**Can Digital Tablet "Marking" be used to meet Forest Health Objectives?**

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**Abstract**

Digital tablet ""marking"" is a process in which digital polygons are created in the field to designate treatments for harvesting through Designation by Prescription. Tablet ""marking"" is beginning to replace traditional leave tree "marking" for silvicultural prescription implementation. Concerns exist over different operator implementation techniques and preferences influencing the ability for tablet ""marking"" to successfully meet forest health objectives, such as reducing southwestern dwarf mistletoe (*Arceuthobium vaginatum* subsp. *cryptopodium*) infection levels in ponderosa pine (*Pinus ponderosa* var. *scopulorum*). For this case study, we established 33, 1/10th acre monitoring plots in a ponderosa pine stand prior to harvest, followed by re-measurement immediately after harvest. Data collection included standard forest measurements, tree form data, and evaluation of dwarf mistletoe rating (DMR). We found that post-harvest stand conditions met the target silvicultural prescription for trees ac$^{-1}$ and was slightly above the target for basal area ac$^{-1}$. The mean tree- and stand-level DMR were reduced, but the proportion of defect trees slightly increased. The results of this case study are promising regarding tablet ""marking's" ability to successfully meet forest health objectives, but more case studies and monitoring is needed. In addition to the case study, both forest managers and harvest operators were surveyed to better understand differences in preferences on the tablet "marking" technology and its implementation. Detailed results from the survey will be presented at a later date, along with implications for management.

**Management and Policy Implications**

Digital tablet "marking" is becoming a common replacement for traditional leave-tree marking because of its ability to reduce layout costs and increase efficiency (TNC 2017). Tablet “marking” has already begun to evolve, and quality and efficiency will continue to change as its use becomes more frequent. For example, “Tablet Marking Guide”, issued by the US Forest Service, has recently been updated to direct markers to create polygons with smooth edges as opposed to overly detailed edges, making it easier for the operators to navigate the polygons (USDA 2017). Another proposed change is the possible use of a hybrid mark, where small groups of reserve trees within regeneration openings are marked with paint to simplify cutting and improve contractor efficiency (USDA 2018). This hybrid method could also be used to reduce operator-choice related to leaving or harvesting individual trees (e.g. forest managers choose which forest health problems warrant tree removal). However, uncertainty in whether tablet “marking” can adequately meet silvicultural forest health objectives is cause for monitoring. This case study focused on the presence and removal of defect and dwarf mistletoe infected trees. It would be beneficial for future case studies to compare the results of tablet “marked” and leave-tree marked dwarf mistletoe infected stands.

## Introduction

### ***What is tablet “marking”?***

The purpose of tree marking is to clearly communicate silvicultural prescriptions from silviculturists to harvest operators who are implementing the silvicultural treatments (Dickinson and Cadry 2017). The specific marking method employed is critical to the effectiveness and efficiency of treatment implementation (Dickinson and Cadry 2017). Traditionally, tree marking is done by physically painting all trees that are either to be cut (cut-tree marking) or left (leave-tree marking) according to the silvicultural prescription (USDA 2004). Digital tablet “marking” is a new way to implement silvicultural treatments without painting trees. Tablet “marking” is done using Designation by Prescription (DxP), also known as Operator Select, methods in conjunction with digital polygons created on tablets. When using DxP, the silvicultural prescription and instructions are provided to harvest operators in written form. Then the operators, instead of a tree marking crew, choose which trees to remove in order to meet the objectives in the prescription (TNC 2017). In the field, digital polygons are created with tablets to designate where specific treatments or groups[1] of trees are placed in a stand using ArcGIS online and the Collector App (Esri Copyright © 2012-2019; TNC 2017). Polygons are color-coordinated to match with specific treatment types. The space between the polygons is designated as "interspace[2]", which has its own cutting guidelines outlined in the silvicultural prescription (Table 1).

Whereas traditional DxP provides the operator with a written description of the desired treatment outcomes (USDA 2008; Dickinson and Cadry 2017), digital polygons provide more guidance to operators in implementing the prescriptions by showing them the desired objectives in each polygon. After polygon designation, the tablets can be placed inside the cabs of logging equipment. Operators then have access to a digital map of the designated polygons within the harvest unit, in addition to roads, boundaries, and aerial imagery (TNC 2017). While the operators are harvesting, the GPS-enabled tablets inside the cabs of logging equipment record productivity data—number of trees harvested per unit of time—to evaluate efficiency (TNC 2017). The tablets can also record real-time data such as spatial location and potentially diameters of trees harvested; however, post-harvest data still needs to be analyzed to assess the effectiveness of treatment implementation (TNC 2017).

### ***Benefits of tablet "marking"***

Tree marking influences stand structure and ensures sustainable forest management (LuVı´tkova´ et al. 2016); but, it can be inefficient and expensive. Digital tablet "marking" is a way to reduce the layout costs in forests that contain low-value, small-diameter timber, as is the case in the southwestern United States, where the success of tablet "marking" could make restoration efforts more economically viable. A time and effort study found that over 500 person days were used to prep a 2,000-acre task order in the Four Forests Restoration Initiative (4FRI) area (TNC 2018), making US Forest Service thinning goals of 50,000 acres per year for 4FRI unsustainable with the available resources (TNC 2018). By having operators select trees directly from the machine cab, forest managers save the resources required to physically mark entire stands with paint after a unit is laid out. Tablet "marking", like traditional DxP, can also avoid painters selecting trees for removal that are inaccessible to the operator (Spinelli et al. 2016).

Due to the high resource requirements (e.g., time, vehicles, paint), traditional tree marking methods can be extremely expensive. Pilot work on tablet "marking" in southwestern ponderosa pine (*Pinus ponderosa* var. *scopulorum*) showed "marking" capabilities of 40-60 acres per day per person with tablets compared to 8 acres per day per person with traditional paint marking, decreasing layout costs from about $40 per acre to under $16 per acre (TNC 2017). Besides saving time and costs, tablet "marking" could increase clarity on traditional DxP prescriptions and the comfort of the operators. Operator select methods may cause the operators more discomfort because of uncertainty regarding whether they are meeting the silvicultural prescription objectives (Dickinson and Cadry 2017). By giving operators tablets that show them which treatments should be done in each polygon, tablet "marking" could give operators more clarity and confidence that they are meeting the prescription objectives. Another non-monetary benefit from tablet "marking" is not exposing tree-markers to paint products. If trees are not being painted, tree-markers are not exposed to harmful chemicals that can impact human health. Not painting trees could also improve the aesthetic quality of the stand for the public.

***Where is the use of tablet "marking" appropriate?***

Even if the objectives are clearly stated in prescriptions and the polygons on the tablets are sufficient guides for stand treatments, one concern is that selection of individual trees can be subjective and may vary depending on the operator. A study looking at how much agreement there is in tree marking found there is not a significant difference in tree marking between different professional groups (i.e., Forester versus Logger), but there is a substantial lack of agreement for individual tree selection (Spinelli et al. 2016; Pommerening et al. 2018). However, after being trained on a new type of thinning (i.e. thin from below), experts, or those who have more experience, may have difficulty implementing the new method, causing more disagreement between and within professional groups (LuVı´tkova´ et al. 2016; Pommerening et al. 2018). If there are specific forest health or other issues that increase the importance of which trees operators cut or leave, there may be a difference in opinion depending on the operator who is doing the harvesting. This could be exacerbated by the possible inability for an operator to correctly and easily identify forest health problems on individual trees from inside the cab of their logging equipment.

Even in a single-species forest, forest health issues may be complex, including insect outbreaks, fungal diseases, effects of fire, and dwarf mistletoe infestations. So, while, tablet "marking" may have positive economic impacts in a simple, single-species stand, it does not mean that the forest health issues will be simple to manage. When even one forest health issue exists, it greatly complicates the prescription and harvesting objectives. As more forest health issues occur simultaneously in one stand, the objectives become increasingly complex. This complexity is compounded as the forest type complexity increases, such as multiple forest health issues within an uneven-aged, mixed-species stand. Since the newness of tablet "marking" and lack of both literature and monitoring data leave uncertainty in whether the method can adequately meet silvicultural objectives related to forest health, we carried out a case study in a single-species forest as a simple way to begin assessing the ability for tablet "marking" to meet forest health objectives. Surveys with both forest managers and harvest operators were also conducted to better understand different perspectives on the technology and find out where improvements can be made.

***A case study on southwestern ponderosa pine***

We used the southwestern ponderosa pine forest type as a case study to gain a greater understanding of the effects of digital tablet "marking". We aimed to meet two objectives: 1) determine if digital tablet "marking" can adequately meet forest health objectives; and 2) relay both forest managers' and forest operators' perspectives on the technology. We were specifically interested in the forest health parameters related to southwestern dwarf mistletoe (*Arceuthobium vaginatum* subsp. *cryptopodium*) and tree form as specified in the silvicultural prescription for the site (Table 1).

