Digital technology enhances tree marking effectiveness in meeting restoration objectives in southwestern ponderosa pine.

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Abstract

Traditional, paint-based methods for marking trees prior to harvest are time consuming, resource intensive, and demand a great deal of skill to create desired structural conditions. In Northern Arizona ponderosa pine forests, current demand for meeting restoration objectives outpaces the ability to implement traditional designation methods, namely leave-tree marking. Recent technological developments promise to improve marking efficiency. These digital technologies include Tablet Marking, a technique that relies on spatially explicit designation of leave-tree groups using GIS or both GIS and aerial lidar in the field, and Heads-Up-Digitizing, which uses GIS and aerial lidar in an office setting. Our objective was to compare the effectiveness of tree marking techniques in meeting silvicultural prescription objectives. In a 360-acre treatment area, we implemented 3 replications of 6 different tree designation techniques to meet the same objectives. Additionally, we installed 185 plots to ground-truth stand density, tree form and vigor, and the location of large trees (> 18 inches, DBH) before harvest; plots will be re-measured following harvest. We quantified pre-harvest conditions across replicates and used GIS to assess prescription objectives across marking methods. If units are harvested according to their current marking, the results indicate that digital marking methods were better than leave-tree-marking at achieving desired basal area and tree-group size distributions. All designation methods retained a similar amount of large and high-quality trees in groups. Post-harvest data collection and analysis is needed to determine the actual "on-the-ground" results of different treatment methods.

Introduction

Ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) is the dominant forest overstory species in northern Arizona forests at elevations of approximately 7,000 to 8,000 ft (Pearson 1931). Prior to European American settlement, ponderosa pine forests experienced frequent, low-severity surface fires which created open, low-density overstory conditions (Covington and Moore 1994). Additionally, frequent surface fire maintained an aggregated structure composed of groups of trees with interlocking or touching crowns (Larson and Churchill 2012). The arrival of European-American influence through intensive grazing, logging, and fire suppression led to altered fire-regimes and subsequent high-density, homogeneous overstory conditions present today. In addition to altered ecological structure and function, climatic shifts have resulted in forests that are increasingly susceptible to large, high-severity, stand-replacing fire events (Singleton et al. 2019). Currently, forest managers in Arizona have identified the need to reduce overstory densities and forest floor fuel loads, increase spatial heterogeneity, and restore more frequent low-severity fire in ponderosa pine forests (Covington et al. 1997; Reynolds et al. 2013).

Unfortunately, current demand for mechanical treatments exceeds the ability to execute those treatments. For example, the Four Forests Restoration Initiative (4FRI) is a collaborative, landscape-scale restoration project that seeks to mechanically treat 50,000 ac per year across northern Arizona forests (USDA 2015). However, between 2010 to 2019, approximately 25,000 acres per year were mechanically harvested (USDA 2020). Such demand necessitates the development of new techniques to efficiently implement silvicultural treatments with the objectives of restoration and fuels reduction.

Typical silvicultural prescriptions executed under the auspices of 4FRI call for creating "groups" of trees having interlocking or touching crowns separated by canopy gaps, or "interspace" (Appendix A, Figure A1). The overall objectives are to reduce density and create a heterogeneous, aggregated horizontal structure (Moore et al. 1999; Harrod et al. 1999; Sanchez Meador et al. 2011; Larson and Churchill 2012; Tuten et al. 2015). Mechanical harvesting is used to create these structural characteristics from existing stand conditions (Reynolds et al. 2013; USDA 2015).

In implementing mechanical treatments, managers must effectively achieve the desired density and spatial objectives according to the prescription. To do so, tree marking, or designation, is the accepted and legal method for determining which trees should be harvested, and which should be left standing (U.S. Code § 472a). However, one "bottleneck" in the process of preparing forest stands for mechanical treatment is the time- and personnel-intense nature of traditional, paint-based Individual-Tree Marking techniques (Dickinson and Cadry 2017). Individual-Tree Marking entails a marking crew systematically moving through the stand, applying paint to ("marking") individual trees for retention or harvest. Marking trees that are to be harvested is called Cut-tree Marking (CTM); marking trees to retain in the stand is called Leave-tree Marking (LTM). While Individual-Tree Marking has long stood as the primary method of designating trees for harvest or retention, it is costly in terms of material (paint), personnel, and time. Therefore, solutions to more efficient tree designation are needed.

Designation by Prescription (DxP) is one solution (U.S. Code § 472a; USDA 2016). DxP eliminates the need for traditional, paint-based Individual-Tree Marking, instead relying on the logger to implement the prescription. The logger is responsible for determining which trees need to be cut and which to leave in accordance with the prescription. This method has been shown to be faster and less resource intensive for foresters, but concerns have been raised about meeting prescription targets and ecological objectives (Dickinson and Cadry 2017; Camenson 2019). From a silvicultural standpoint, concerns include the lack of monitoring the quality of the mark in terms of meeting prescription objectives and the potential for loggers to incorporate bias into their tree selection decisions. Concerns from an operations standpoint include the increased time involved in selecting trees and the increased need for administrative oversight of the logger.

The use of digital technology promises to address the concerns about DxP's effectiveness and efficiency. Managers for the Coconino and Kaibab National Forests, as well as the Nature Conservancy have developed "Tablet Marking" (hereafter DxP + Imagery; TNC 2017; Camenson 2019; TNC 2020). This spatially explicit technique aims to meet silvicultural objectives by creating polygons in a mobile Geographic Information System (GIS) (Table 1). Using DxP + Imagery, a prescription for mechanical treatment might be implemented in the following manner. The marker walks through the stand looking for potential groups of high-quality trees as well as areas appropriate for creating interspace. The ESRI World Imagery background layer is displayed on a tablet, along with unit boundaries (Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community). Polygons are digitally drawn or streamed around groups of desirable trees for retention. The driplines of the outermost trees of the groups define the polygon boundaries.

Because each group-polygon may need to have trees removed, the tablet marker enters its target basal area (BA) per unit area into a corresponding field in the attribute table. Additional information such as group area, treatment type, current BA, and notes are also associated with each polygon. Any area not covered by polygons is designated as interspace and all second-growth trees are to be cut from it. During harvest, operators refer to their location in the stand using a tablet mounted in their machinery. This allows them to locate designated leave-tree groups and apply the associated prescription component.

Recent developments in aerial Light Detection and Ranging (hereafter lidar) technology have resulted in numerous digital products that promise to improve foresters' overall understanding of the density, composition, structure, and aggregation of the stands they are treating (Maltamo et al. 2014; Niemi and Vauhkonen 2016; Jeronimo et al. 2018; Wiggins et al. 2019). Lidar technology uses the reflection of lasers to measure the height of the ground and structures above the ground (Maltamo et al. 2014). In particular, lidar can be used to create a Canopy Height Model (hereafter CHM), which provides an accurate raster map of the height of the canopy and position, often to a horizontal precision of less than one meter. A CHM allows users to locate dominant trees to an acceptable level of accuracy (Lim et al. 2003; Wiggins et al. 2019). The tallest, dominant trees in an even-aged stand may be, hypothetically, the "best" trees for retention in a stand (Tappeiner et al. 2015; Oliver and Larson 1996). Therefore, it is possible that CHM data available to tablet markers could enhance the quality of the mark, making retention of the most vigorous trees more likely. Additionally, the CHM could be used to identify existing seedlings or advance regeneration, which would determine the best places to create openings enabling the recruitment of new cohorts. The incorporation of this technology represents the next step in the evolution of tablet marking. Hereafter, the use of the lidar CHM as a background map when tablet marking is called DxP + Lidar (Table 1).

The high resolution and accuracy of lidar data presents the opportunity to delineate group-polygons off-site, on an office-based desktop computer. This designation method is implemented using GIS software, the details of the CHM, and aerial photography. Details such as dominant overstory trees, advance regeneration, and existing canopy gaps allow the marker to determine the placement of tree-groups, interspace, and regeneration openings. This designation method is referred to as Heads-Up Digitizing (hereafter HUD; Table 1).

Previously, D x P + Imagery only has been shown to be effective in meeting forest health and stand density objectives (Camenson 2019). However, DxP + Lidar and HUD have not been compared with other designation methods. Additionally, the ability of digital designation methods (DxP + Imagery, DxP + Lidar, and HUD) to achieve an aggregated horizontal structure within explicit group size constraints is untested. Furthermore, the overall efficacy of digital designation methods in general remains in question, as well as the ability of emerging technology to improve outcomes. Therefore, a comprehensive analysis of the effect of different marking techniques is needed to ensure that the silvicultural objectives of treated stands are attained.

The six designation methods discussed in this paper are as follows (Table 1). Two t*raditional methods*: LTM and DxP; Three *digital methods:* D x P + Imagery, D x P + Lidar, HUD; and no marking (Untreated). The objective of this study was to assess current stand conditions and to compare digital designation methods with traditional methods in achieving silvicultural objectives in a pure ponderosa pine forest in northern Arizona.

Table 1. Description of designation methods and abbreviations used in this paper. Designation was implemented for all methods except NoCut. And DxP, which do not require marking of individual trees or spatially explicit groups.

Method Abbreviation	Designation Method	Description
NoCut	Untreated/Unmarked	No designation or harvest
LTM	Leave Tree Marking	Trees marked for retention by ground-based crews using orange paint.
DxP	Designation by Prescription	No trees marked. Logger follows prescription.
DxP + Imagery	Tablet Marking	Polygons drawn around groups for retention by ground-based crews using aerial photographs as a guide.
DxP + Lidar	Tablet Marking with lidar	Polygons drawn around groups by ground-based crews using a lidar canopy height model as a guide.
HUD	Heads-Up Digitizing	Polygons drawn from a remote location (office) using a lidar canopy height model and aerial photography as a guide.

Methods

Site Description

The study site was located on the Coconino National Forest in northern Arizona, about 1.5 miles from the unincorporated community of Bellemont (Figure 1). The 360-acre site was located within the 4FRI planning area, was part of the "Walker Hill" timber sale, and was approximately centered at the intersection of sections 22, 23, 26, and 27, Township 22N, Range 5E, Gila and Salt River Baseline and Meridian. Topographically, the site was mostly flat with shallow drainages oriented toward the south. The elevation ranged between 7200 and 7300 feet above sea level. The climate was semi-arid, with about 19 inches per year of precipitation, an annual high temperature of 60°F and annual low temperature of 26°F (Flagstaff Weather Forecast Center 2018). Soils were a clay loam, derived from basalt parent material (Miller et al. 1995).

The vegetation of the site was dominated by an overstory of 100% ponderosa pine (*Pinus ponderosa* var. *scopulorum*). Understory vegetation was primarily grasses, predominantly composed of Arizona fescue (*Festuca arizonica*) and blue grama (*Bouteloua gracilis*). The site was logged as recently as 1990. Past treatments included a mix of pre-commercial thinning and commercial thinning across the study site.

