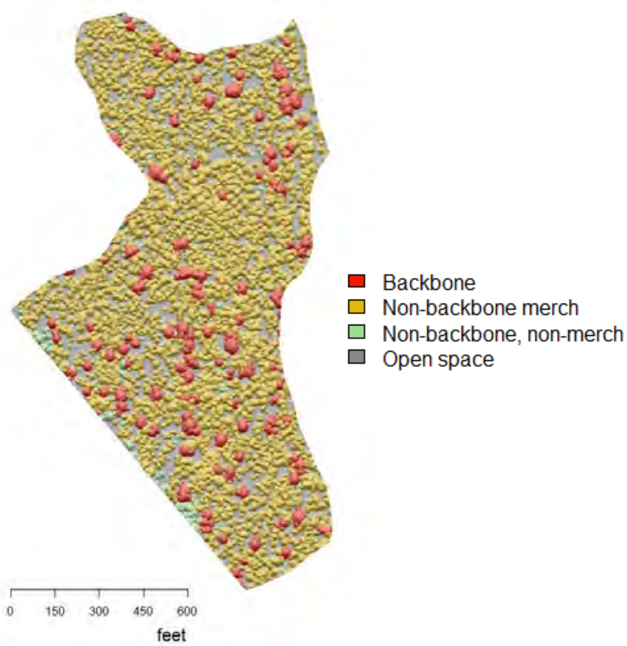
Unit 1300

Acres: 28.2
Backbone TPA: 5.9
Backbone BA: 29.7
Non-backbone merch TPA: 83.5
Non-backbone, non-merch TPA: 6.6









Prescription Recommendations

Target TPA: 18

Non-backbone retain TPA: 12.1

Clumping level: Low

Clumping targets:

- Add 3 individuals per acre
- Add 2 small clumps per acre
- Add 1 medium clump per 2 acres

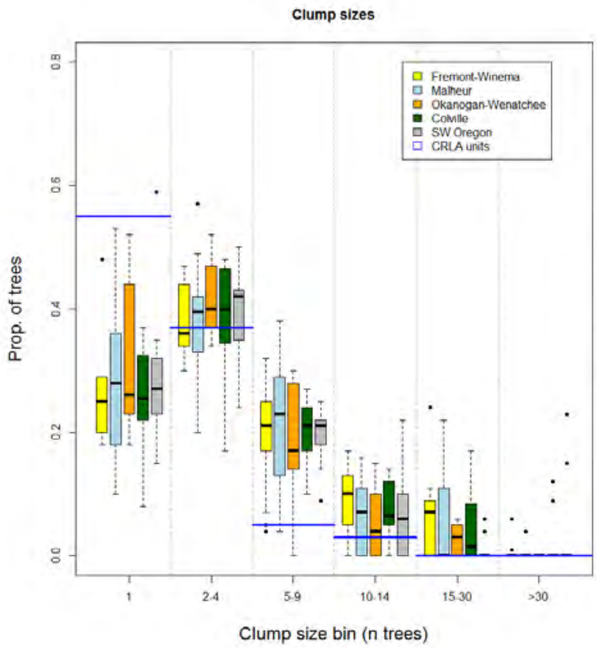
Opening targets:

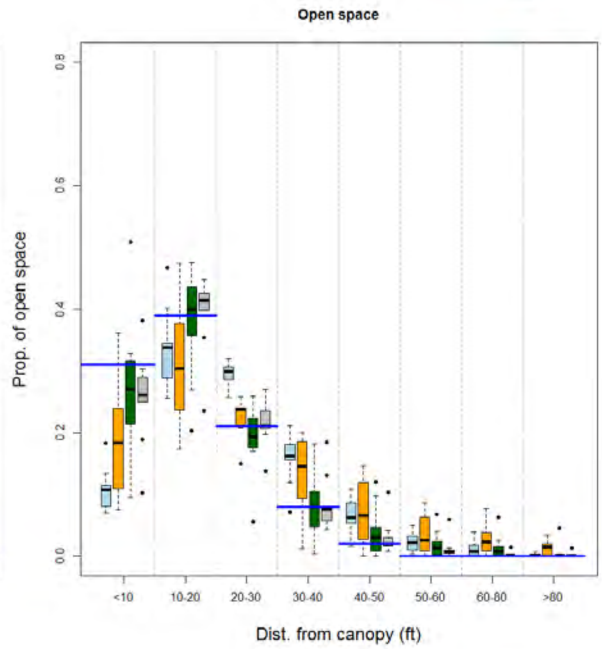
- Removing most of the non-merchantable trees will provide plenty of open space

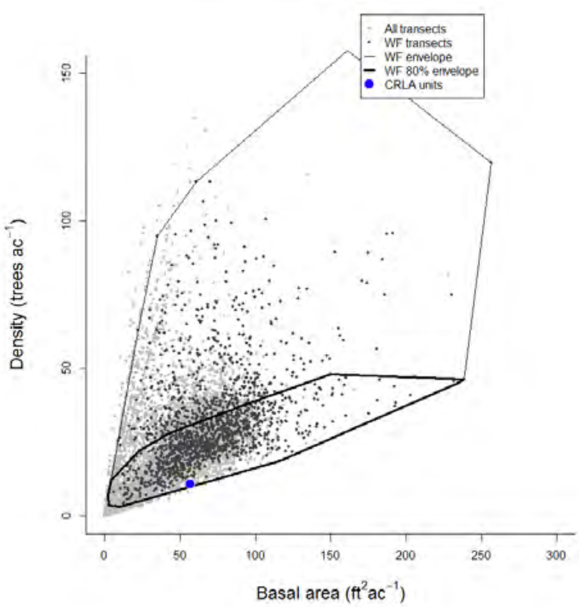
Non-commercial treatment: Not enough information due to high large-tree canopy cover