## Methods

***Case study location and description***

The study site was located in unit 10 of the Fort Valley – Chimney Spring project, located just northwest of Flagstaff, AZ (Fig. 1a and 1b). The unit was 118 acres in size and harvested by ground-based logging equipment between November 2018 and January 2019. The unit has a 0-10% slope, a south facing aspect, is between 7,600-7,800 ft in elevation, and has a basalt parent material. The stand characteristics of the unit, as described in the silvicultural prescription, consisted of relatively even-aged trees with a basal area[3] averaging about 110 $ft^2$ $ac^{-1}$. Yellow pines[4] and ponderosa pine regeneration were abundant, but patchily distributed. Although ponderosa pine was the dominant tree species, incidental Gambel oak (*Quercus gambelii*), white pine (*Pinus strobiformis*), and elderberry (*Sambucus nigra* ssp. *cerulea*) were present. The dwarf mistletoe infection was light to moderate and the stand also contained incidental bark beetle damage.

Southwestern dwarf mistletoe is a native pathogen in southwestern forests that infects ponderosa pine and provides important ecological benefits, including providing food and nesting for wildlife (Conklin and Fairweather 2010). The abundance of dwarf mistletoe has likely increased because the forests are denser today than historically existed (Conklin and Fairweather 2010). Current management recommendations to control dwarf mistletoe in ponderosa pine forest types are to create groups and openings where less than 25% of the acreage is infected, and irregularly spaced even-aged prescriptions where more than 25% of the acreage is infected (Conklin and Fairweather 2010).

***Silvicultural prescription***

The prescription objectives were to reduce stand density, improve individual tree vigor and growth, reduce the overall level of dwarf mistletoe infection, maintain species diversity, and reduce the hazard of crown fire. The prescription also specified to retain yellow pines and the majority of trees >18 inches in diameter (Table 1). Density objectives were to achieve 30-50 trees $ac^{-1}$ and retain an overall basal area of 50-60 $ft^2$ $ac^{-1}$ at the stand-level. The stand was predominately a Vegetative Structural Stage (VSS)[5] 4-5, meaning most of the basal area was in trees 12.0 and 23.9 inches in diameter at breast height (DBH). Treatment polygons varied in size from 0.1 to 1 acre(s), averaging 0.25-0.5 acres. Regeneration openings were specified to generally range from 0.5 to 1 acre(s) in size, increasing up to 4 acres to fully encompass pockets of mistletoe infection, with a maximum width of 200 feet for openings (Table 1). However, regeneration openings of up to 4 acres were permitted to fully encompass pockets of mistletoe infection, thus limiting the number of infected overstory trees available around the edge of the opening to infect new regeneration.

**Objective 1-Field monitoring**. To address objective 1, we installed pre- and post-harvest monitoring plots across four treatment types designated in the prescription. Prior to sampling, the US Forest Service created digital polygons containing the following treatment types: thin from below, free thin, regeneration opening, and no cutting (Table 1).

Using the unit map containing the treatment polygons (Fig. 2), random points for each treatment type were created using Esri ArcGIS (Esri 2018) with a 7-meter buffer from edge of treatment polygon and a minimum of 15 meters between plots. These random points were then loaded onto a Garmin GPSMAP 64st, with an accuracy of 16 to 33 feet under normal conditions. We aimed to install 10 plots per treatment, but due to logistical constraints (time and ongoing logging operations), a total of 33 plots were installed (Table 1). No plots were placed in the interspace because the expected residual density of ponderosa pine in these areas is 0-2 trees ac$^{-1}$ (Table 1). Due to this assumption, results are provided both excluding and including the interspace as an estimated range when discussing live ponderosa pine.

Plots were circular, fixed-radius, and 1/10th acre (37.2 ft radius) in size. Each tree 4.5 ft or taller inside the plot radius was recorded and assigned a tree number, moving clockwise from north. For each tree, we recorded live or dead status, DBH, crown ratio (visually estimated), crown class (USDA R3FG), tree form and defects, and Hawksworth 6-class dwarf mistletoe rating (DMR) (Hawksworth 1977). To assign tree form and defects, the Region 3 Stand Exam Guide was used as reference for the categories and names of the defects (USDA R3FG: Appendix K). Crown class designations were: dominant, co-dominant, intermediate, suppressed, and understory (USDA R3FG). Total tree height and crown base height were also recorded for the first two trees in each 10-inch diameter class (USDA R3FG). After harvesting was complete, plots were revisited to record harvested trees. Plots within the no cutting treatments were not installed until after harvesting was complete.

*Data analysis.* Following data collection, height to diameter ratios, trees $ac^{-1}$ and basal area ($ft^2\ ac^{-1}$) were calculated. We predicted heights and height to diameter ratios for the trees that did not have a height recorded in the field using linear regression. Trees with a height to diameter ratio greater than 80:1 (Wonn and O'Hara 2001) and a crown ratio less than 30%, were downgraded a crown class, unless previously marked as suppressed (n= 12). Understory trees with 20% or less crown ratios were categorized in the suppressed crown class (n= 8) while understory trees with a DBH greater than 5 inches were categorized as intermediate crown class (n= 6). Cut stumps were recorded within 5 of the plots installed in the no cutting polygons. DBH was estimated using stump diameter (Myers 1963). We were unable to estimate the rest of the missing data for these trees. Cut stumps in no cutting polygons contributed a total of 23 trees $ac^{-1}$ and 33.5 $ft^2\ ac^{-1}$ basal area, which we included in our pre-harvest stand estimates for no-cutting polygons.  Trees other than ponderosa pine, referred to as “other species” (OS), that occurred in the study were Gambel oak, white pine, and elderberry. These other species were measured in the same way as ponderosa pine.

Plot data were summarized to per unit area by treatment and as an overall mean. The "overall mean" is the mean of all the treatment means. Data were also summarized by three diameter classes (0.0-9.9 inches (small trees), 10.0-17.9 inches (medium trees), and >18 inches (large trees)), and by crown classes. The diameter classes were chosen to make better comparisons with the prescription specifications (e.g., generally retaining trees larger than 18 inches in diameter). Tree form and dwarf mistletoe data are also reported in percentage of trees and stand affected.

**Objective 2-Perspectives on the technology.** To address objective 2, surveys were conducted following Northern Arizona University Institutional Review Board (IRB) approval and protocol. We interviewed 10 forest managers and 3 harvest operators via telephone, secure email, or in-person. Survey questions differed for forest managers and harvest operators (Table 2). The responses from the surveys are being summarized and will be presented at a later date.

## Results

### *Trees per acre and basal area targets*

Overall, we found operators met the density objectives for trees $ac^{-1}$ and were slightly above density objectives for basal area ($ft^2$ $ac^{-1}$). Though the stand remained pine dominated post-harvest, there was a shift in relative dominance for the other species due to the reduction in pine density. We found other species made up 3.0% of the stand pre-harvest and 5.9% of the stand post-harvest.

*Trees per acre.* Overall trees $ac^{-1}$ across the stand were reduced (Fig. 3, Fig. 4a-1–4d-1). Total mean live trees $ac^{-1}$, including all species, was 114.2 pre-harvest and 53.2 post-harvest, a 53.4% reduction, excluding the interspace. We estimate that including the interspace provides an overall mean of between 43.2 and 43.6 trees ac$^{-1}$ post-harvest. The mean live trees ac$^{-1}$ for ponderosa pine was reduced by 54.9% excluding the interspace, and to between 40.1 and 40.5 trees ac$^{-1}$ including the interspace (Table 3). The mean for live OS trees ac$^{-1}$ remained unchanged at a mean of 3.1 (Table 3, Fig. 3). The mean number of snags per acre, combining all tree species, decreased by 42.8% excluding the interspace (Table 3, Fig. 3).

Pre-harvest, 39.2% of trees were 'small trees', 34.7% of trees were 'medium trees', and 26.1% of trees were 'large trees' (Fig. 5). The proportion of trees within these diameter classes decreased by 16.7% in small trees and 1.5% in medium trees, and increased by 27.0% in large trees. Out of 360 pre-harvest, live ponderosa pine tree counts, 5.8% were dominant, 44.2% co-dominant, 26.9% intermediate, 14.2% suppressed, and 8.9% understory crown classes (Fig. 6). Of the 190 post-harvest ponderosa pine trees counted, the proportion of dominant trees increased by 53.4%, co-dominant trees increased by 7.2%, intermediate trees decreased by 25.8%, suppressed trees decreased by 3.4%, and understory trees increased by 12.5%.

*Basal area per acre.* The overall mean live basal area (ft$^2$ ac$^{-1}$) was reduced from 142.2 ft$^2$ ac$^{-1}$ pre-harvest to 78.9 ft$^2$ ac$^{-1}$ post-harvest when excluding the interspace (Fig. 7). Including the interspace would provide an overall mean of between 64.8 and 68.0 ft$^2$ ac$^{-1}$ post-harvest (Table 3). Live ponderosa pine had a mean basal area of 137.6 ft$^2$ ac$^{-1}$ pre-harvest and 74.3 ft$^2$ ac$^{-1}$ post-harvest, a reduction of 46.0% when excluding the interspace, or between 59.4 and 63.4 ft$^2$ ac$^{-1}$ when including the interspace (Table 3). The mean basal area of live OS was unchanged at 4.6 ft$^2$ ac$^{-1}$ (Table 3).