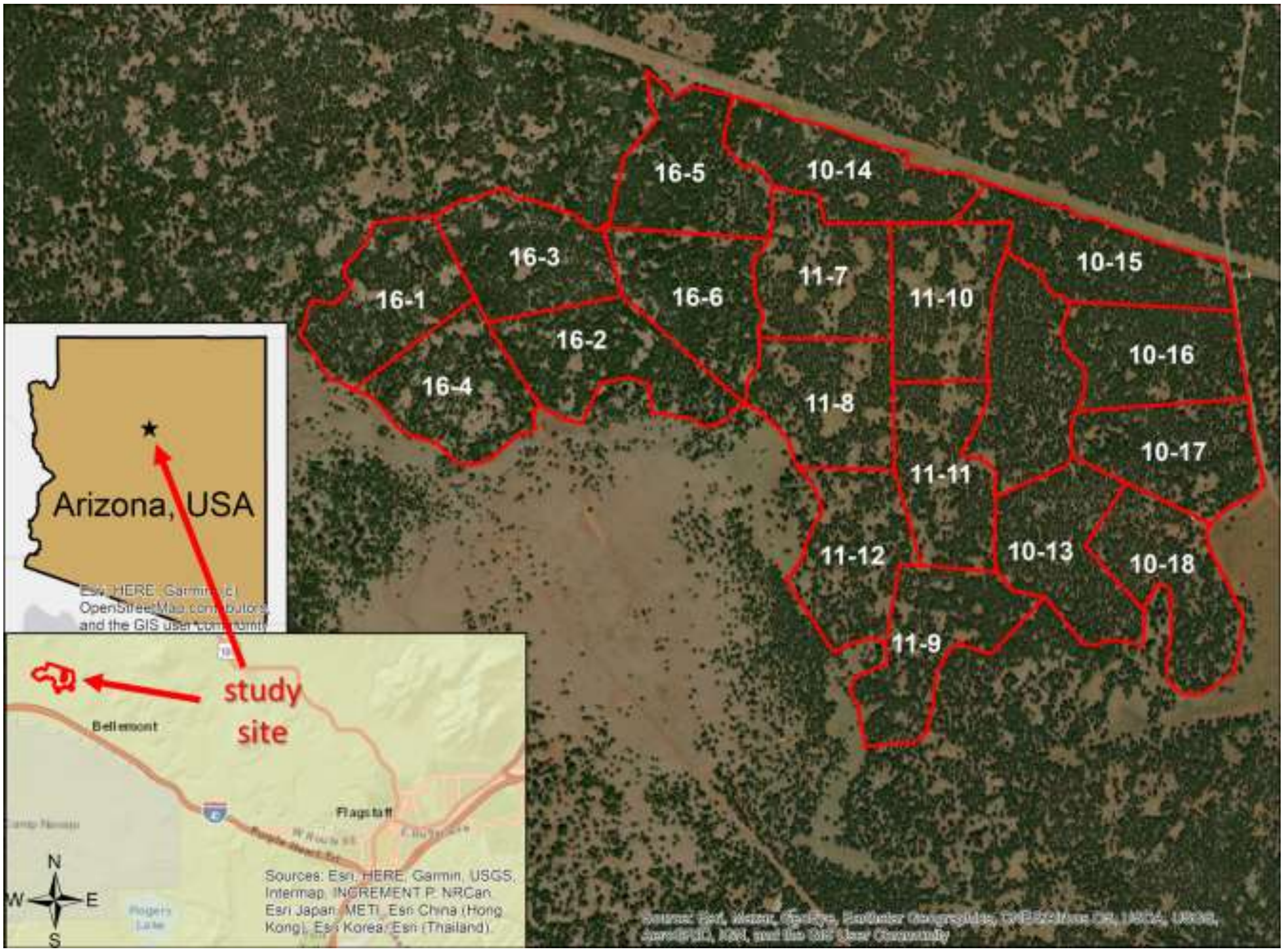

Figure 1. Study site location and 20-acre experimental units. Experimental unit numbers indicate the block number first, followed by the unit number after the hyphen. See text for additional detail regarding the study site and experimental design.

Silvicultural Prescription

The intent of the silvicultural prescription is to approximate historic reference conditions in the ponderosa pine ecosystem type (Moore et al. 1999; Reynolds et al. 2013). Designated as a "UEA40" (Uneven-Age, 40% interspace) treatment according to Appendix D 4FRI Final Environmental Impact Statement (FEIS; USDA 2015), the prescription follows a modified group selection silvicultural system which seeks to regenerate a new cohort, while reducing density throughout the stand (Appendix B). Additionally, the intent is to create a heterogeneous horizontal structure characterized by groups of trees with interlocking or near-interlocking crowns and "interspace," or canopy gaps between tree groups.

The following is a description of specific quantitative objectives detailed in the prescription, which can be found in Appendix B. First, the prescription calls for an average target stand-level BA of 50 sq ft ac^{-1}, with 40% to 55% of the stand area on average to be interspace, and 45% to 60% to be in tree-groups (Table 2). Because all trees in interspace are to be harvested, with the exception of yellow-pine, the residual BA in interspace will be at or near 0, while the BA of designated tree-groups will be thinned to a BA higher than 50 sq ft ac^{-1} so that the total stand-level BA will be at the prescribed objective. Additionally, tree group sizes are to be distributed across three classes: 0.1 to 0.25 ac, 0.25 to 0.5 ac, and 0.5 to 1.0 ac, with the number of groups in each class to be distributed as 30%, 30%, and 40%, respectively. Using the midpoint of each group size class and the aforementioned distribution, the average group size is0.45 ac.. According to the prescription, tree groups should be located in areas having trees of the best quality (Appendix B). Healthy advance regeneration is defined as trees greater than 3 ft tall and less than 5.0 in diameter-at-breast-height (dbh), measured 4.5 ft from ground level. Regeneration openings should target removal of all second-growth trees less than 18” dbh and greater than 6” dbh, thus creating space for the establishment of a new cohort of trees, or release of existing advance regeneration, and shifting the future age structure to be more uneven-aged. In regeneration openings larger than 1 acre, 3 – 5 trees may be left as a seed source.

For the digital designation methods, the prescription further defines three Group Types. Free Thin group-polygons are to be thinned to the target BA by harvesting trees across diameter classes. Thin From Below group-polygons are to be thinned by removing the smallest diameter trees a to aBA target defined by the marker. No Cutting groups are designated to have no trees harvested in them due to BA already being close to desired levels, or the group being inoperable due to terrain (i.e. rocky ground). Group type information is associated with each polygon and is available to the logger during harvest.

Additionally, the prescription calls for all old trees (“yellow-pine”) tobe retained. Old trees are defined as over 150 years in age, according to the 4FRI FEIS, Appendix D (USDA 2015), and are identified by the yellow, platy bark that covers the majority of the bole’s height.

Table 2. Silvicultural prescription spatial targets. Tree-groups are canopy patches that are to be retained in the stand. Regeneration openings are canopy gaps to be created for the recruitment of a new cohort. Interspace is the canopy gaps created through the creation of an aggregated structure.

Tree-Groups	Regeneration Openings	Interspace
45% - 60% of stand area	10% of stand area	40% - 55% of stand area
0.1 – 1.0 acres per group	0.3 – 0.8 acres per opening, on average	60 – 100 feet wide (maximum width = 200 feet)
Group size distribution: (a) 30% 0.1-0.25 acre (b) 30% 0.25-0.5 acre (c) 40% 0.5-1.0 acre	Target existing healthy advance regeneration or areas with a preponderance of small trees with poor form	Utilize existing openings or areas with low-quality trees.

Marking and Experimental Block Design

The 360-acre project area was divided into three 120-acre blocks (Figure 1). Blocks were created using existing Forest Service stand boundaries and boundaries were adjusted in ArcGIS to be a) similar in size and b) include relatively similar overstory conditions within each block. Each block was further divided using ArcGIS into six 20-acre (+/- 0.2 ac) experimental units.All unit boundaries were marked with double orange horizontal stripes on trees approximately 1-2 chains apart. Boundary tree locations were recorded using an Archer GPS. Final unit boundaries were digitized using the UTM coordinates of the boundary trees. The same prescription was applied to all experimental units across all blocks. Each experimental unit was randomly assigned one of the six designation methods (Table 1; Appendix A, Figure A2).

All personnel who carried out the marking were employees of the Coconino National Forest. For the LTM units, a three-person marking crew implemented the marking following standard Forest Service procedures. This crew was composed of members who had at least three seasons experience marking timber using a variety of designation methods. Each crew member marked a different, randomly chosen, unit. For the DxP + Imagery and DxP + Lidar units, marking was completed by a Silviculture Forester. HUD units were marked by a District Silviculturist. For, the digital methods (DxP + Imagery, DxP + Lidar, and HUD) the markers recorded group type, estimated current and target within-polygon BA. Additionally, DxP and Untreated units remained unmarked because neither requires pre-implementation marking.

Following the completion of LTM in the appropriate units, we defined group-polygons in the field using the same general technique as tablet marking with polygons being drawn by following the dripline of the outermost marked trees in the group using a GPS receiver linked to ArcCollector mobile GIS software (ESRI 2020).

Field Data Collection

To ground-truth remote sensing data and obtain information on pre-implementation stand structure, we established field plots across all experimental units. We used a stratified sample design (Freese 1976) with two strata, designated as a) blackjack and b) yellow-pine. The blackjack stratum was defined as the matrix of largely even-aged, second-growth pine forest. We used the lidar CHM in ArcGIS software to draw polygons designating yellow-pine stratum areas according to the following criteria: areas that exhibited trees over 70 ft tall, relatively open conditions, and the presence of advance regeneration of height greater than 3 feet and less than 10 feet. Yellow-pine stratum polygons were then “ground-truthed” for accuracy by visual inspection in the field. Any non-yellow pine areas were removed from the yellow pine stratum and minor boundary adjustments were made.

We established ten $1/10^{th}$ acre fixed-radius circular plots per experimental unit (Appendix A, Figure A3), resulting in a 5% sample. The number of plots assigned to each stratum in each unit was proportionate to the relative area of that stratum in that unit . In the yellow-pine stratum, plots were randomly placed, with a minimum number of 2 plots. In the blackjack stratum, plot locations were placed using a randomly positioned systematic grid using the “sp” Package in R (Pebesma and Bivand 2005; R Core Team 2020). Due to their irregular shape, units 16-3, 10-16, and 10-18 were assigned more than the required number of plots in units. In this case, plots were randomly removed down to the 10 plots per unit sampling rate. Plots that were initially located on a road, or plots whose center was less than 37.2 ft (radius of a $1/10^{th}$ ac plot) from a unit boundary, were offset a random distance and azimuth such that they would fall fully within the unit.

We recorded the UTM coordinates of each plot center using a Trimble sub-meter GPS receiver. Plot coordinates were differentially corrected after collection. We divided the circular plot into three “sectors” by extending imaginary lines radially from plot center to azimuths 000, 120, and 240 degrees. In each sector, we recorded the distance from plot center to the bole of the nearest live tree >5.0 inches dbh.