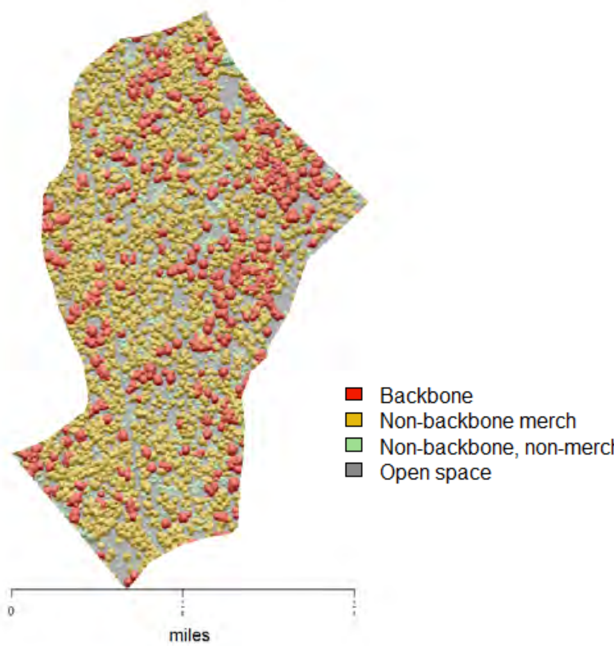
Unit 1400

Acres: 38.3
Backbone TPA: 10.7
Backbone BA: 57.1
Non-backbone merch TPA: 49.1
Non-backbone, non-merch TPA: 13.2









Prescription Recommendations

Target TPA: 23

Non-backbone retain TPA: 12.3

Clumping level: Low

Clumping targets:

- Add 2 individuals per acre
- Add 2 small clumps per acre
- Add 1 medium clump per 2 acres

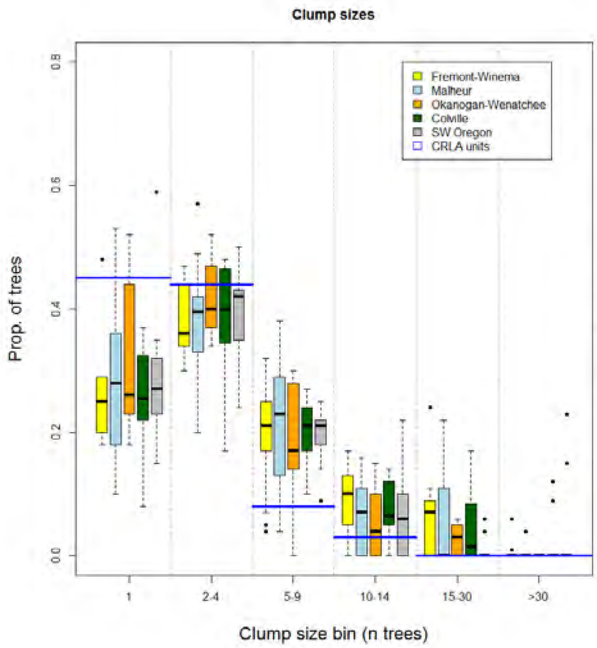
Opening targets:

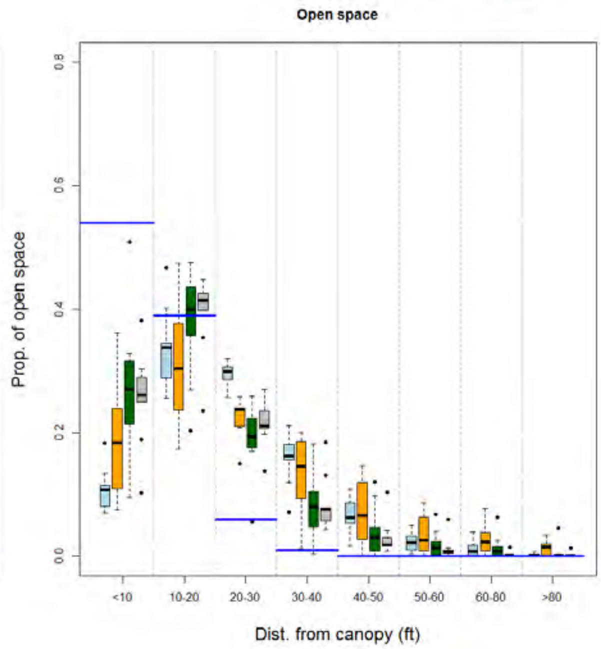
- Removing most of the non-merchantable trees will provide plenty of open space