***Tree form***

The total count of live ponderosa pine with defects was 114 pre-harvest and 67 post-harvest, a 41.2% reduction. Pre-harvest, the three most common defects across the stand were 1) forked top (37 occurrences), 2) crook or sweep (33 occurrences), and 3) dead top (16 occurrences); post-harvest, the three most common defects were 1) forked top (27 occurrences), 2) crook or sweep (15 occurrences), and 3) dead top (9 occurrences) (Fig. 8a). Forked top, crook or sweep, and dead top defects each decreased by 27.0%, 54.4%, 43.8% respectively post-harvest.

Although the total number of trees with defects was reduced overall, the proportion of trees with defects increased by 3.6% (Fig. 8b). Pre-harvest, the proportion of trees with defects within each treatment was 26.9% for thin from below, 29.3% for free thin, 30.0% for regeneration opening, and 40.8% for no cutting. Post-harvest, the treatments had 25.0%, 31.3%, 66.7%, and 40.8% respectively.

Of the total trees with defects, most were found in the no cutting units (36.8%), followed by thin from below (34.2%), with 21.1% in free thin treatments, and 7.9% in regeneration opening treatments, while 62.7%, 19.4%, 14.9%, and 3.0% of the defected trees existed in the respective treatments post-harvest. When considering only defect trees, the percentage of large trees with defects increased post-harvest by 22.8%, while decreasing in the other diameter classes (Fig. 9). Of the total trees with defects, 4.4% were dominant, 37.7% were co-dominant, 28.9% were intermediate, 19.3% were suppressed, and 9.6% were understory (Fig. 10). The proportion of dominant trees, co-dominant, and suppressed trees increased, while the proportion of intermediate and understory trees decreased (Fig. 10).

***Dwarf mistletoe infection***

At the individual tree scale (only considering trees with a dwarf mistletoe rating (DMR) greater than 0), the overall mean DMR was 3.1 pre-harvest (SE = 0.1) and 2.3 post-harvest (SE = 0.8), a decrease of 23.6% (Fig. 11). The no cutting treatments contained the highest mean pre-harvest level of DMR at 3.4 (SE=0.7), with the lowest being the regeneration opening treatments at 2.7 (SE=0.9). The free thin treatments contained the highest mean post-harvest level of DMR at 3.5 (SE=0.7), with the lowest being the regeneration opening treatments at 0.0 (SE=0.0). Across the unit, the maximum DMR recorded was 6 and the minimum DMR was 0, both pre- and post-harvest.

At the stand level (including trees with a DMR of 0), the overall mean DMR decreased by 41.3% (Fig. 12) and the overall mean of trees per $ac^{-1}$ infected decreased by 61.0% (Fig. 13a). The total dwarf mistletoe infected tree count was 108 pre-harvest and 44 post-harvest, a 59.3% decrease, and the proportion of trees infected decreased by 6.8% (Fig. 13b). Out of the total infected trees, pre-harvest, 20.4% were small trees, 38.9% were medium trees, and 40.7% were large trees (Fig. 14). The number of dwarf mistletoe infected trees within these diameter classes decreased by 55.4% in small trees and 0.6% in medium trees, and increased by 28.3% in large trees. Also when only considering infected trees, there were 5.6% dominant, 58.3% co-dominant, 25.9% intermediate, 10.2% suppressed, and no visible understory infections pre-harvest (Fig. 15). Post-harvest, the proportion of infected dominant trees increased by 63.6%, co-dominant trees increased by 5.2%, intermediate trees decreased by 38.6%, suppressed trees decreased by 33.9%, and there was no change in understory trees.

## Discussion

### *Trees per acre and basal area*

Results from this case study conducted in a southwestern ponderosa pine stand show that tablet "marking" can successfully meet the silvicultural prescription objectives for density. Post-harvest mean trees $ac^{-1}$ was reduced to the target of 30-50 trees $ac^{-1}$ when including the interspace, considering either all tree species or just ponderosa pine (Table 3). Thus, the silvicultural prescription objective for trees $ac^{-1}$ was successfully met. Post-harvest mean basal area $ac^{-1}$ was slightly above the target of 50-60 $ft^2$ $ac^{-1}$ for all tree species and live ponderosa pine when including the interspace. While the treatment exceeded that target, the results are not far from the objectives and the lower end of the estimated basal area $ac^{-1}$, when including the interspace (with 0 trees $ac^{-1}$), was within the target basal area $ac^{-1}$ range. This data supports the finding that, even without paint on the trees, harvest operators can reduce the stand density to meet silvicultural objectives while using tablet "marking".

***Tree form***

Results show that the proportion of trees with defects increased, even though the total number of trees with defects decreased. The three most common defects—crook or sweep, forked top, and dead top—remained the same pre- and post-harvest. However, the prescription explicitly says to retain all yellow pines and other species regardless of the tree form, health, or vigor. The prescription also specifically says to retain all conifers with a DBH >18 inches which possess existing cavities, dead tops, and lightning scars as wildlife trees. All of these factors could have affected why the proportion of defect trees did not decrease. It is worth noting that only 7.2% of >18-inch DBH trees across the stand had defects pre-harvest and 10% had defects post-harvest. Furthermore, the prescription says desirable trees[6] will have no defects, it adds that minor defects which do not weaken the tree within dominant or co-dominant trees are acceptable. We believe these minor defects in dominant and co-dominant trees likely explain the increase in defects post-harvest, as almost half of all trees with defects were found in these two crown classes, and we did not separate major and minor defects in our data collection.

The no cutting treatment proportionally contained the most defect trees pre- and post-harvest at 36.8% and 62.7% respectively, which would also cause the percent of defect trees to remain high. Regeneration openings contained the highest proportion of trees with defects post-harvest because of the large reduction in trees $ac^{-1}$, causing the proportion of trees that remained with defects to greatly increase. Although there are multiple factors to consider, overall, we found that when analyzing trees proportionally, the silvicultural prescription objective to favor desirable trees with no defects was not met.

***Dwarf mistletoe infection***

One of the main concerns in this study was whether or not dwarf mistletoe infection levels would be reduced when using tablet "marking". The silvicultural prescription objective to reduce the overall dwarf mistletoe infection was met at both the individual tree scale and the stand level. The operator was successfully able to decrease the overall mean DMR to 0.7 at the stand level (all trees) and to 2.3 at the tree level (only trees with a DMR >0), both being considered a light infection (Province of BC). The percentage of trees across the stand and the overall mean of infected trees $ac^{-1}$ also decreased, which means there are fewer trees present in the stand with the ability to infect other trees, especially advanced regeneration[7]. At both the tree- and stand-levels, the regeneration opening treatment DMR decreased the most because all of the trees except yellow pines and one group of 3-5 reserve trees (if the opening was >1 acre in size) were removed. Again, this means that advanced regeneration will have an increased chance of not becoming infected; although, latent infections may be present and are unaccounted for. The results provide support that visible dwarf mistletoe infection levels can be reduced using tablet "marking" in single species stands when they are not heavily infected.

***Case study conclusions***

Data collected during this case study provides more insight on how successful tablet "marking" is during the harvesting period within a single species forest. We found that the operator was able to meet the objectives of the silvicultural prescription including reducing the tree density to within the target trees $ac^{-1}$ and being reasonably close to the basal area $ac^{-1}$. Dwarf mistletoe infection rates were also reduced. However, although the number of trees containing defects was reduced, the proportion of trees with defects slightly increased. Overall, this case study provides support that silvicultural objectives for both density and forest health issues have the potential to be met using the tablet "marking" method. It is cautioned that the results for dwarf mistletoe infection could differ if a stand has a higher percent stand level infection, even in a similar single-species pine-dominated forest. These results are also not transferrable to a more complex forest type with additional forest health issues and would require appropriate studies for the forest type.

***What do we call this new technology?***

From a silvicultural perspective, calling this new method of silviculture prescription implementation "tablet *marking*", may be problematic, since there is no marking being done on individual trees. Incorrect use of terminology has negative consequences for clear communication, consistency, and introduces legal concerns.

The US Forest Service on the Coconino National Forest, Flagstaff Ranger District has already begun to tackle this terminology concern, officially calling this method a "Digital Prescription Guide" or "DPG". The term "guide" is used because the digital polygons are seen as a guide for the harvesters and not what the harvester is bound to within a contract; it is also a means to implement silvicultural prescriptions through DxP, with the additional assistance of tablets (Youtz 2019). Silviculturists on the Coconino NF believe Digital Prescription Guide

(DPG) could be a good fit because it describes the end product that comes from the act of tablet "marking". DPG also acts as supplemental information to the original prescription and implementation (marking) guide. Therefore, the harvest operators receive both the DPG and the implementation guide.