Starting at north and moving clockwise, we tagged each on-plot tree, measured and recorded dbh to the nearest 0.1 inch, and recorded form according to the prescription's marking guide (Appendix B). Form classes were Desirable, Acceptable, and Non-desirable, and were defined based on tree live crown ratio, amount of defect, crown class, and insect/disease presence. For trees greater than 17.9 in dbh, we recorded the distance and azimuth from plot center to the face of the tree at 2.5 ft above the ground. In LTM units, we recorded tree designation (leave or cut). Additionally, the total number of seedlings and saplings were tallied. Seedlings were tallied in two size classes, 1 to 2.9 ft tall, and 3 ft tall to 0.9 in dbh. Saplings were tallied in 4 diameter classes, 1.0 to 1.9 in, 2.0 to 2.9 in, 3.0 to 3.9 in, and 4.0 to 4.9 in. Saplings were further classified as desirable or non-desirable according to their form. Desirable saplings were defined as those saplings exhibiting straight growth form with no forking, a live crown ratio greater than 40%, and a position not suppressed or overtopped by competing trees. Saplings not meeting those criteria were classified as non-desirable.

Even-numbered plots were included as part of a sub-sample in which more detailed measurements were taken. These measurements included canopy cover, as well as each tree's total height, height to crown base, and crown radii. For each tree, crown radius was measured in each of the four cardinal directions (N,S,E,W) from the center of the bole to the edge of the dripline. Heights were measured with a hypsometer and canopy cover was measured using a densitometer (moosehorn) on a 15 x 15 ft grid of 25 points per plot (Appendix A. Figure A3).

Analysis

Plot and Stand Level Characteristics

To establish current structure, we calculated mean basal area per acre and trees per acre for each unit. To account for within-unit variability we calculated the standard error of these estimates. We used the tree form data to determine the unit-level percent composition of each form class. Using the subsample of tree heights, canopy base heights, and crown radii, we determined the means and standard errors of these metrics within each unit.

To quantify openness, we used the canopy cover data to establish mean percent canopy cover in each unit.

GIS Analysis

We classified each polygon created by each designation method (LTM, DxP+ Imagery, DxP+ Lidar, HUD) according to its designated treatment type (thin-from-below, free-thin, etc.). For each polygon, we used ArcGIS software (ESRI 2020b) to measure the area and coefficient of variation of area and analyzed the distribution of group areas by designation method and group type. We estimated stand-level residual BA per ac by multiplying each group-polygon's area by its target BA indicated by the marker, summing these results, and dividing them by total stand area.

Using ArcGIS, we determined which field-plots intersected group-polygons for each treatment type. Plots whose centers intersected group-polygons were classified as "in-group" while plots whose centers intersected interspace were classified as "in-interspace." We then assessed mean tree form and average DBH for in-group and in-interspace plots. Additionally, we converted the large tree (>17.9 in. DBH) polar coordinates to UTM coordinates and plotted these points along with the group-polygons. We then tallied the percentage of large, non-yellow pine trees that intersected group-polygons in each unit.

Results

Current overstory conditions. Overstory metrics for each designation method are shown in Table 3. The designation method with the lowest mean BA was HUD at 116.5 sq. ft. ac^{-1}, while the DxP + Imagery units exhibited the highest mean BA at 168.3 sq. ft. ac^{-1}, or 44% higher than HUD (Figure 2). Again, HUD units had the lowest density on average at 152.3 trees ac^{-1}, and the DxP + Lidar units had the highest density at 251.4 trees ac^{-1}, or 65% higher than HUD. Additionally, mean canopy cover varied across designation methods, with HUD at the lowest canopy cover of 45% and DxP + Imagery and DxP units at the highest with 56.8% (Table 3). Variability across the three experimental units was enough that the differences between designation methods were likely not significant. One exception to this is the 90% confidence interval estimates of BA did not overlap for the DxP + Imagery and LTM methods (Table 3).

The proportions of form classes by designation method are presented in Figure 3. Across the designation methods, the relative amount of desirable or acceptable trees was similar with the possible exception of the LTM units, which had notably more desirable or acceptable trees.

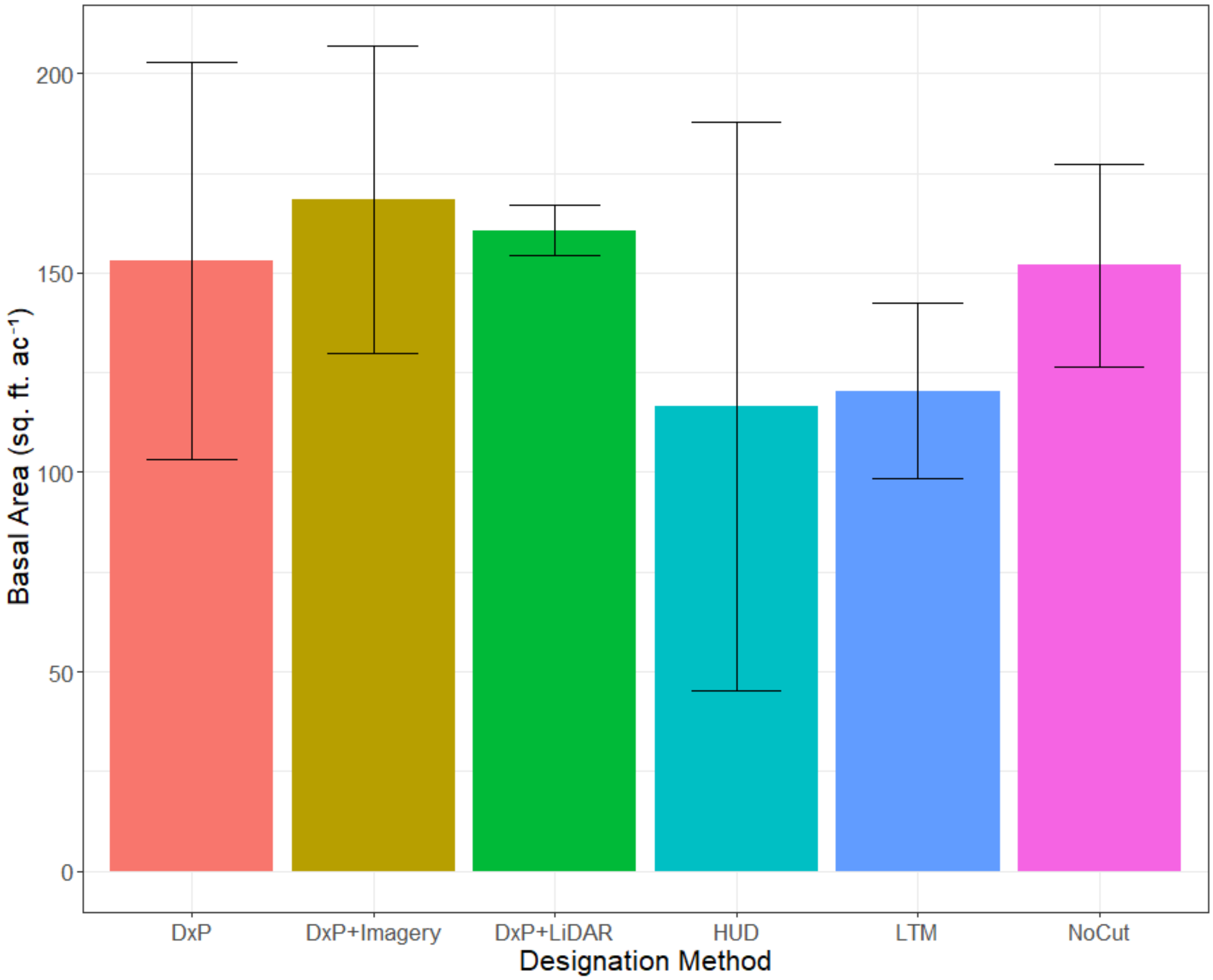

Figure 2. Mean basal area by designation method. Bar heights represent the mean basal area of the three units assigned to each designation method. Error bars indicate 90% confidence intervals. Descriptions of designation methods are found in Table 2.

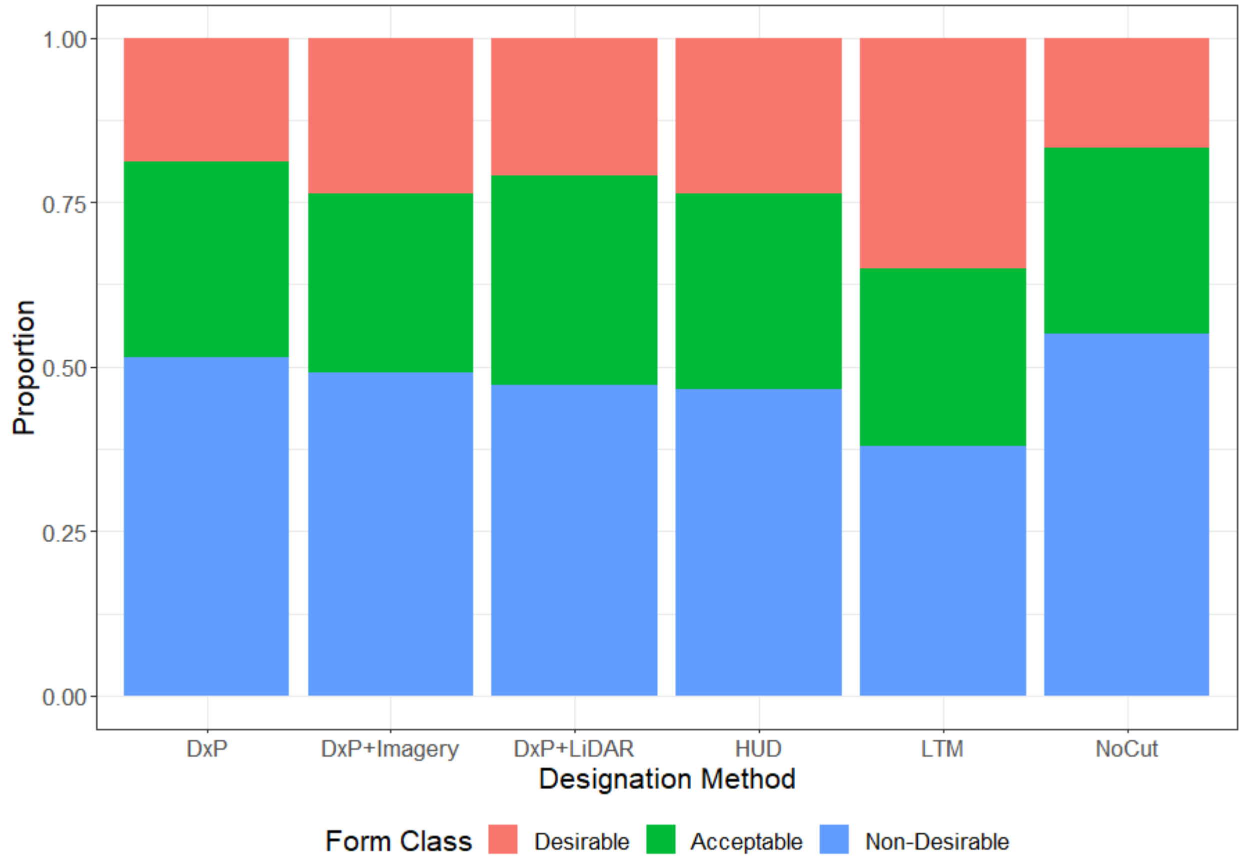

Figure 3. Composition of form classes by designation method. Bar heights represent the cumulative proportion of each form class represented on average in the three units assigned to each designation method. Descriptions of designation methods are found in Table 2.