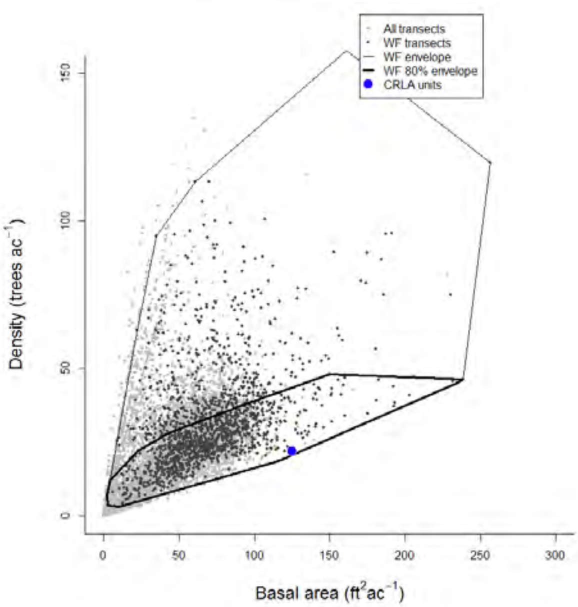
Non-commercial treatment: Clear non-merchantable trees to promote large openings

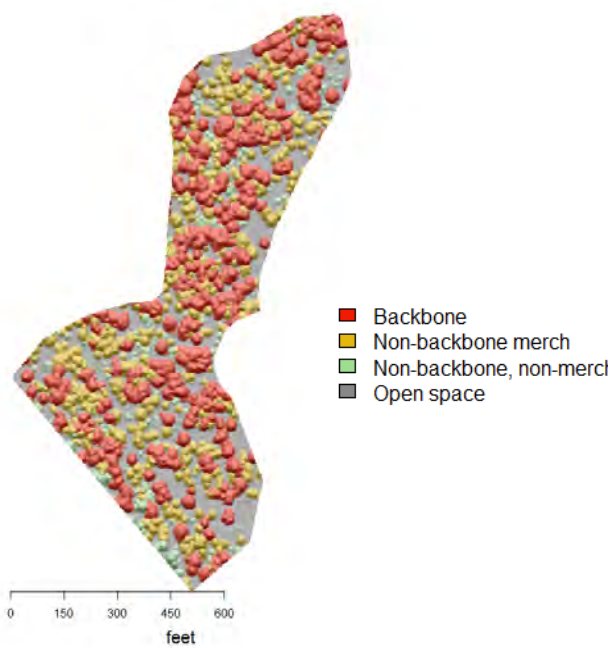
Unit 1500

Acres: 13.6
Backbone TPA: 22
Backbone BA: 124.9
Non-backbone merch TPA: 25.5
Non-backbone, non-merch TPA: 11.4









Prescription Recommendations

Target TPA: 35

Non-backbone retain TPA: 13

Clumping level: High

Clumping targets:

- Bring 3 individuals per acre into small and medium clumps
- Add 1 small clump per acre
- Add 1 medium clump per acre
- Add 1 large clump per 2 acres
- Add 1 super clump per 10 acres

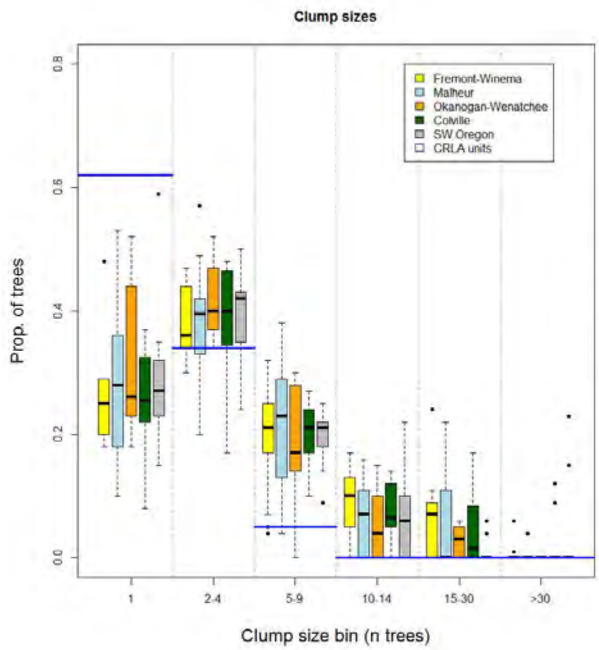
Opening targets:

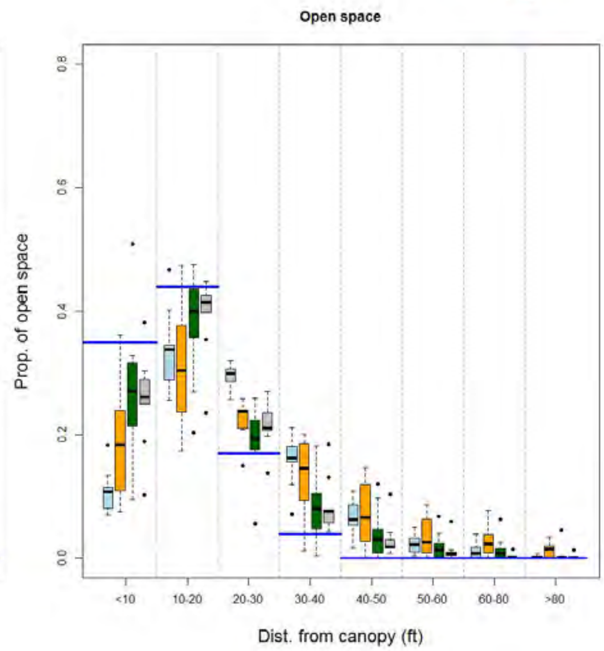
- Leave retention clumps in patches rather than dispersing them
- Leave at least 1 large opening per 8 acres