However, the term "tablet *marking*" is still used unofficially to describe the act of collecting the data because it ties into the fact that the work is still performed by a marking crew on the ground. The simplified term also makes conversations with the marking crews easier by letting them know what type of "marking" they are going to be doing for a particular unit. An example of how this would be communicated to the tree markers is: DxP – tablet mark. The unofficial term "tablet *marking*" is also being used to communicate to the public. This is because it is easier for the public to relate to: people are already familiar with tablets and it is easy for them to associate it as a replacement for paint-marking trees.

However, these terms are not consistent with other organizations and agencies. A representative from The Nature Conservancy (TNC) in Flagstaff, AZ said their official term for this new method is "Digital Restoration Guide", but "tablet *marking*" is still used unofficially as well (Chapman 2019). TNC enters into DxP agreements with the US Forest Service since there is no actual tree marking being done; this distinction is important because "marking" implies contractual language with the US Forest Service (Chapman 2019). They also do not believe that tablet "marking" should be a contractually binding tool because the technology is still being developed (Chapman 2019).

Consistent terminology is important for this new technology as it begins to evolve and grow beyond the scope of ponderosa pine forests and the Southwest. The newness of this technology should be taken advantage of by consistently using the same contractual and unofficial language while it is still being developed, and before more widespread use. Consistency will ensure clear communication as both tree markers and forest operators move to different job sites, or even to different agencies using the same technology.

***Other concerns***

During data collection, we discovered that harvesting had taken place within the no cutting treatment polygons. The number of cut stumps found within the no cutting plots does raise a question of how effective the polygons actually are. Although these polygons are "guides", the treatments within them still need to be achieved to be worthwhile over traditional DxP. The most probable cause of these trees being cut is the accuracy of the GPS on the tablets. Typically, when the US Forest Service is creating the polygons in the field, they are using GPS signal enhancing devices, such as a Garmin GLO, connected to the tablets to get better accuracy (typically down to 5-10 feet). However, there are currently no requirements in the contracts for harvest operators to use similar devices while using the tablets during harvest operations. The accuracy errors could compound during harvest and cause the operator to be much farther away from the actual polygon outline than appears on their tablet. Also, we used a handheld GPS to navigate to the plots, which could have served as another source of error (reported accuracy is 16 to 33 feet). As the technology is developed and guidelines are updated for this harvesting method, setting and requiring accuracy limits and accuracy enhancing equipment is recommended for both the tree markers creating the polygons and the harvest operators implementing the prescription.

## Summary

Initial pilot work by The Nature Conservancy (TNC) has shown that digital tablet "marking", in concurrence with Designation by Prescription (DxP), can greatly reduce layout costs in southwestern ponderosa pine forests, from $40 per acre with traditional paint marking to under $16 per acre with tablets (TNC 2017). Efficiency can also be greatly increased for the tree markers, from 8 acres per day per person with traditional paint marking to 40-60 acres per day per person with tablets (TNC 2017). However, there is a lack of both literature and monitoring data on this new technology, which leaves uncertainty in whether the method can adequately meet silvicultural objectives including those related to forest health. We aimed to bridge the knowledge gap on tablet "marking" through field data, forest manager and operator surveys, and provide insight on the importance of using correct terminology as this harvesting method continues to be developed and expanded. The case study results showed that density objectives were met, dwarf mistletoe was reduced to acceptable levels, and the number of defect trees was reduced. The results of this case study are promising in tablet "marking's" ability to successfully meet forest health objectives, although, monitoring should continue.

**Ethics**

Forests supply valuable resources and provide ecosystem services, such as clean air and water, to humans and wildlife. This is why professional foresters need to follow sustainable forest practices and make ethical decisions when managing forests. The Society of American Foresters (SAF) has a list of "Principles and Pledges" for professional foresters to abide by, with the following being the principles that resonate with me the most: 1) sound science is the foundation of the forestry profession; we pledge to strive for continuous improvement of our methods and our personal knowledge and skills; to use the most appropriate data, methods, and technology; 2) public policy related to forests must be based on both scientific principles and societal values; we pledge to challenge and correct untrue statements about forestry; 3) honest and open communication, coupled with respect for information given in confidence, is essential to good service; 4) we pledge to respect the needs, contributions, and viewpoints of others; and to give due credit to others for their methods, ideas, or assistance (SAF 2000).

These forestry ethics were followed in every part of this study. Appropriate methods and technology were used throughout the process. New personal knowledge was gained and new information can now be provided the forestry profession. The surveys in this study were conducted following appropriate approval and protocol, and will retain the identity of the participants. All participants and contributors to this study are appreciated and were given due credit. When considering whether the use of digital tablet “marking” is appropriate, managers should base their decision on both the scientific evidence provided from this study and similar future studies, and the values this harvesting method can bring to society, such as increased restoration efforts, forest aesthetics, and human health. More case studies and monitoring on this harvesting method should be implemented to strive for continuous improvement in forestry as technology and objectives continue to change.

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**Glossary**

[1]**Groups:** groups of trees that have a defined group edge; groups can have interlocking crowns or nearly interlocking crowns with the ability to achieve interlocking crowns in the foreseeable future; trees within groups are typically of similar age, but variable ages and different species may occur

[2]**Interspace(s):** open space(s) between tree groups intended to be managed for grass/forb/shrub vegetation (rather than tree regeneration) over the long term. Interspace(s) may include scattered individual trees

[3]**Basal area ac$^{-1}$:** cross-sectional area of all trees, measured in square feet per acre at 4.5 feet diameter at breast height (DBH)

[4]**Yellow pine(s):** mature ponderosa pine approximately 150 years or older; bark ranges from reddish brown, shading to black on top with moderately large plates between fissures, to reddish brown to yellow, with very wide, long, and smooth plates; tops range from pyramidal or rounded (occasionally pointed) to flat (making no further height growth); branches in the lower third of the crown are generally drooping, and in older trees, are often large, gnarled or crooked.

[5]**Vegetation Structural Stage:** a method of describing forest age and tree size from seedling to old forests; VSS classification is based on the size class comprising the highest proportion of the basal area (ft$^2$ ac$^{-1}$) over a given area and is an indication of the dominant tree diameter distribution

[6]**Desirable tree:** Meets the following criteria for ponderosa pine:

- >40% live crown ratio
- Dominant or co-dominant crown class
- No form defects
- No damaging agents
- No dwarf mistletoe

[7]**Advance(d) regeneration:** seedlings and saplings (< 5” DBH)

[7]**Dripline:** vertical projection from the edge of a tree’s crown to the ground

**Table 1.** Explanation of the purpose and description for each treatment type, based on the silvicultural prescription, that existed in this case study. The number of plots for each treatment type are found next to the treatment name.

| **Treatment (n= # of plots)** | **Purpose** | **Description/Goal** |
|---|---|---|
| Thin from Below (n=9) | Create even-aged structure where largest trees are retained; also used to open space around yellow pines, aspen clones, and large oak clumps | • Retain most trees > specified upper DBH limit (UDL) (18”)<br>• cut most trees < UDL (18”)<br>• Retain all conifers >18” DBH with existing cavities, dead tops, and lightning scars as wildlife trees |
| Free thin (n=10) | Create an uneven-aged structure where the most desirable trees are retained and/or where dwarf mistletoe is sanitized | • Retain the most desirable trees from across the range of available DBH classes at the specified avg. spacing (actual spacing between individual trees would vary)<br>• Retain all conifers >18” DBH with existing cavities, dead tops, and lightning scars as wildlife trees |
| Regeneration opening (n=4) | Create an area where new regeneration can establish and/or existing advance regeneration is retained/released | • Create irregularly shaped openings across 15% of the unit<br>• Placed in areas containing no infected yellow pines that will be surrounded by little to no mistletoe infection after opening is created<br>• Sizes range from 0.5 to 1 acre(s), but may be as large as 4 acres to fully encompass pockets of mistletoe infection<br>• The maximum width for openings is 200 feet<br>• Cut all ponderosa >5” DBH except:<br>  o Yellow pines<br>  o Desirable young ponderosa 5-7” DBH<br>  o In openings >1 acre not containing an abundance of desirable young ponderosa <7” DBH (>50 trees $ac^{-1}$), retain one group of 3-5 reserve trees |
| No cutting (n=10) | Leave areas within the stand that already meet desired conditions without cutting; designate areas where operations should be avoided (arch sites, rocky outcrops) | • Retain all trees |
| Interspace(s) (n=0) | Managed for grass/forb/shrub vegetation (rather than tree regeneration) over the long term | • Average space from dripline[7] to dripline to be 40-60 ft<br>• Distance between groups at the upper end of the range if one group is infected with dwarf mistletoe and the other is not.<br>• Cut all ponderosa pine 5-18” DBH, except yellow pines<br>• Retain 1-2 individual ponderosa >18” DBH per acre between groups that meet all characteristics of a desirable tree |