Table 1. Current overstory conditions as measured by field plots. Values represent 90% confidence intervals across the three units assigned to each designation method. See Table 1 for descriptions of designation methods.

Designation Method	Basal area (sq. ft. ac^{-1})	Density (trees ac^{-1})	Height (ft)	Crown base height (ft)	Crown Radius (ft)	Canopy Cover (%)
DxP+ Imagery	129.7 – 206.8	62.7 – 395.8	38.5 – 54.4	17.4 – 27.8	5.6 – 8.1	45.3 – 68.4
DxP+ LiDAR	154.2 – 166.9	168.5 – 334.3	39.8 – 49.6	20.3 – 25.0	3.9 – 8.6	49.2 – 65.9
HUD	45.4 – 187.7	9.8 – 294.8	34.0 – 56.7	12.8 – 23.7	4.9 – 9.7	29.8 – 61.1
LTM	98.3 – 142.4	59.6 – 245.3	32.3 – 58.5	12.5 – 26.5	5.5 – 8.5	34.6 – 58.8
DxP	103.1 – 202.8	102.3 – 294.1	41.7 – 55.9	23.1 – 25.1	5.9 – 10.0	43.6 – 70.0
NoCut	126.5 – 177.3	99.1 – 312.1	34.1 – 53.2	12.8 – 32.7	4.9 – 8.0	36.2 – 71.1

Initial Mark Results – Comparison with silvicultural prescription objectives

Overall objectives: Implement modified group selection and thin to create groups surrounded by grassy interspaces. The mark was successfully implemented between July 2020 and March 2021. In all, about 240 acres were marked by a combination of LTM, D x P + Imagery, D x P + Lidar, and HUD. See Appendix A, Figures A4 – A7 for maps of the group-polygons produced by each of the designation methods.

Objective 1: Target BA 50 sq ft ac^{-1}. According to the tally of marked trees on plots, the mean residual BA of the LTM method's units was 40.9 sq ft ac^{-1}, approximately 18% under target. The 90% confidence interval ranges from 35.0 to 46.8 sq ft ac^{-1}. Estimating from polygon size and within-polygon residual BA, the estimated BA of DxP + Imagery, DxP + Lidar, and LTM units was 49.0, 50.3, and 41.6 sq ft ac^{-1}, respectively. For these estimates, 90% confidence intervals are presented in Table 5.

Objective 2: Create groups across 45 to 60% of the stand area. On average, the units marked with DxP + Imagery, DxP + Lidar, and LTM had group-polygons under the prescribed 45% minimum target (Figure 4). Only HUD was in the prescribed range, having 47% of the stand area covered by group-polygons. LTM units were marked with the lowest group-polygon coverage, at 39%.

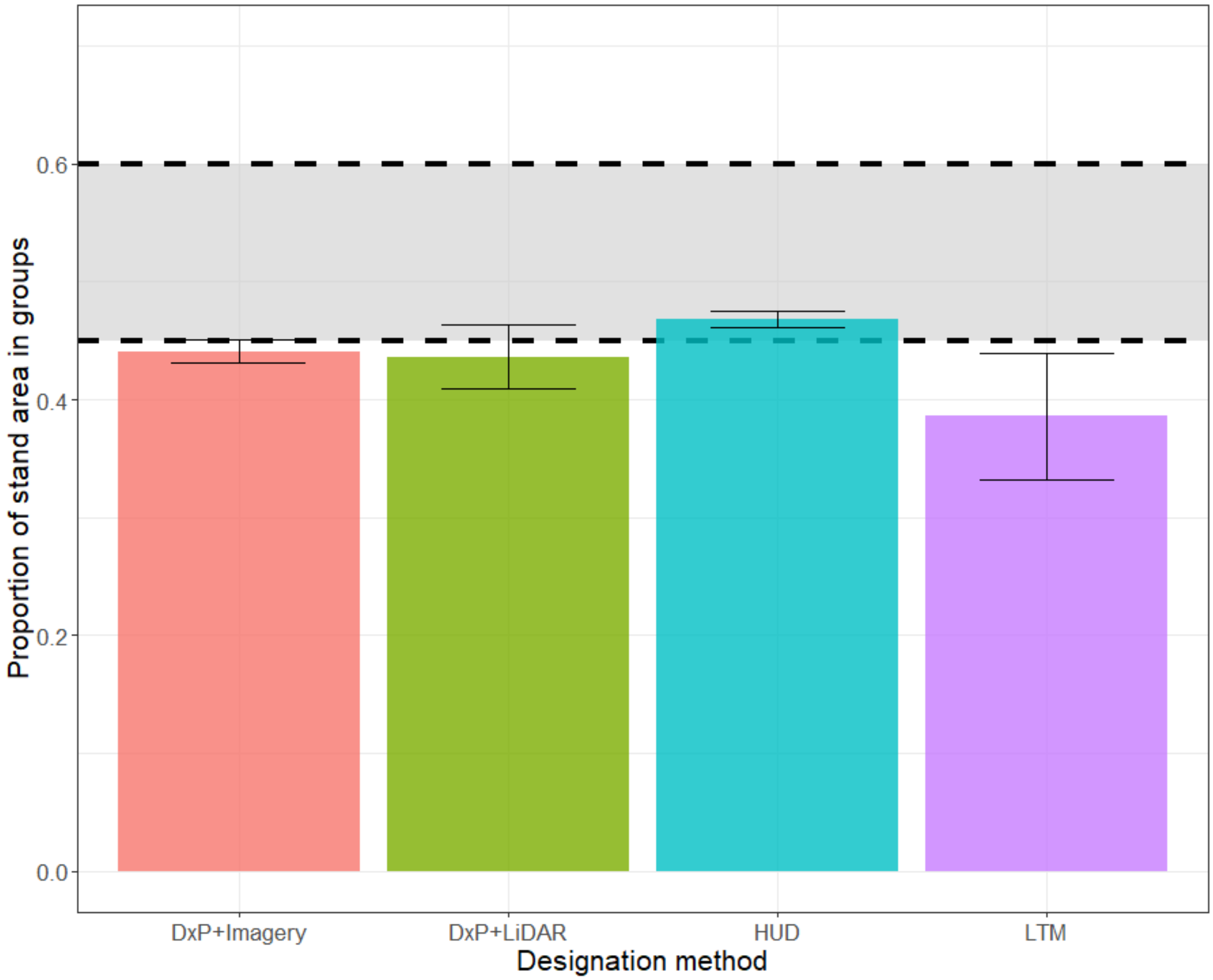

Figure 4. Mean group-polygon percent cover by designation method. Bar Heights represent the mean proportion of stand area included in groups by the digital methods, as well as Leave-Tree Marking. Dashed lines and shaded region indicate prescribed group cover range of 45 – 60%. Error bars represent 90% confidence intervals.

Objective 3: Group size. Visual comparisons between marked units' polygons indicate a variety of group sizes (Appendix A, Figure A4 – A7). Mean group size was 0.30, 0.46, 0.43, and 0.57 acres in LTM, DxP + Imagery, DxP + Lidar, and HUD designation methods, respectively. Corresponding coefficient of variations were 0.69, 0.54, 0.54, and 0.47.

Group size varied across designation methods, with the most similarity between methods occurring at the 0.25 to 0.5 ac size category (Table 4). DxP + Lidar and DxP + Imagery were the closest to prescription targets. LTM units were marked with 18% of their groups smaller than the prescription's 0.1 ac minimum. HUD underrepresented the 0.1 to 0.25 ac category, with only 8% of its groups in this size class. All methods created groups greater than the 1.0 ac prescribed maximum, with the largest group-polygon size 1.96 ac in DxP + Lidar unit 11-9.

Group-polygon size distributions also varied across methods (Figure 5). The large amounts of small sized groups in the LTM units occurred in all group types (Free thin, No cutting, Thin from below). In the HUD units, group sizes were skewed toward the largest category (0.51 to 1.0 ac). Additionally, HUD No-cutting groups were the among the largest for that designation method, which is the inverse of the trend in the LTM, DxP + Imagery, and DxP

+ Lidar units, where no-cut groups were typically the smallest of all group types. All of the methods achieved the prescribed 10% cover of regeneration openings across their respective stands (Table 4).

Table 4. Group-polygon size comparisons to specific prescription targets. Values are the percentage of group-polygons that fall within each size category in the units assigned to each designation method. For full prescription, see Appendix B.

	Group Size Categories (Acres)					Regeneration Openings
Method	< 0.10	0.1 to 0.25	0.26 to 0.50	0.51 to 1.0	1.01 +	
DxP + Imagery	0%	21%	42%	33%	3%	10.3%
DxP + LiDAR	1%	19%	48%	24%	7%	10.0%
HUD	0%	8%	42%	47%	3%	11.8%
LTM	18%	33%	28%	18%	4%	12.8%
Prescription Targets	0%*	30%	30%	40%	0%*	10%

*The silvicultural prescription did not call for any groups to be less than 0.1 ac or greater than 1.0 ac in size.