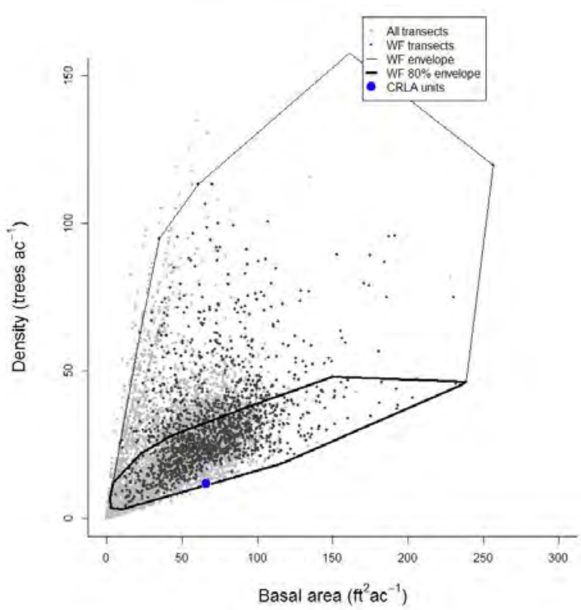
Non-commercial treatment: Save scattered pine regen patches, remove all else

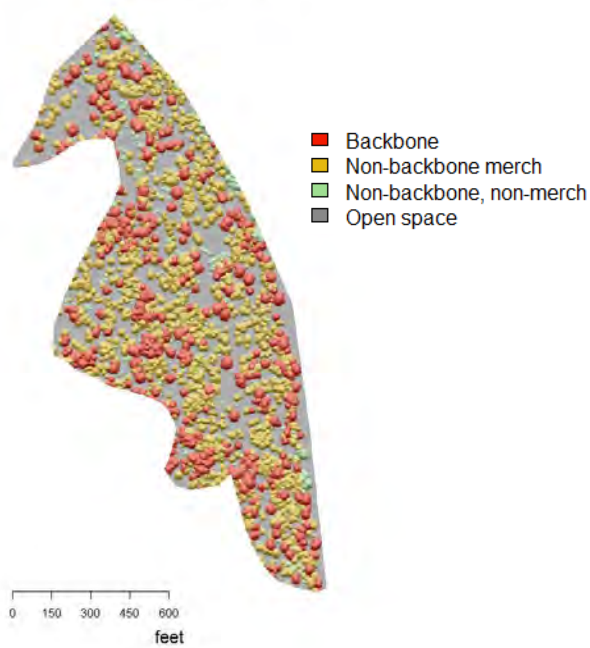
Unit 1600

Acres: 27.8
Backbone TPA: 11.8
Backbone BA: 66.1
Non-backbone merch TPA: 33.8
Non-backbone, non-merch TPA: 7.2









Prescription Recommendations

Target TPA: 20

Non-backbone retain TPA: 8.2

Clumping level: Low

Clumping targets:

- Add 2 small clumps per acre
- Add 1 medium clump per 2 acres

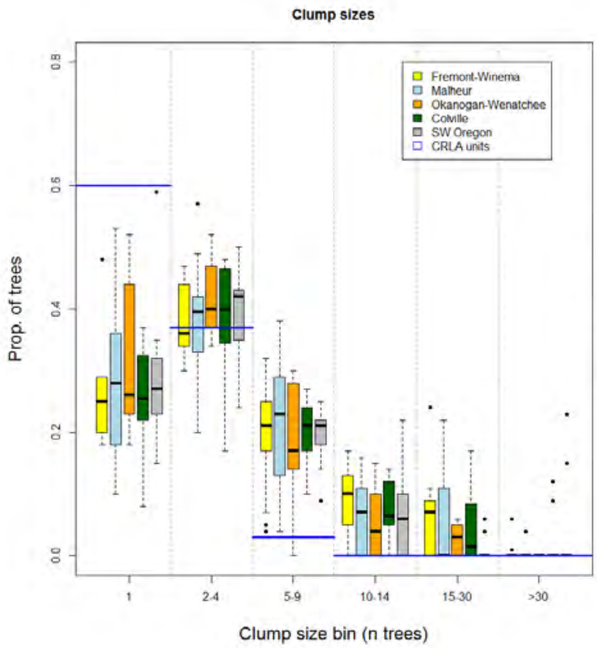
Opening targets:

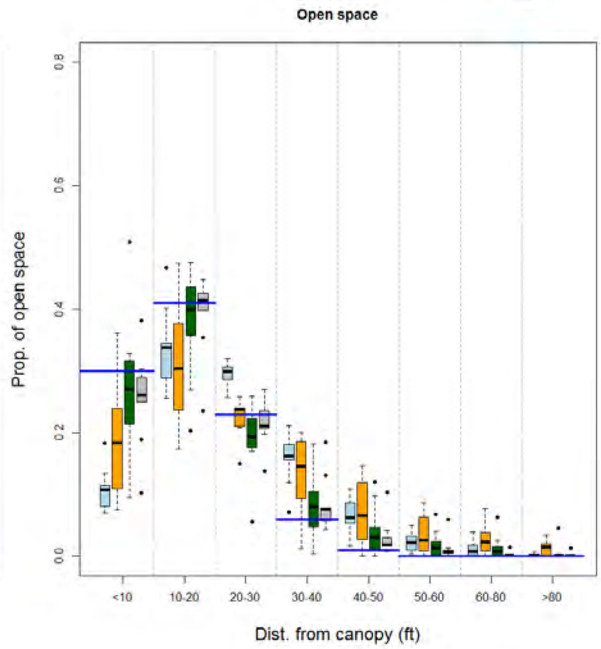
- Removing most of the non-merchantable trees will provide plenty of open space

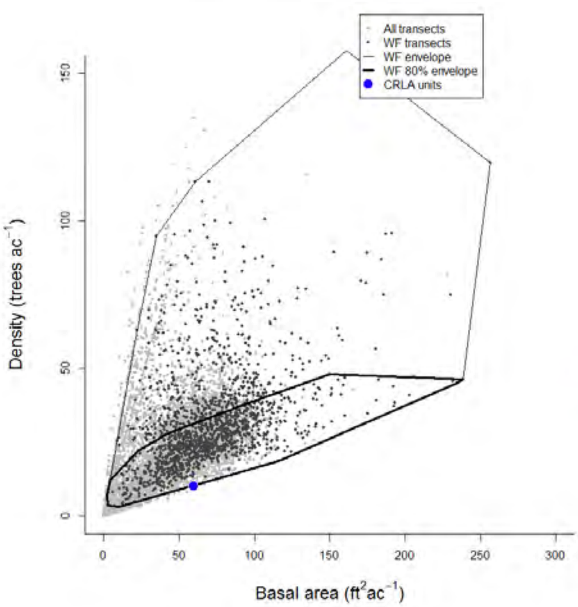
Non-commercial treatment: Save scattered pine regen patches, remove all else

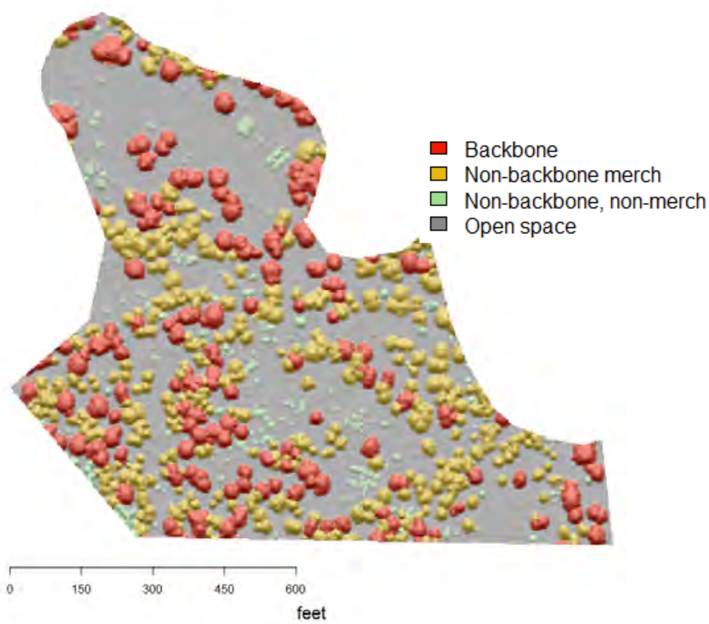
Unit 1700

Acres: 18.5
Backbone TPA: 10.1
Backbone BA: 59.7
Non-backbone merch TPA: 21.5
Non-backbone, non-merch TPA: 10









Prescription Recommendations

Target TPA: 14

Non-backbone retain TPA: 3.9

Clumping level: Low

Clumping targets:

- Bring 1 individual per acre into small or medium clumps
- Add 1 small clump per acre
- Add 1 medium clump per 3 acres

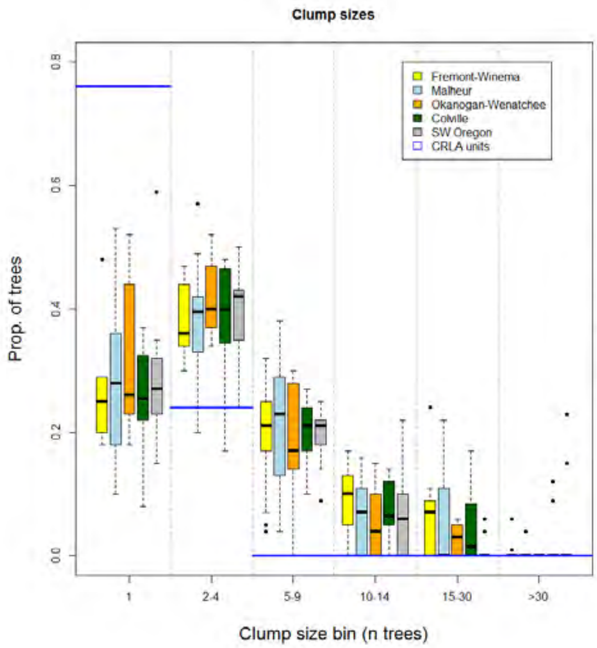
Opening targets:

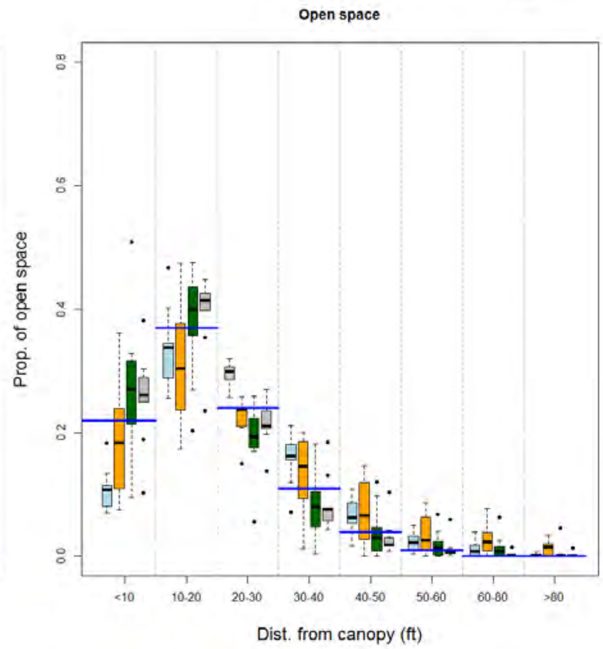
- Removing most of the non-merchantable trees will provide plenty of open space

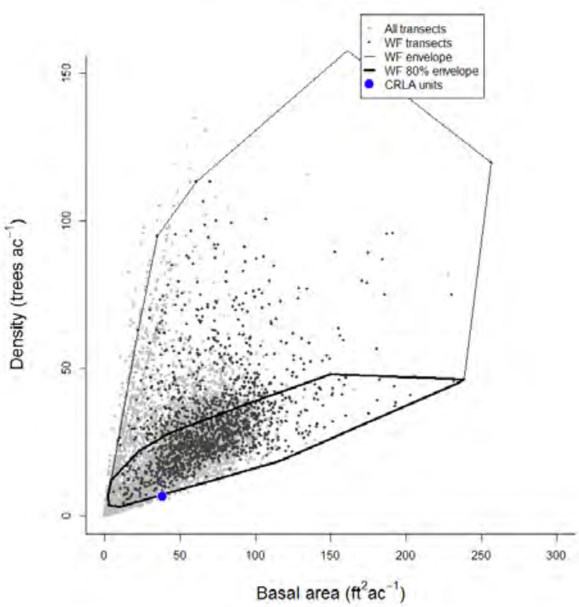
Non-commercial treatment: Save scattered regen patches, remove all else

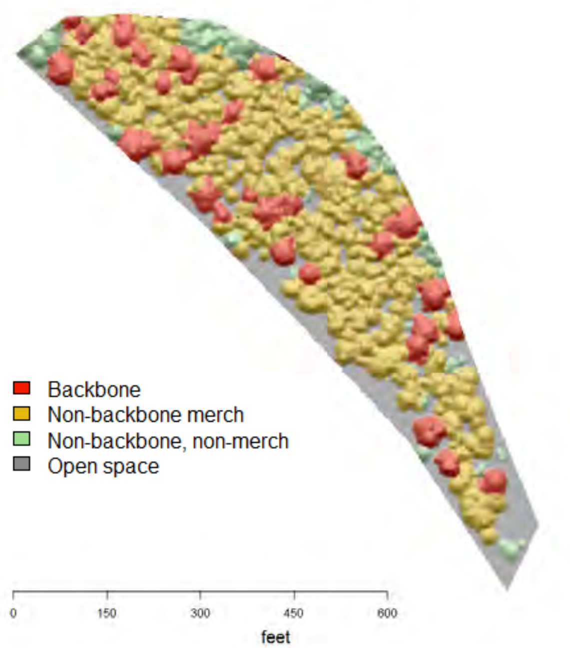
Unit 1900

Acres: 5.8
Backbone TPA: 6.6
Backbone BA: 38.6
Non-backbone merch TPA: 57.6
Non-backbone, non-merch TPA: 3.3









Prescription Recommendations

Target TPA: 12

Non-backbone retain TPA: 5.4

Clumping level: Low

Clumping targets:

- Bring 1 individual per acre into small or medium clumps
- Add 1 small clump per acre
- Add 1 medium clump per 3 acres

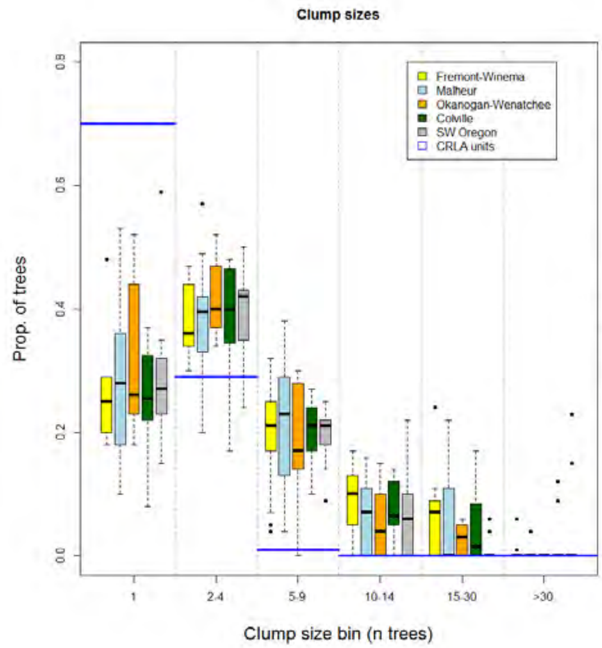
Opening targets:

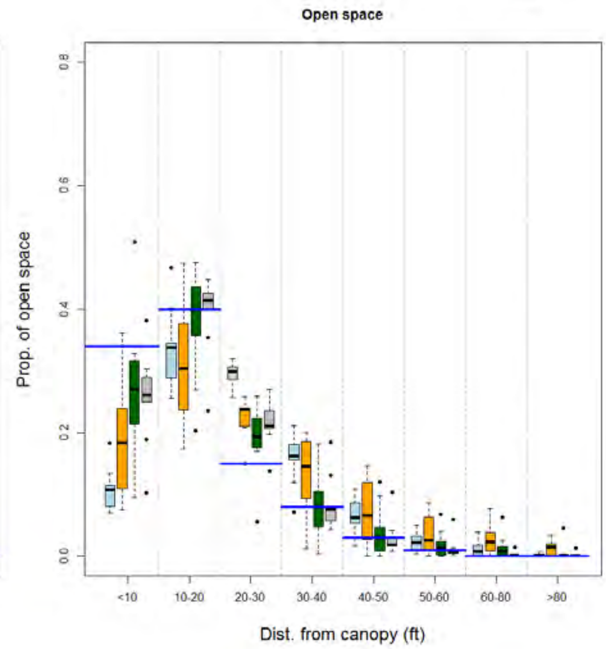
- Removing most of the non-merchantable trees will provide plenty of open space

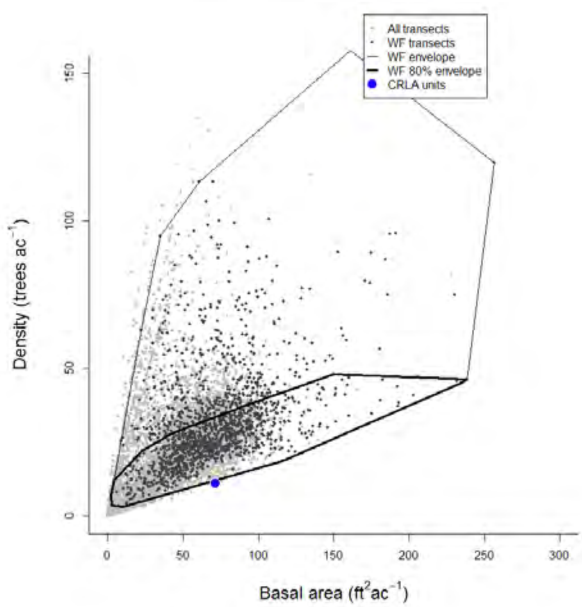
Non-commercial treatment: Not enough information due to high large-tree canopy cover

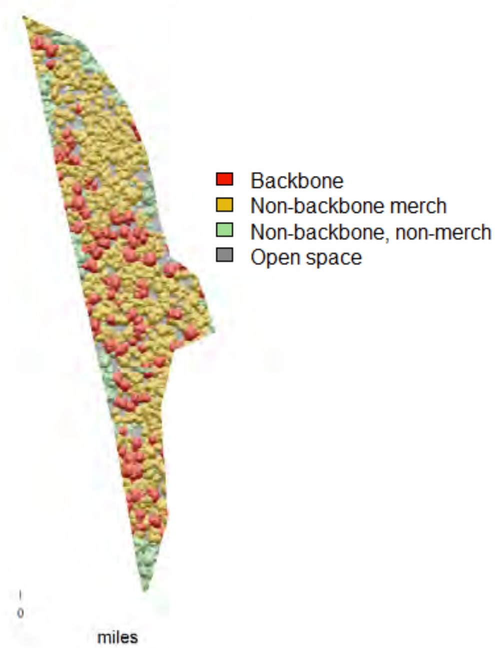
Unit 2000

Acres: 9.8
Backbone TPA: 11
Backbone BA: 71.5
Non-backbone merch TPA: 57.1
Non-backbone, non-merch TPA: 4









Prescription Recommendations

Target TPA: 18

Non-backbone retain TPA: 7

Clumping level: Medium

Clumping targets:

- Bring 3 individuals per acre into small or medium clumps
- Add 1 small clump per acre
- Add 1 medium clump per 2 acres
- Add 1 large clump per 5 acres

Opening targets:

- Removing most of the non-merchantable trees will provide plenty of open space

Non-commercial treatment: Not enough information due to high large-tree canopy cover

Appendix C: Description of data products delivered

All geospatial data products are in the Oregon Statewide HARN International Feet projection.