**Table 2.** Survey questions asked during interviews with either forest managers or harvest operators.

| Forest Managers | Harvest Operators |
|---|---|
| How long does paint stay on the trees with traditional marking? | What has been the biggest challenge with implementing tablet "marking"? |
| How much does the paint alone normally cost? | Was there a learning curve? Has it become easier? |
| What has been the biggest challenge with implementing tablet "marking"? | Are you more confident in meeting the prescriptions than just DxP/operator select? |
| How cost effective has it been? | Have you been more efficient or less efficient? |
| What suggestion do you have to make tablet "marking" easier/simpler in the future? | Do you actively look for mistletoe in trees? |
| What changes would you make to the process? | How much do you look at tree form, such as forked tops, when choosing which tree to cut? |
| What do you suggest to make this easier for the silviculturist? | |
| How do you account or adjust for the accuracy of using GPS? Do the harvest operators do this as well? | |
| In your opinion, how different are the results between harvest operators? | |
| What feedback have you received from the harvest operators? | |
| Can this only be used with feller bunchers? | |
| How easy would this be for other forests to implement? | |
| How could this be used on mixed conifer forests? | |
| What are tradeoffs (what have you gained and what have you lost) from using tablet "marking" instead of traditional paint marking? | |

**Table 3.** Mean ponderosa pine (PIPO) and other species (OS; Gambel Oak, southwestern white pine, and elderberry) trees $ac^{-1}$ and basal area ($ft^2$ $ac^{-1}$) for each treatment type, pre- and post-harvest. Standard error is given in parentheses. Means including interspaces assume a range of residual live ponderosa pine trees $ac^{-1}$ from 0-2 (see text for further details).

| | **Thin from below** | | | **Free thin** | | | **Regeneration opening** | | | **No cutting** | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Live PIPO** | **Live OS** | **Total snags** | **Live PIPO** | **Live OS** | **Total snags** | **Live PIPO** | **Live OS** | **Total snags** | **Live PIPO** | **Live OS** | **Total snags** |
| **Trees $ac^{-1}$ pre-harvest** | 161.1 (20.1) | 5.6 (4.4) | 13.3 (8.0) | 82.0 (12.6) | 0.0 (0.0) | 4.0 (3.1) | 75.0 (13.2) | 0.0 (0.0) | 0.0 (0.0) | 126.0* (22.8) | 7.0 (7.0) | 5.0 (2.2) |
| **Trees $ac^{-1}$ post-harvest** | 57.8 (13.8) | 5.6 (4.4) | 7.8 (5.5) | 32.0 (3.9) | 0.0 (0.0) | 0.0 (0.0) | 7.5 (4.8) | 0.0 (0.0) | 0.0 (0.0) | 103.0 (15.4) | 7.0 (7.0) | 5.0 (2.2) |
| **Basal area $ac^{-1}$ pre-harvest** | 142.0 (26.0) | 0.2 (0.1) | 18.1 (11.2) | 131.2 (10.9) | 0.0 (0.0) | 2.9 (2.1) | 132.8 (39.9) | 0.0 (0.0) | 0.0 (0.0) | 144.5* (23.7) | 18.1 (1.8) | 6.8 (3.8) |
| **Basal area $ac^{-1}$ post-harvest** | 84.7 (16.7) | 0.2 (0.1) | 18.0 (11.2) | 73.2 (12.1) | 0.0 (0.0) | 0.0 (0.0) | 18.2 (13.9) | 0.0 (0.0) | 0.0 (0.0) | 121.1 (13.3) | 18.1 (1.8) | 6.8 (3.8) |

| | **Overall Mean** | | | |
|---|---|---|---|---|
| | **Live PIPO excluding interspace** | **Live PIPO including interspace** | **Live OS** | **Total snags** |
| **Trees $ac^{-1}$ pre-harvest** | 111.0 (20.2) | N/A** | 3.1 (1.8) | 5.6 (2.8) |
| **Trees $ac^{-1}$ post-harvest** | 50.1 (20.4) | 40.1-40.5 (18.7-18.5) | 3.1 (1.8) | 3.2 (1.9) |
| **Basal area $ac^{-1}$ pre-harvest** | 137.6 (3.3) | N/A** | 4.6 (4.5) | 6.9 (4.0) |
| **Basal area $ac^{-1}$ post-harvest** | 74.3 (21.3) | 59.4-63.4 (19.7-22.2) | 4.6 (4.5) | 6.2 (4.3) |

*Reconstructed trees $ac^{-1}$ and basal area $ac^{-1}$ (see text for details)
**N/A: no data collected

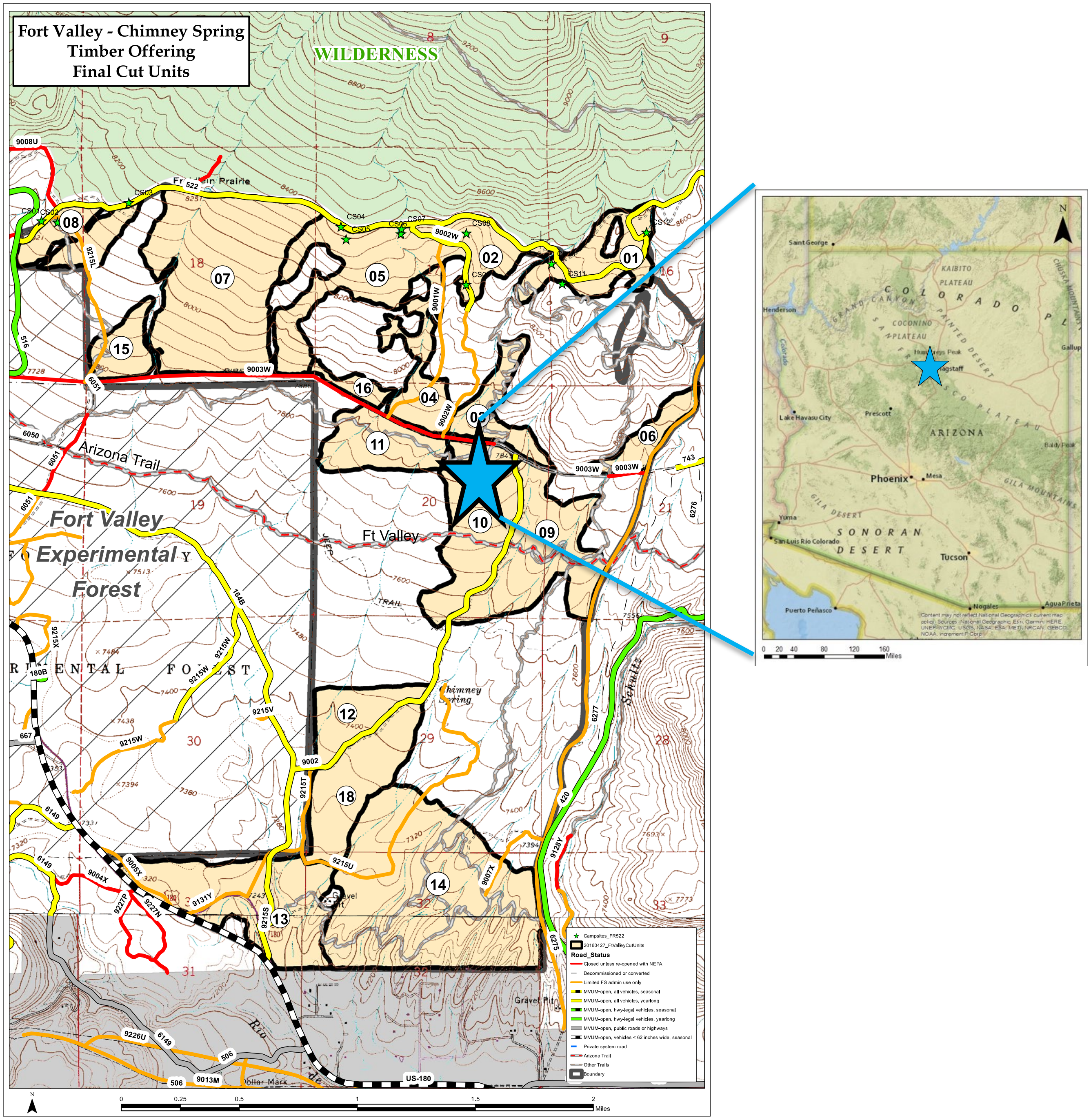


**Figure 1.** a) Map of project site within the Fort Valley – Chimney Spring Timber Offering. The blue star locates unit 10, where the study took place. b) Overview of where the study site is located within Arizona, blue star locates where the study took place.