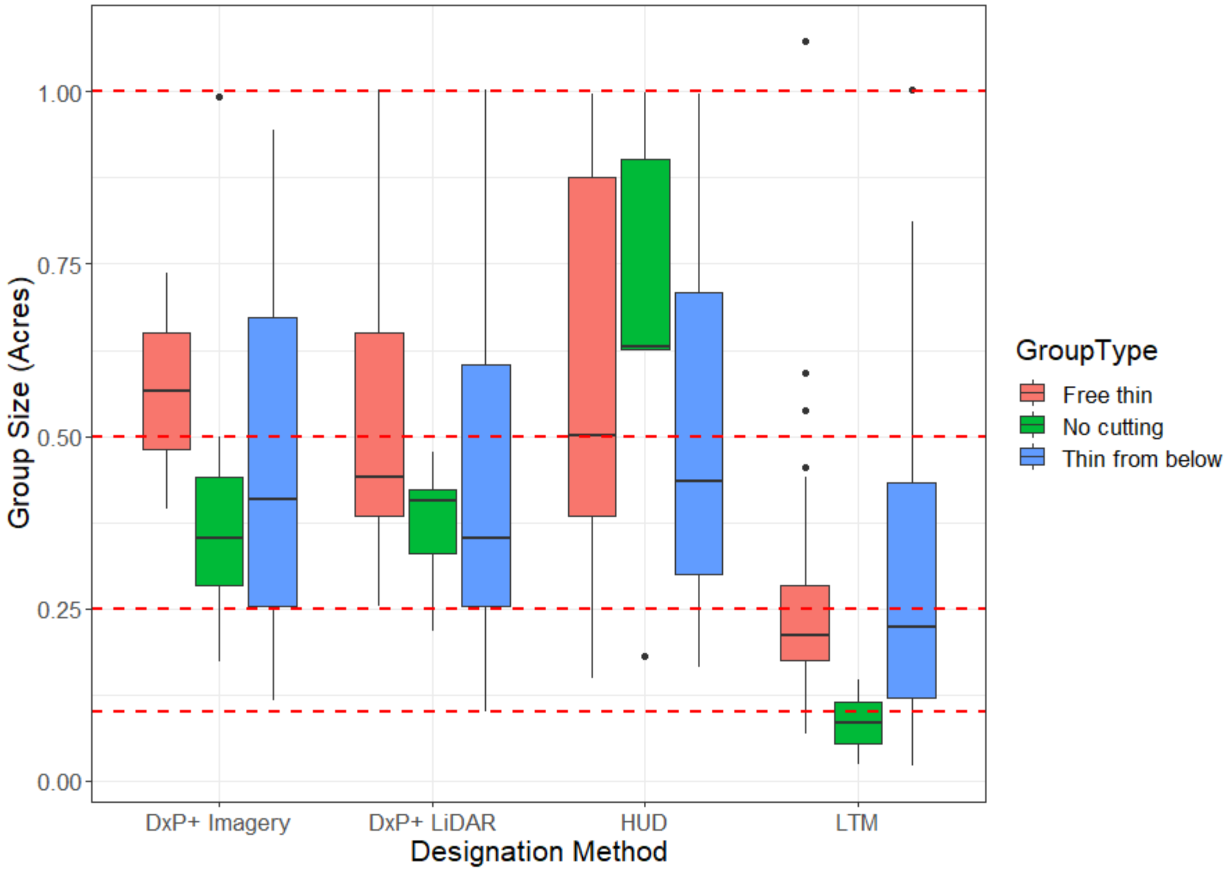

Figure 5. Group size distribution box and whisker plots by designation method and group type. Data represent the count of each type of group-polygon in each designation method, with bold lines indicating median values, box ends at the 1st and 3rd quartiles, and whisker ends at the nearest value within 1.5 times the 1st and 3rd quartiles. Red dashed lines represent prescription group size target cutoffs. The prescription calls for 30% of groups to be 0.1 to 0.25 ac, 30% of groups to be 0.25 to 0.5 ac, and 40% of groups to be 0.5 to 1.0 ac in size. Descriptions of designation methods are found in Table 2.

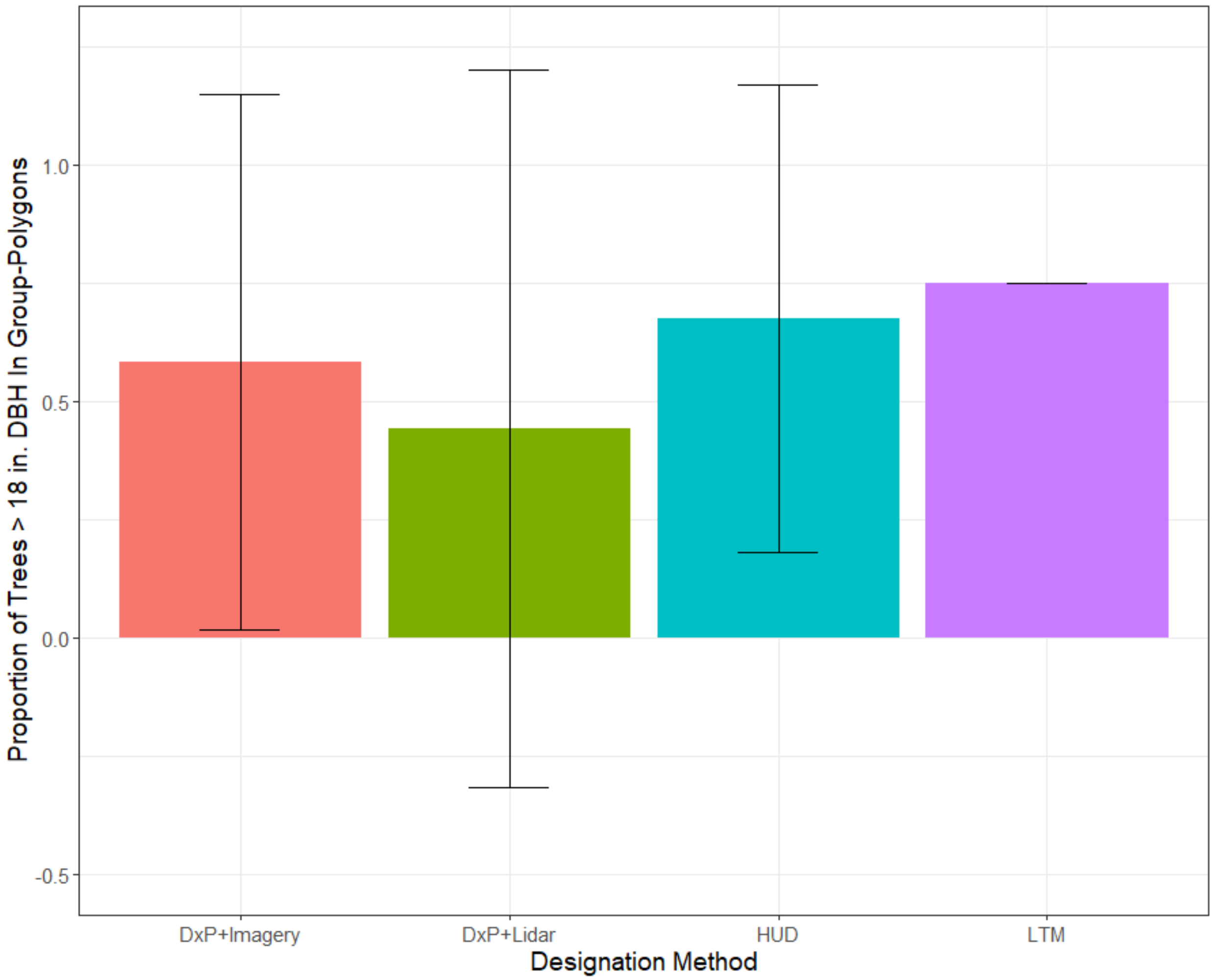

Figure 6. Average proportion of large second-growth trees (>18 in dbh) that were included in groups in units marked by each of the designation methods(+/- 1 SE). Descriptions of designation methods are found in Table 2.

Objective 4: Include large blackjack trees in groups. The field plots contained a total of 132 large trees (at least 18 in dbh) across the study area (Appendix A8). The average dbh of all large trees sampled was 20.1 in. The LTM units included the highest mean proportion of trees greater than 18 in dbh with about 75% of the large trees included in groups (Figure 6). The DxP + Imagery units included the smallest proportion of large trees in groups at less than 50%. Between unit variability resulted in 90% confidence intervals that overlapped among designation methods (Figure 6).

Comparison of all objectives. An overall comparison of the mark is displayed in Table 5. Each of the designation methods is projected to attain the general intent of the prescription. Not all specific prescription objectives were met by each method. In particular, estimates of BA and group size were under the prescribed amounts for LTM. The percentage of large trees captured in each group is displayed in Table 5, although no specific desired value is given in the prescription.

Table 5. Comparison of different designation methods' achievement of silvicultural prescription objectives. Values represent 90% confidence intervals across the three units assigned to each designation method.

Objective	Target Value	LTM	DxP + Imagery	DxP + LiDAR	HUD
Basal Area (sq ft ac^{-1})	50	35.8 – 47.4	47.3 – 50.7	48.6 – 51.9	N/A*
Group Coverage (%)	45 – 60	33 - 44	43 - 45	41 - 46	46 - 47
Mean group size (acres)	0.45	0.13 – 0.46	0.44 – 0.48	0.38 – 0.49	0.48 – 0.67
Large Trees	Include in groups**	75%	0 – 115%	0 – 120%	0 – 117%

*HUD basal area values were not calculated due to lack of group-level residual basal area data. **No specific value for retention of large trees in groups is included in the prescription.

Discussion

Following implementation, each of the designation methods is projected to achieve the overall silvicultural prescription objectives of reduced density, increased spatial heterogeneity, and improvement of timber quality (Appendix B). Harvest of the project area is scheduled for Summer of 2022. Thus, our analysis of the preharvest results assumes that the mark will be faithfully executed during harvesting. Overall, our results indicate that none of the designation methods in this paper do significantly worse than the others in meeting the objectives of the silvicultural prescription. All methods (LTM, DxP + Imagery, DxP + LiDAR, and HUD) met residual BA, mean group size, and large tree objectives (Table 5). However, LTM was the only method that did not achieve the prescribed coverage of tree-groups across its units.

Estimating residual basal area using GIS, we found that DxP + Imagery, DxP + Lidar, and LTM all were within 10 sq ft ac^{-1} of the silvicultural prescription's BA objective of 50 sq ft ac^{-1}. Given that the acceptable error range of 4FRI prescriptions is usually +/- 10 sq ft ac^{-1} (M. Nabel personal communication), all designation methods were reasonably close to the BA objective. However, the average residual BA of LTM units was much farther away (18%) from the BA objective than the field-based digital methods' units, which were within 2% of the target. Additionally, estimating residual BA using the tally of marked trees, rather than group-polygons, LTM units also missed the BA target by a about 18%. While postharvest measurement will confirm this difference, these initial results show that LTM is not necessarily the "gold standard" of tree designation methods. Most likely, the relatively low BA of the LTM units was attributable to the smaller than average group sizes, which resulted in the least amount of coverage of tree-groups than any other designation method. It is worth noting that we did not estimate current or residual BA using HUD polygons because we did not develop a method for determining BA remotely. While quantification of fine-scale forest structure has been shown to be possible using lidar data (Wiggins et al. 2019), such methods are limited to filtering results to the most dominant trees and were beyond the scope of this study.

Recent trends in implementing spatially complex prescriptions in western US forests have challenged traditional designation methods' ability to create the desired aggregated, heterogeneous horizontal structure (O'Hara et al. 2012; Churchill et al. 2013; Dickinson and Cadry 2017). Similarly, the LTM units in this study were marked with group sizes below target, which will likely lead to increased interspace, and low residual basal area across the stand. Furthermore, the largest group size class was underrepresented in LTM units, suggesting a tendency of LTM to create more homogeneous structural conditions. Without mobile GIS software, markers needed to rely on visual estimates of group area and keep track of group size distributions qualitatively. This shortcoming of LTM points to the need for alternative methods of tracking spatial targets, such as the Individuals, Clumps, and Openings method suggested by Churchill et al. (2013), or the variable-density thinning methods analyzed by O'Hara et al. (2012).