Table 1 Files and folders with descriptions

File name	File type	Description
CHM	Folder	Canopy height model in metric units
CanopyHeight.img	Raster	0.75 m resolution raster of canopy height above ground level in meters
CanopyHillshade.img	Raster	0.75 m resolution raster of hillshade treating the canopy height model as topography
CHM_ft	Folder	Canopy height model in English units
CanopyHeight.img	Raster	0.75 m resolution raster of canopy height above ground level in feet
Openings	Folder	Metrics related to open space in the canopy in metric units
IntertreeSpace.img	Raster	0.75 m resolution raster giving distance to the nearest tree in meters for every cell that is not covered by canopy
Openings_12mDia.img	Raster	0.75 m resolution binary raster delineating openings, with the value 1 representing area in openings of at least 12 m in diameter
BackboneIntertreeSpace.img	Raster	Same as IntertreeSpace.img, except calculated after removing all non-backbone trees
BackboneOpenings_12mDia.img	Raster	Same as Openings_12mDia.img, except calculated after removing all non-backbone trees
Openings_ft	Folder	Metrics related to open space in the canopy in English units
IntertreeSpace.img	Raster	0.75 m resolution raster giving distance to the nearest tree in feet for every cell that is not covered by canopy
BackboneIntertreeSpace.img	Raster	Same as IntertreeSpace.img, except calculated after removing all non-backbone trees

Rx-units	Folder	Prescription information for each unit
Rx_units.shp	Shapefile	Polygons with unit boundaries and an attribute table containing prescription targets. See Table 2 for metadata
TAO	Folder	Tree-approximate object layers in metric units
TAO_HighPoints.shp	Shapefile	Point file containing the high point for each TAO along with metrics about the TAO. See Table 3 for metadata.
TAO_MaxHeightMap.img	Raster	0.75 m resolution raster where each cell takes on the maximum height, in meters, of the TAO that it is associated with
TAO_UniqueIDs.img	Raster	0.75 m resolution raster where each cell takes on a value corresponding to the unique ID of the TAO that it is associated with
TAO_ft	Folder	Tree-approximate object layers in English units
TAO_HighPoints.shp	Shapefile	Point file containing the high point for each TAO along with metrics about the TAO. See Table 3 for metadata.
TAO_MaxHeightMap.img	Raster	0.75 m resolution raster where each cell takes on the maximum height, in feet, of the TAO that is associated with

Table 2 Metadata for Rx_units.shp

Attribute	Data Type	Description
Unit	Text	ID number of treatment unit
Acres	Number	Number of acres in unit
TargetTPA	Number	Target density in trees per acre
BckBnTPA	Number	Number of backbone trees per acre of the unit
ClumpLvl	Text	Target clumping level: Low, Medium, or High (See Table 4 in the main text)
TgtInd	Number	Target proportion of trees as individuals, with no neighbors within 20 feet
TgtSmall	Number	Target proportion of trees in small clumps of 2-4 trees using a 20 ft limiting distance
TgtMed	Number	Target proportion of trees in medium clumps of 5-9 trees using a 20 ft limiting distance
TgtLarge	Number	Target proportion of trees in large clumps of 10-14 trees using a 20 ft limiting distance
TgtSuper	Number	Target proportion of trees in super clumps of 15-30 trees using a 20 ft limiting distance
AddInd	Text	Number of individual trees to add per acre to simultaneously meet TPA and clumping targets. Sometimes this is a negative number; in this case the given number of individual backbone trees should be added into clumps
AddSmall	Text	Number of small (2-4 trees) clumps to add per acre to simultaneously meet TPA and clumping targets
AddMed	Text	Number of medium (5-9 trees) clumps to add per acre to simultaneously meet TPA and clumping targets
AddLarge	Text	Number of large (10-14 trees) clumps to add per acre to simultaneously meet TPA and clumping targets
AddSuper	Text	Number of super (15-30 trees) clumps to add per acre to simultaneously meet TPA and clumping targets

Table 3 Metadata for TAO_HighPoints.shp

Attribute	Data Type	Description
Basin	Number	Unique ID for each TAO
X	Number	X position (feet) of TAO high point in Oregon Statewide HARN International Feet projection
Y	Number	Y position (feet) of TAO high point in Oregon Statewide HARN International Feet projection
MaxHt	Number	Maximum LiDAR return height measured in the TAO, units are feet (English) or meters (metric)
ClumpID	Number	ID of clump that this TAO is a member of
ClumpSize	Number	Size of clump that this TAO is a member of
ClumpBin	Text	Binned size of clump that this TAO is a member of: Individual, Small (2-4), Medium (5-9), Large (10-14), or Super (15-30)
Backbone	Binary	1 if this TAO is a backbone TAO, 0 otherwise
CrownArea	Number	Area of delineated TAO crown in square feet (English) or square meters (metric)
BbClumpID	Number	ID of clump that this TAO is a member of, only considering backbone TAOs
BbClumpSz	Number	Size of clump that this TAO is a member of, only considering backbone TAOs
BbClumpBn	Text	Binned size of clump that this TAO is a member of, only considering backbone TAOs: same bins as ClumpBin
DBH	Number	Estimated DBH of the dominant tree in the TAO in inches (English) or centimeters (metric)
RxUnit	Number	Unit this TAO is in, corresponding to Unit in Rx_units.shp
Merch	Binary	1 if this TAO's estimate DBH is ≥9 in, 0 otherwise