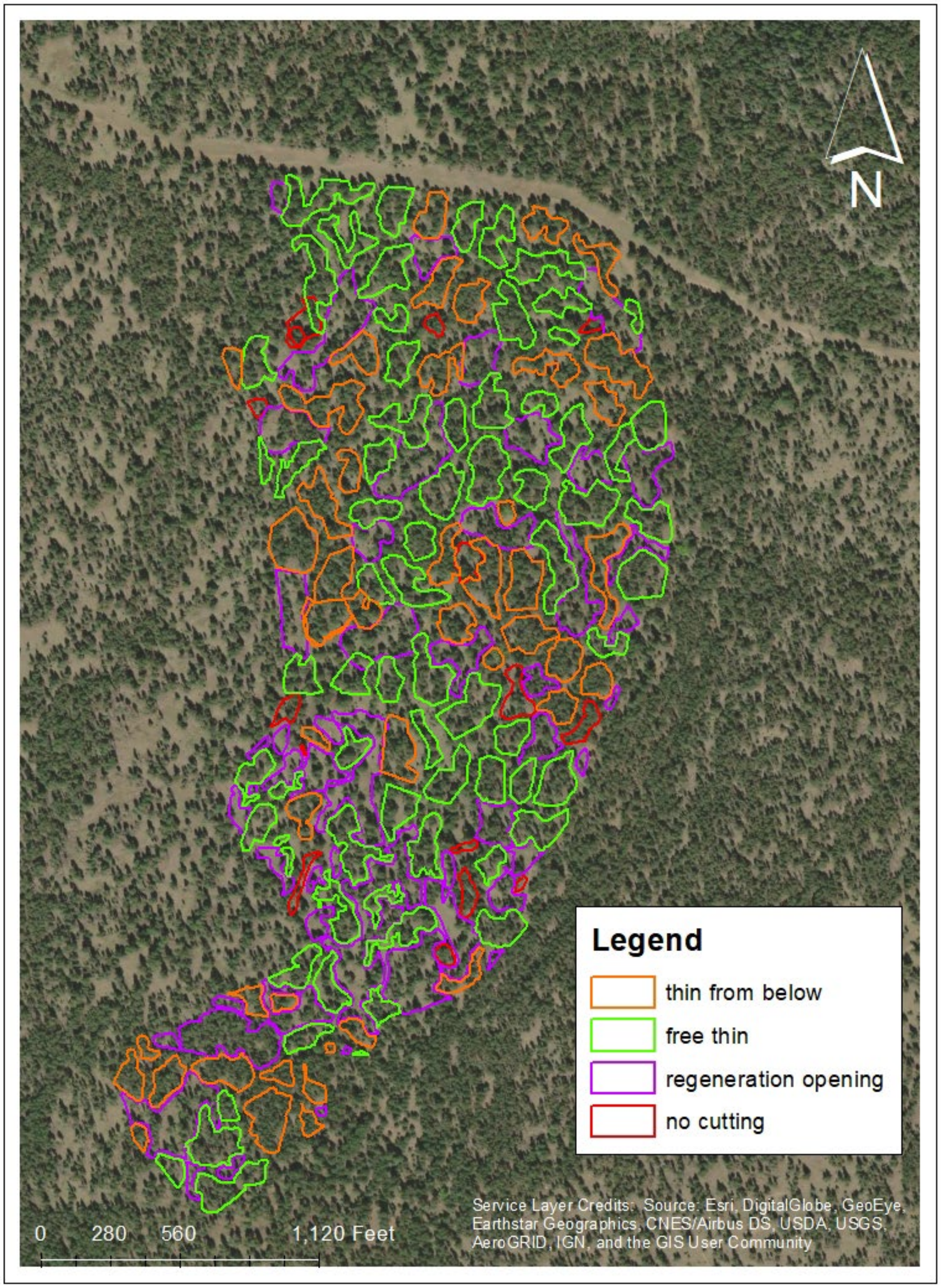


**Figure 2.** Map of unit 10 with the digital polygons created to designate the treatment types.

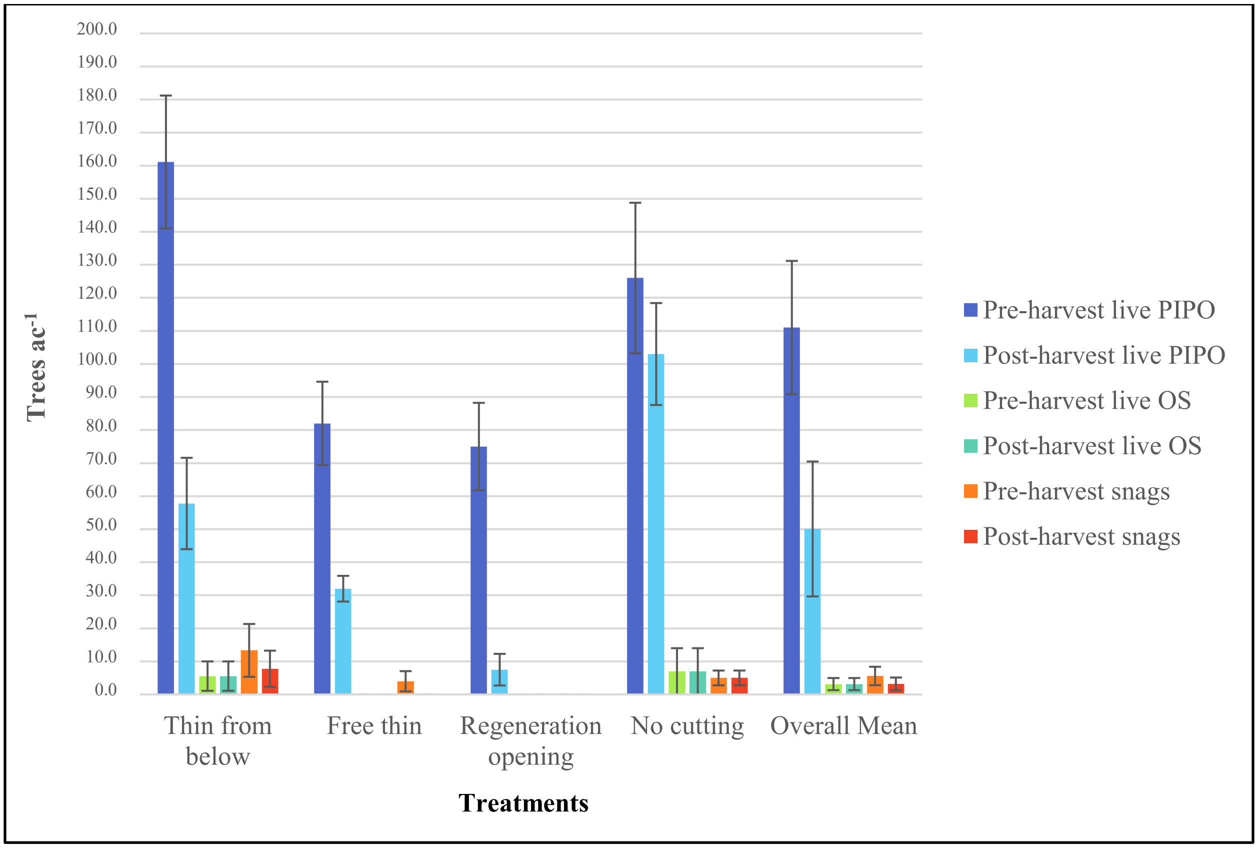


**Figure 3.** Mean trees ac$^{-1}$ by treatment type. The no cutting treatment and overall mean include reconstructed trees inadvertently removed in the no cutting unit. Figure shows ponderosa pine (PIPO), other species (OS)—includes Gambel oak, southwestern white pine, and elderberry, and snags combining all species.


**Figure 4a-1**. Pre-harvest thin from below treatment. Photos taken facing each cardinal direction from plot center.

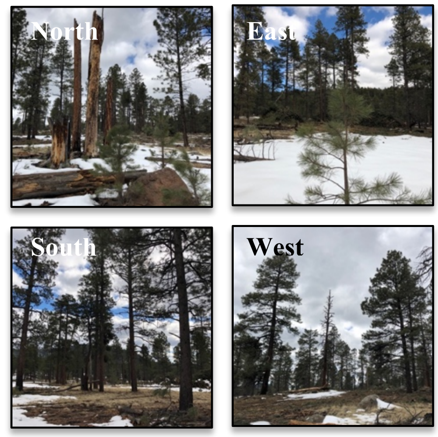


**Figure 4a-2**. Post-harvest from thin from below treatment. Photos taken facing each cardinal direction from plot center.


**Figure 4b-1.** Pre-harvest free thin treatment. Photos taken facing each cardinal direction from plot center.


**Figure 4b-2.** Post-harvest free thin treatment. Photos taken facing each cardinal direction from plot center.


**Figure 4c-1.** Pre-harvest regeneration opening treatment. Photos taken facing each cardinal direction from plot center.

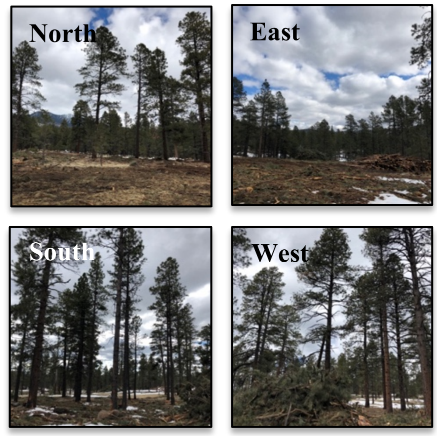


**Figure 4c-2.** Post-harvest regeneration opening treatment. Photos taken facing each cardinal direction from plot center.