In contrast, streamlined processes for digitally tracking BA and group-size can create a more accurate outcome (Maher et al. 2019). We found that the digital methods in this study—DxP + Imagery, DxP + Lidar, and HUD—performed better at meeting group size targets. The ability to rapidly visualize the entire stand and access polygon size data allows for assessing progress toward silvicultural objectives. Mobile GIS software, such as ArcCollector, allows for real-time in-the-field assessment of group size, interspace width, and BA targets. In DxP + Lidar and HUD, the CHM provides the additional benefit of an accurate picture of the dominant trees, advance regeneration, and canopy cover. As a result, it is easier to achieve the desired spatial heterogeneity in stands.

Although every effort was made to construct a study design that minimized variability between units and designation methods, the heterogeneous nature of the study area resulted in some difference between stands. For example, our estimates of current BA with 90% confidence did not overlap each other between DxP + Imagery and LTM.(Figure 2). This variation could confound post-treatment results if different densities somehow affect the outcomes of the mark or harvesting operations. Additionally, difference in past logging activities between units may affect the structural conditions of the stand. For example, units 16-1, 10-13, and 11-10—the LTM units—as well as 11-8—a HUD unit—are characterized by low densities, and higher aggregation (field observations) which is likely due to commercial thinning and roundwood harvesting that took place in the early 1990's (A. Stevenson personal communication). During this time, unit 11-8 (HUD) was thinned to a low density, which is reflected by present day BA values being the lowest of all units. Additionally, the regular spacing sought by Silviculturists in that era makes creating an aggregated structure challenging (Puettman et al. 2008).

Other potential sources of error in this study are related to possible bias of the marking personnel. First, the DxP + Imagery and DxP + Lidar methods were carried out by one forester, while HUD was performed by another. Each of the three LTM units was marked by a different person. Different levels of training, and life-experiences have been shown to influence tree-selection outcomes (Pommerening et al. 2015; Spinelli et al. 2016). Secondly, the markers were aware that the results of their efforts would be assessed, potentially introducing unconscious bias in the ways trees and groups of trees were selected for retention. Furthermore, the accuracy of the estimates of residual BA and group size depends on the accuracy of the software-hardware system that collects the geospatial location of the polygons. Polygon area error for the group-polygons in this study is uncalculated but could be high enough to provide misleading estimates. A potential area of future study is to assess if pre-harvest estimates are accurate enough to provide a reasonable estimation of post-harvest stand structure. Additionally, as portable GPS technology becomes more accurate and affordable, digital designation methods will likely become more accurate at achieving spatial objectives.

In addition to post-harvest remeasurement, there are other opportunities for further research presented by this study. For example, lidar data has been used to assess stand structure (Niemi and Vauhkonen 2016; Jeronimo et al. 2018; Wiggins et al. 2019). Using the CHM, marking personnel could create a point layer containing the locations of dominant trees that serves as a starting point for creating groups. Automation of some or all of the marking process could create preliminary groups that could then be “ground-truthed” by marking personnel. Additionally, analysis of CHM derived canopy-patch characteristics using metrics prevalent in landscape ecology (*sensu* Dickinson and Cadry 2017) could reveal pre-harvest stand spatial heterogeneity.

DxP and tablet marking are often thought to improve the speed with which stands can be marked and offered for contract (Dickinson and Cadry 2015; Camenson 2019; TNC 2020). However, it is not thoroughly understood how placing more demand on the logger to choose trees meeting prescription requirements affects the speed with which they operate. If the time saved by digital marking is offset by increased operating time, the technology may not be worth the investment. Quantitative research on marking and operating times is needed to better understand this balance.

As demand for mechanical silvicultural treatments continues to accelerate across the fire-prone American West, digital tree designation methods will continue to be developed, implemented, and refined. While Leave-Tree Marking may never be replaced fully, DxP + Imagery, DxP + Lidar, and HUD can serve a vital role in efficiently “marking” trees for harvest. Our results indicate that the digital methods may perform just as well as LTM in reaching stand density targets, while enhancing the spatial heterogeneity of the mark in a way that LTM may not. However, a full comparison of the different methods will not occur until full implementation is completed, including harvest in the DxP units, which were not marked. Meanwhile, as digital technology becomes faster, cheaper, and more accessible, it will continue to provide foresters with the opportunity to improve the accuracy and efficiency of tree designation while implementing silvicultural prescriptions.

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Statement of Ethics

Forestry is a profession which hinges on trust. Often a forester works alone, either in the woods, the truck, or the office. However, foresters are almost always performing a service for someone else. This could be a private landowner, a state, or, in the case of federal land management, the American people. The landowners for which a forester works are depending on a trustworthy individual to take the best care of the forest in the landowners' best interest. Even more important, forestry activities today influence forest structure and composition far into the future. Future generations are counting on today's foresters to make decisions that affect the services forests provide them. For these reasons, it is important that foresters follow a strict code of ethics.

The Society of American Foresters (SAF) is the preeminent forestry professional organization. The SAF's Code of Ethics is a comprehensive guide that ensures sound ethical choices are made by its members. As a member of SAF, I believe in following this code as a set of minimum standards. Fortunately, the principles outlined by the SAF Code of Ethics are in alignment with my personal set of ethics. My upbringing, experience in the Coast Guard, and experience working have taught me the importance of making the right choice, even if it is not the easy choice. I have found that honesty, integrity, and respect are bedrock values which guide my life's choices. I see practicing forestry as a way to apply these values in service to people and the planet.

Appendix A

Figure A1. Diagram of groups (clusters of trees) and interspace (canopy gaps) in 4FRI modified group selection treatments. Demonstrates typical aggregated structure created by mechanical treatments in ponderosa pine stands. Image source: Walker Hill Group Selection Implementation Guide (Appendix B)

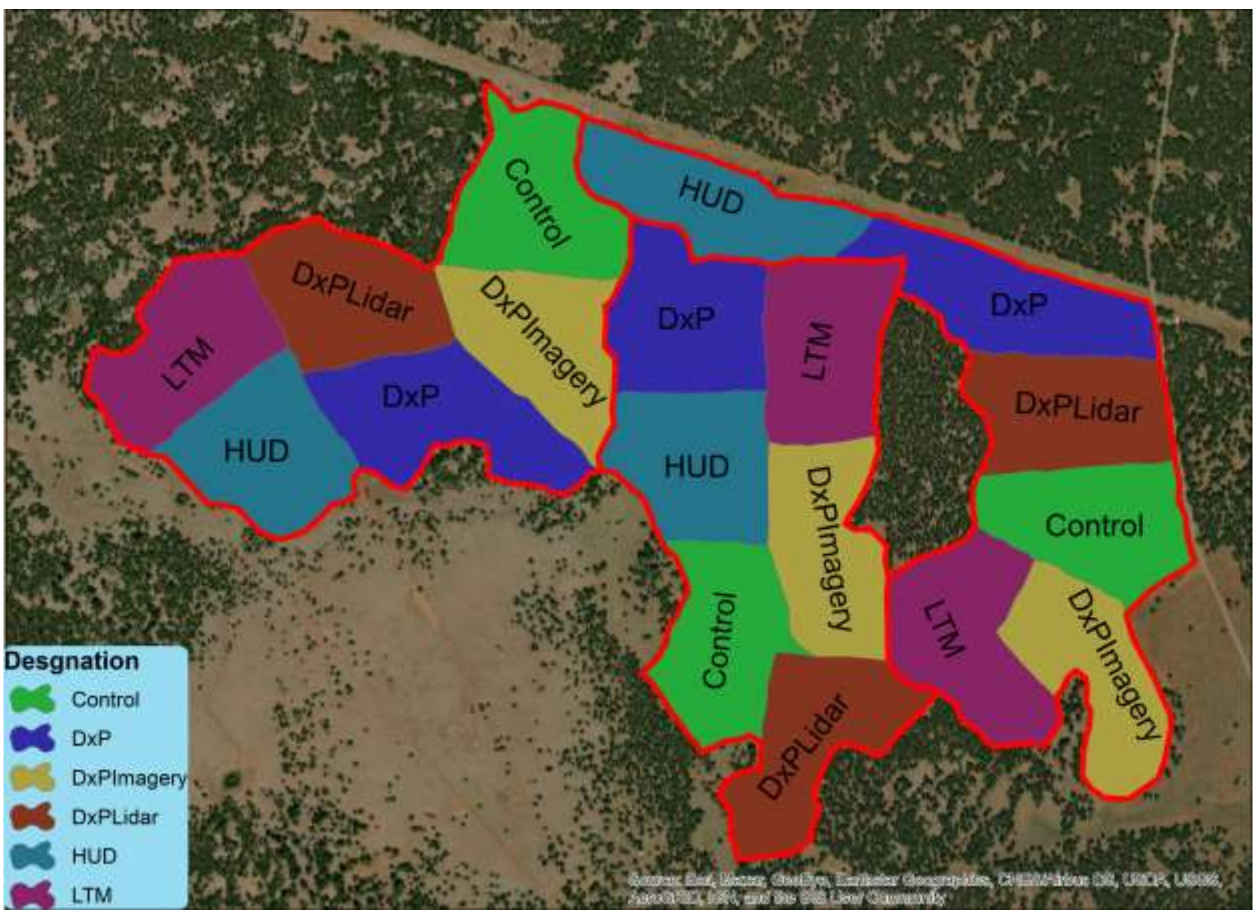

Figure A2. Map of randomly assigned marking methods. Red lines indicate block boundaries.

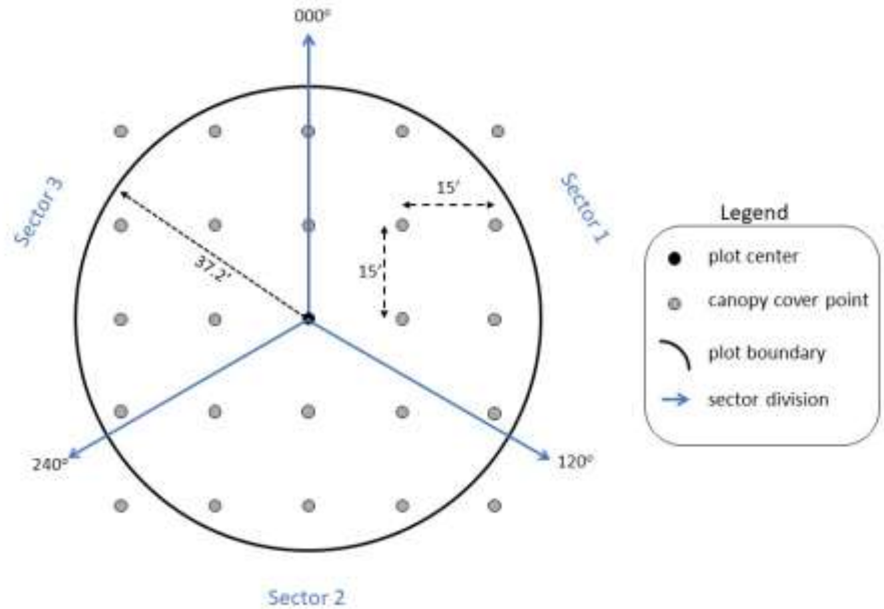

Figure A3. Plot diagram.