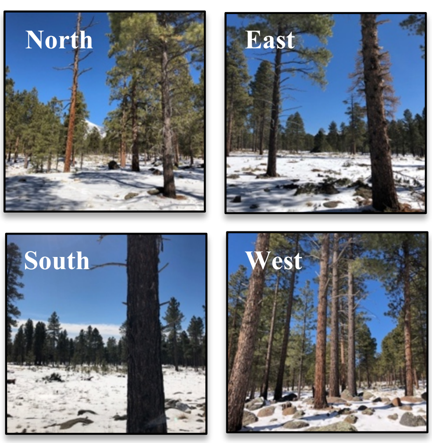


**Figure 4d-1.** Pre-harvest no cutting treatment. Photos taken facing each cardinal direction from plot center.

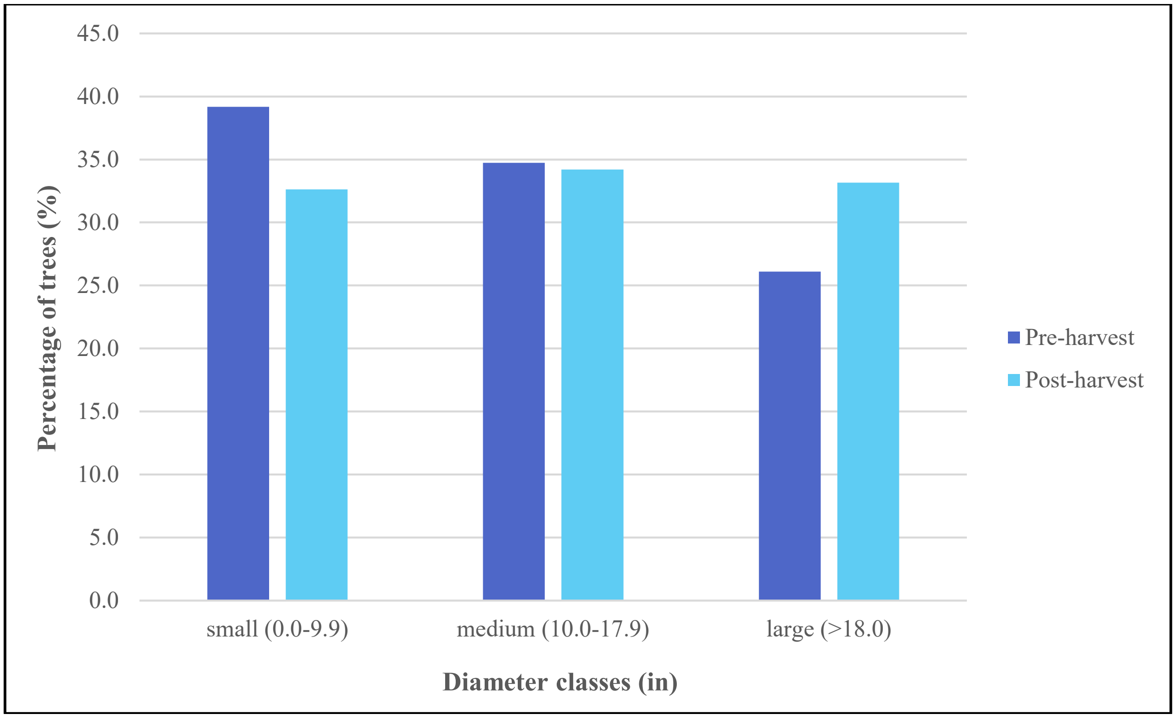


**Figure 5.** Percentage of live ponderosa pine trees within each diameter class pre- and post-harvest.

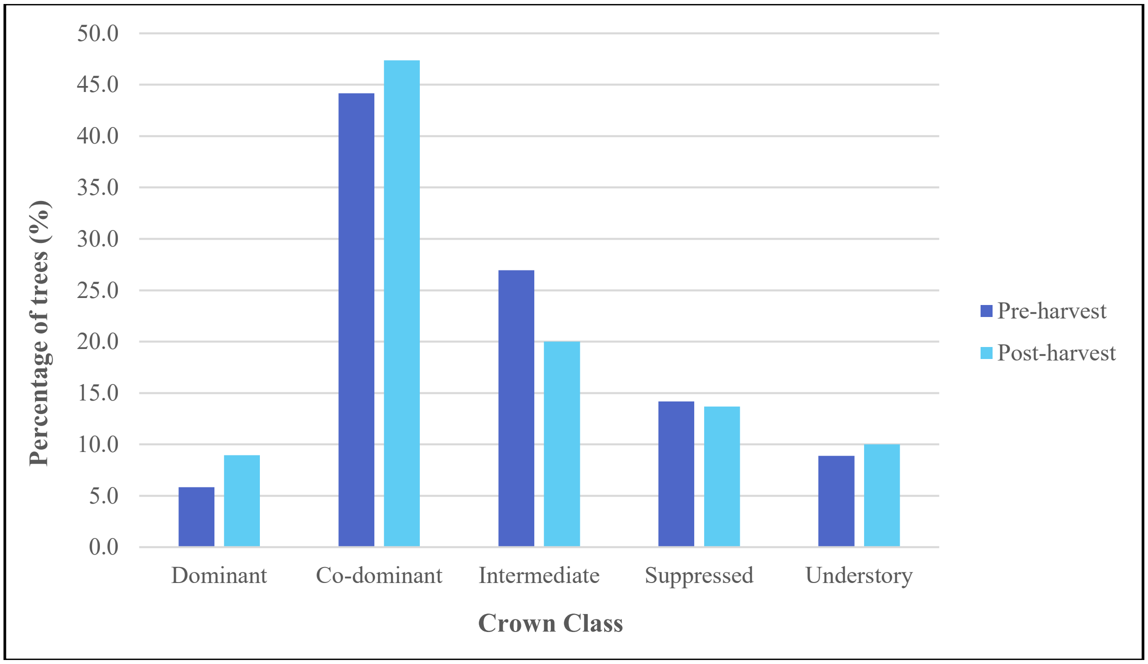


**Figure 6.** Percentage of live ponderosa pine trees within each crown class pre- and post-harvest.

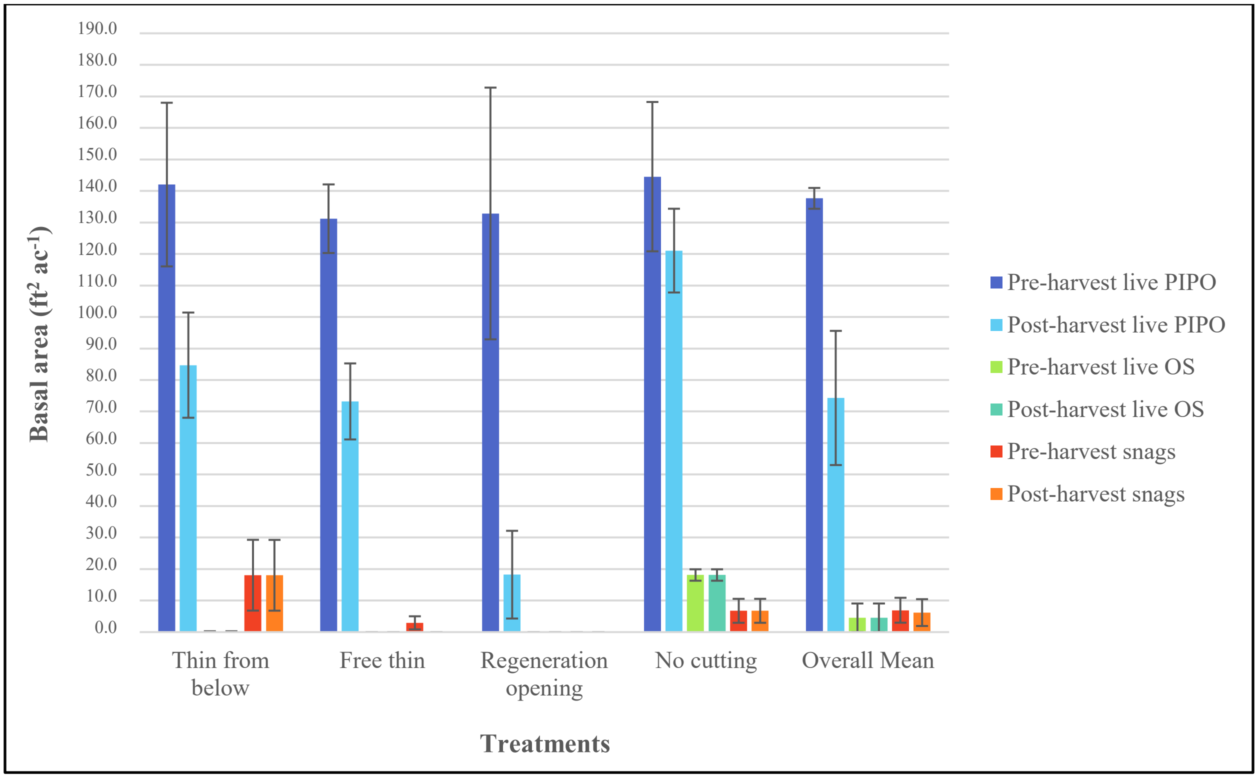


**Figure 7.** Mean basal area ($ft^2$ $ac^{-1}$) by treatment type. The no cutting treatment and overall mean include reconstructed trees inadvertently removed in the no cutting unit. Figure shows ponderosa pine (PIPO), other species (OS)—includes Gambel oak, white pine, and elderberry, and snags combining all species.