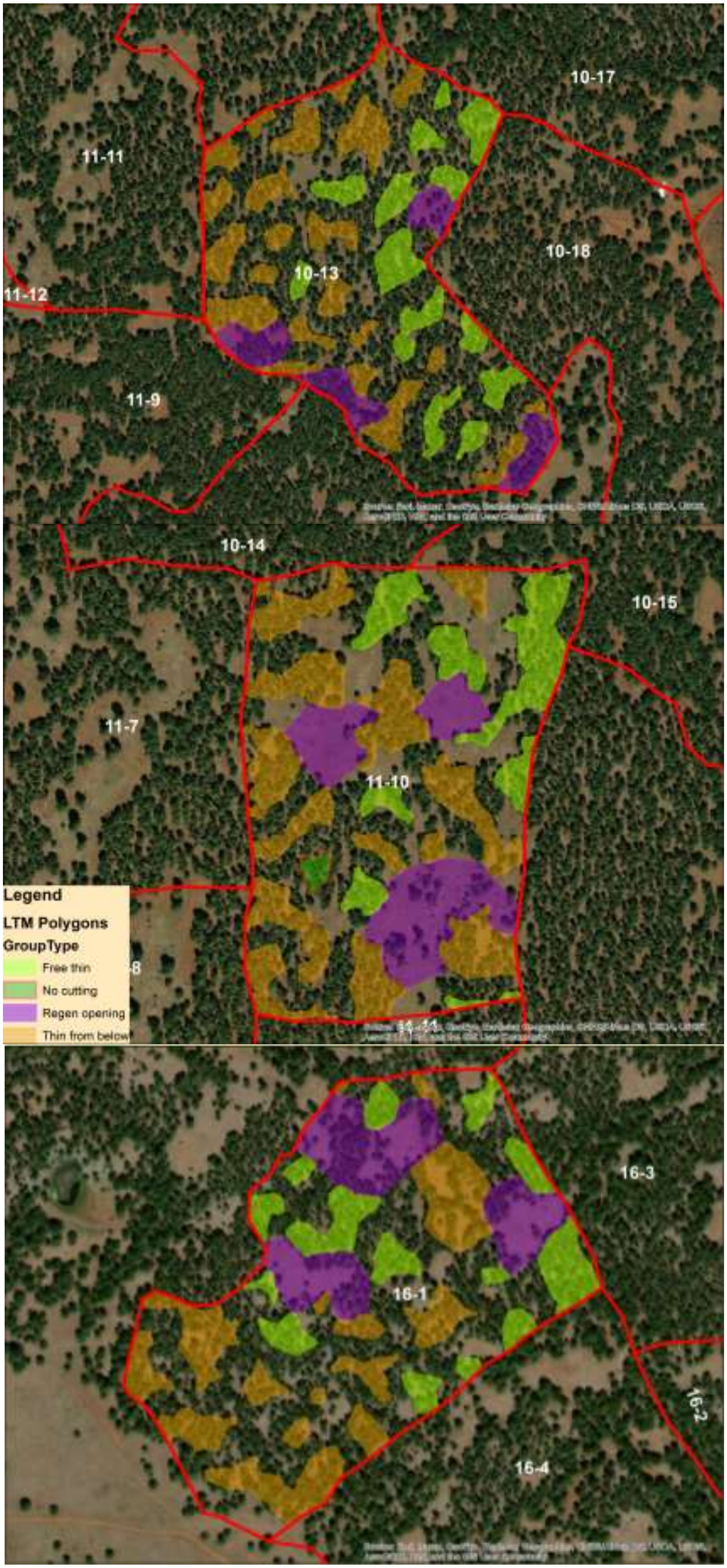

Figure A4. LTM group-polygons.

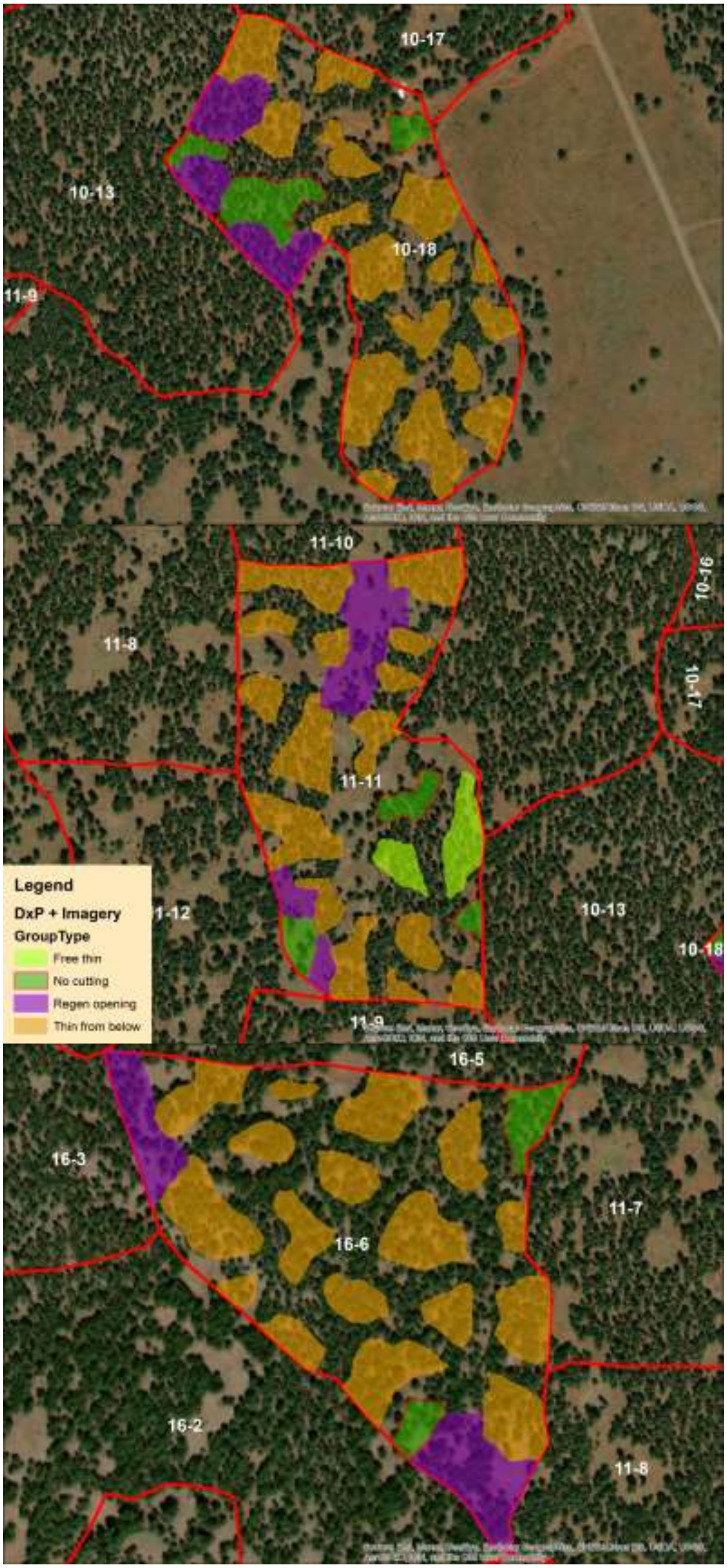

Figure A5. DxP + Imagery group-polygons.

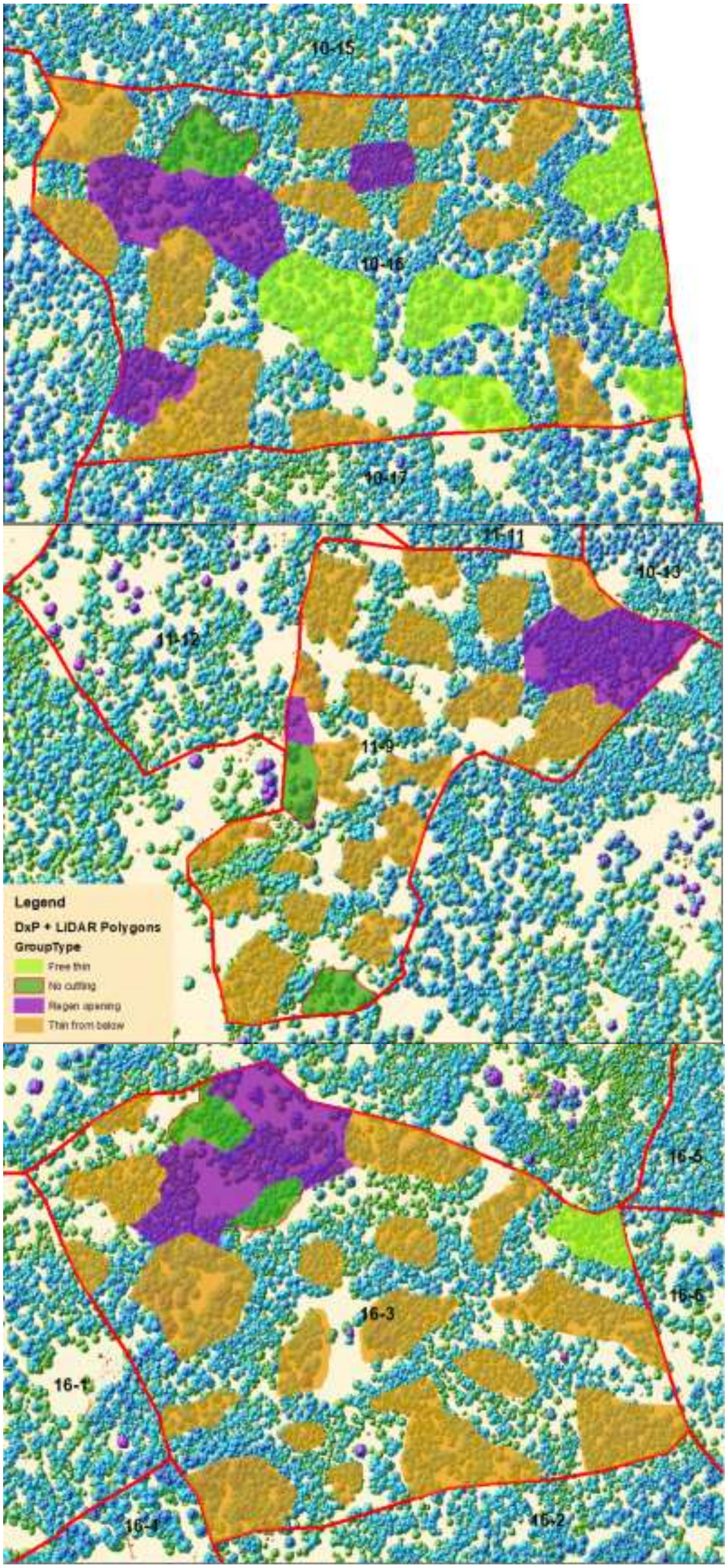

Figure A6. DxP + LiDAR group-polygons.

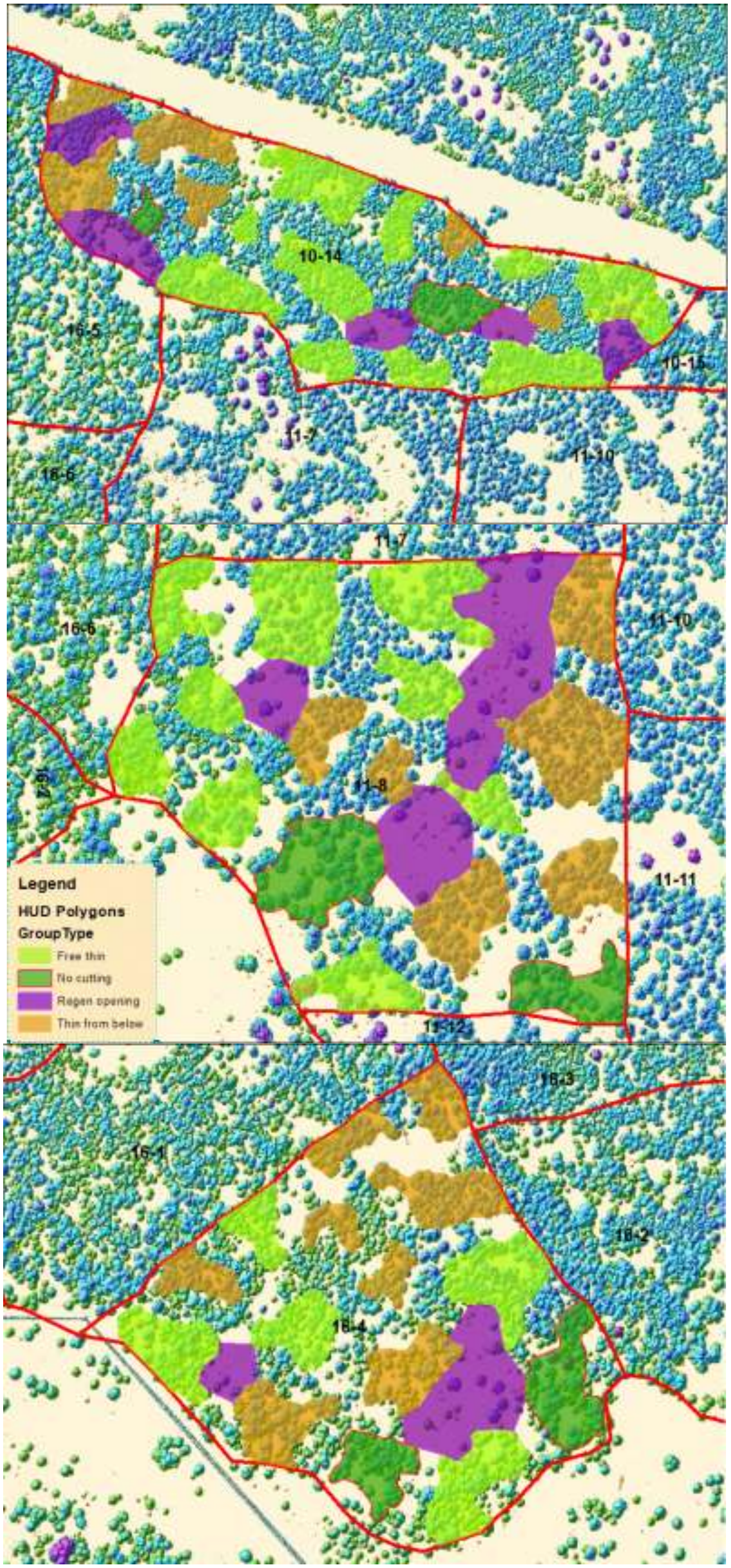

Figure A7. HUD group-polygons.

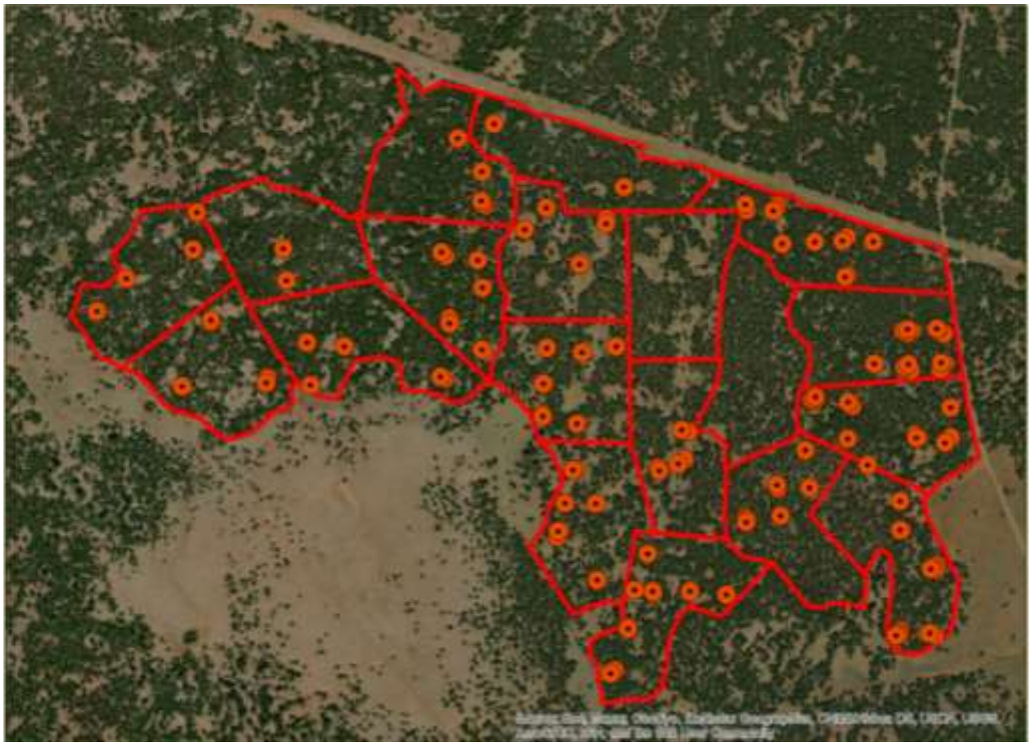

Figure A8. Red circles indicate the location of big trees (at least 18 in dbh) captured on field plots across the Walker Hill study site.

Appendix B

Silvicultural prescription

Silvicultural Treatment:	Modified Group Selection (UEA 40)

Identity

Project Name	NEPA	RX Unit	Acres
Walker Hill	4FRI EIS, 2015	11	165
Forest / District	**Location**	**Site(s)**	
Coconino/Flagstaff	8400	03, 06, 07, 17, 18, 19, 39	

Current Conditions

Stand Structure, Damaging Agents, Fuels, Ground Vegetation, etc.:
The stands are in a southwestern frequent-fire ponderosa pine forest. Current overstory consists of ponderosa pine. Stand structure is relatively even-aged and there is an abundance of mid-aged trees. Site productivity is moderate. The stand is at full site occupancy. Yellow pines and/or historical stumps scattered throughout the unit. Some dispersed camping sites in unit.

Treatment Plan

Prescribed by: Eric Olson	**Date:** 10/01/19
Certified by: A.Stevenson	**Date:**

Treatment Method: Ground based mechanical

Slash Treatment: Whole tree skid; grapple pile tops

Skid Trails:

Constraints and Other Considerations:
Retain all Juniper, Gambel oak and yellow/old pine. See Old Tree Implementation Plan.

Walk potential temp roads with a hydrologist during delineation. Hydrologist may initiate BMP monitoring during implementation.

Follow-up Treatment:

Burn piles, broadcast burning.

Layout

Notes for Layout/Prep:
Layout complete

Tree Designation: DxP cutter select (ponderosa pine ≥ 6” dbh)

Site / Stand Overview

Slope	Asp.	Elev.	Soil P.M.	Site Index	Habitat Type
0-5%	SW	7250	Basalt	Low	PIPO/FEAR

BA Range (Avg.)	BA VSS 5-6	BA VSS 3-4	TPA Sapling	TPA Seedling
30-250 (140)	10	90	Unknown	Unknown

Over/Midstory Composition (by % BA)	Adv Regen Composition (by % TPA)
PIPO 100%	PIPO 100%

DM Severity	% Area Infected	Other Damaging Agents
None	0%	Small animal

Notes	Commercial Thinning 165ac/ Pre-commercial Thinning 165ac

Group selection implementation guide.

Treatment Plan

Silvicultural Treatment: Group Selection with free thinning in matrix			
Prescribed by: E. Olson	**Date:** Spring 2020		
Certified by: A. Stevenson	**Date:**		

Identity

Project Name	**NEPA**	**Forest / District**
Walker Hill South	4FRI EIS, 2015	Coconino NF/ Flagstaff RD
Location(s)	**Site(s)**	**Acres**
6500, 7700, 8400, 226000, 232000	Multiple	Approx. 2001

Treatment Method: Ground-based mechanical

Slash Treatment: Whole tree skid, grapple pile tops at landing

Skid Trails: Free skid at discretion of administrator

Constraints and Other Considerations:

- Eight of the units are PFAs.
- Operate on dry/frozen ground. No hauling may take place on pipelines.
- All painted heritage sites should be avoided by heavy equipment. Refer to Special Instructions (Page 2 of Project-wide silvicultural guidelines) for additional mitigation measures. Any additional sites discovered during operations should be communicated to the district archaeologist.
- **Edges of Individual Units:** Edges of treatment units would be shaped and/or feathered (i.e., create gentle transitions from nest stands, PFA's, savanna) to avoid abrupt changes between treated and untreated areas (see cutting cards for addition info). This transition zone is approximately 150–250 feet wide. (FEIS, Appendix C, Mitigation Measure RS1, page 13)

Notes for Layout/Prep:

Designate and tally areas of regeneration groups prior to marking matrix.
Slopes and inoperable areas will be assessed and delineated by Layout/Sale Admin. Directional mark away from private land, utility lines, major roads and underground pipeline.
"Hard" boundaries (in order of strictness of interpretation) include 1) private land, 2) burn only, 3) PFA or MSO restricted habitat, 4) dPFA.
"Soft" boundaries (in order of flexibility) are 1) adjacent to similar treatment types, 2) adjacent to treatments with less intensive thinning. Less intensive thinning treatments in ranking order are: UEA40 >25 >10, then IT 40 >25>10.

Refer Figure 4. Map of all UEA Treatments pg. 09

Follow-up Treatment (next 5 years):
TSI concurrent with harvesting (preferred), reforestation stocking surveys in group openings, burn grapple piles.

Layout/Marking

Boundary Designation: Double orange horizontal bands facing towards unit, OR at discretion of timber layout program

Tree Designation: LTM: 4 Units, DxP+: 17 Units, DxP Cutter Select: 4 Units

Layout completed by: S. Hunnicutt	**Date:** August 2019
Marking verified by:	**Date:**

Notes

Uneven-Aged Treatments (UEA10, 25, 40 including high end and LOPFA and PFA)