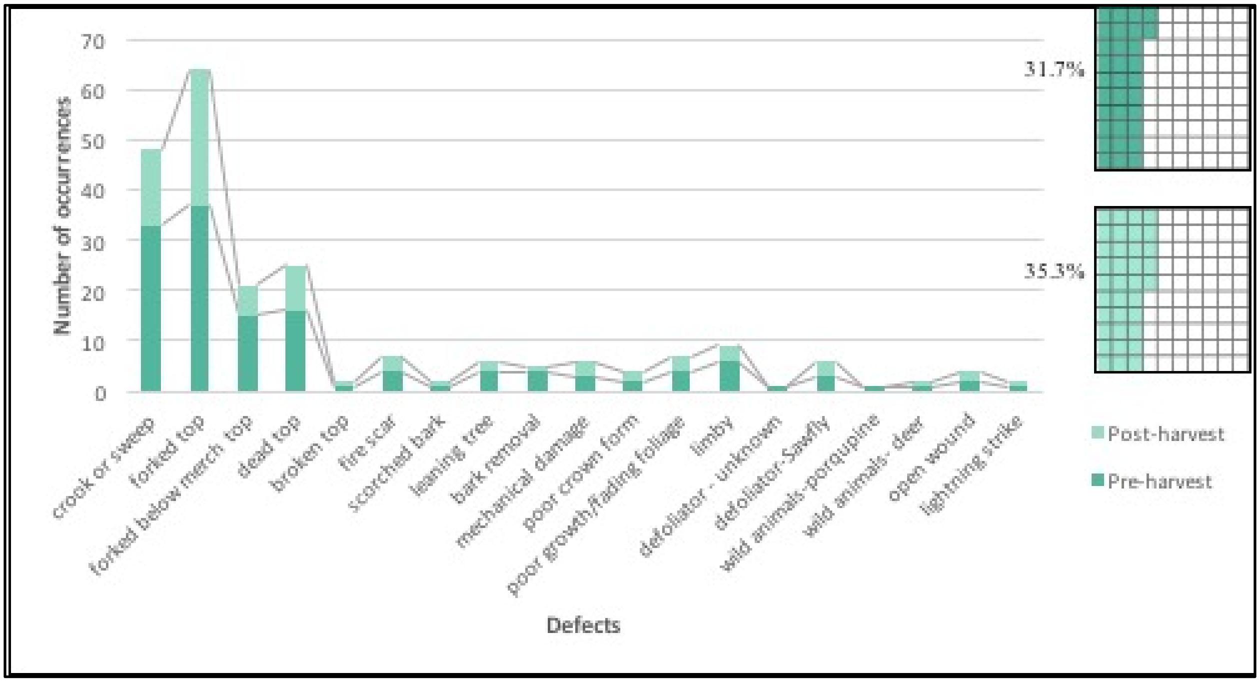


**Figure 8**. a) Count of defects recorded by category; trees with more than one defect show up in more than one category. b) Percentage of trees with defects pre- and post-harvest at the stand level—either a tree had a defect or it did not. Colored squares represent trees with defects out of 100 percent possible.

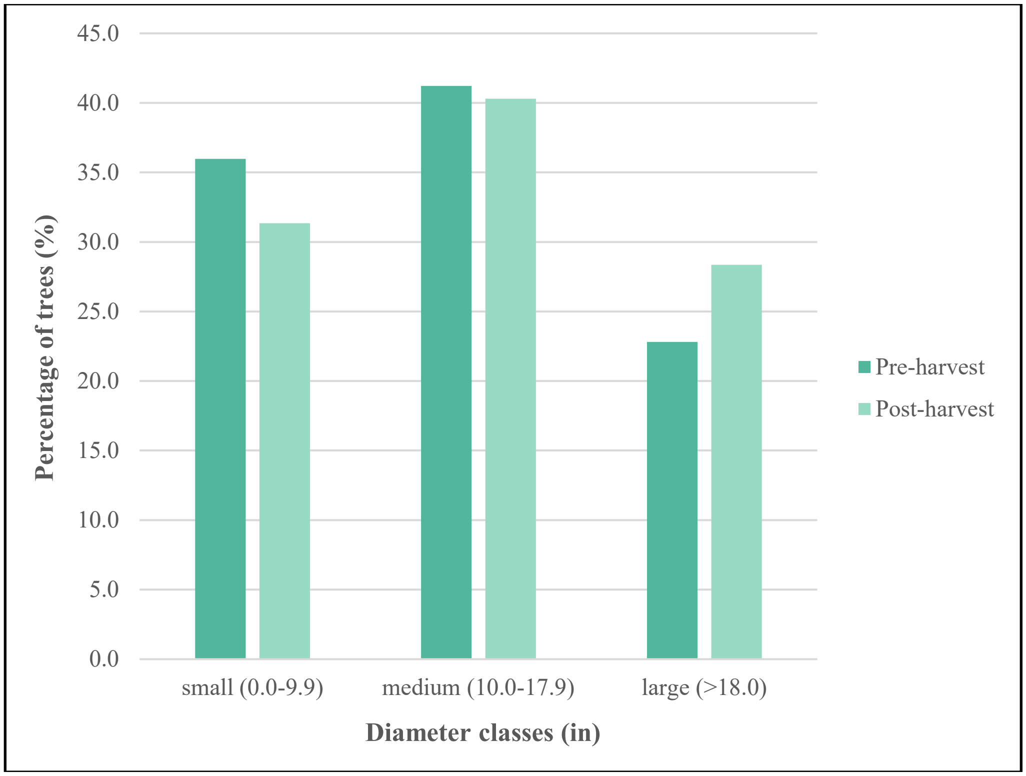


**Figure 9.** Percentage of live ponderosa pine trees with defects by diameter class, pre- and post- harvest.

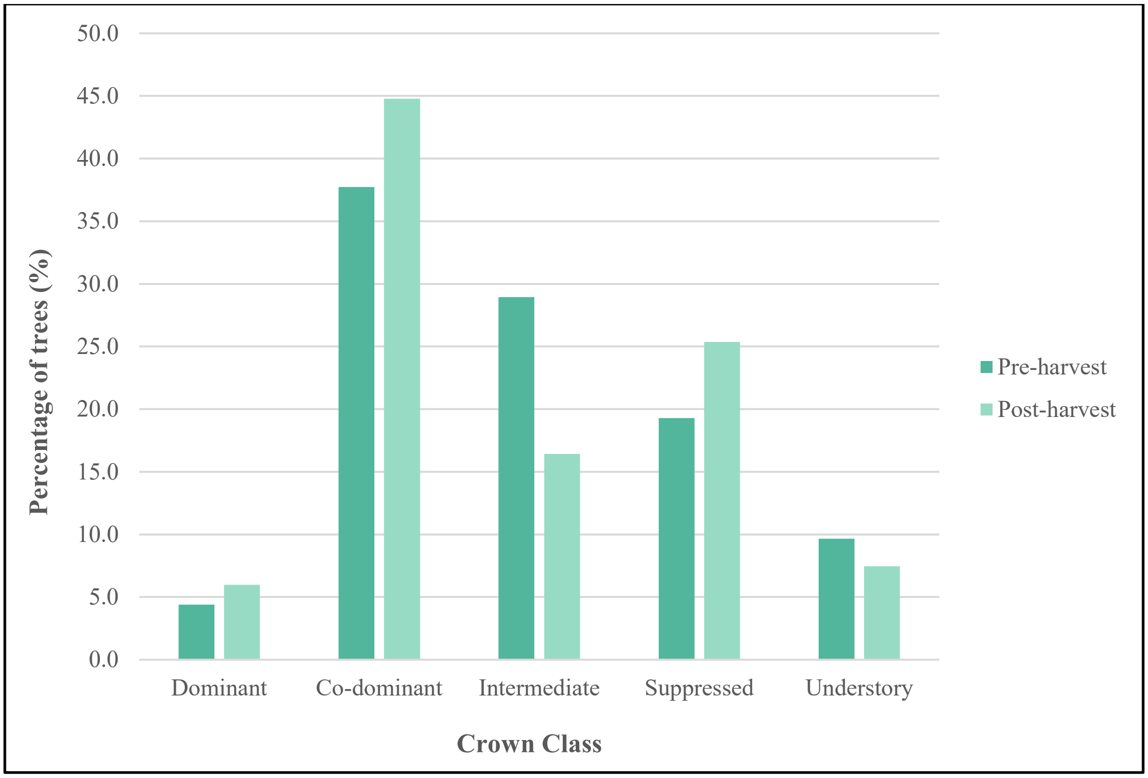

**Figure 10.** Percentage of live ponderosa pine trees with defects by crown class, pre- and post-harvest.

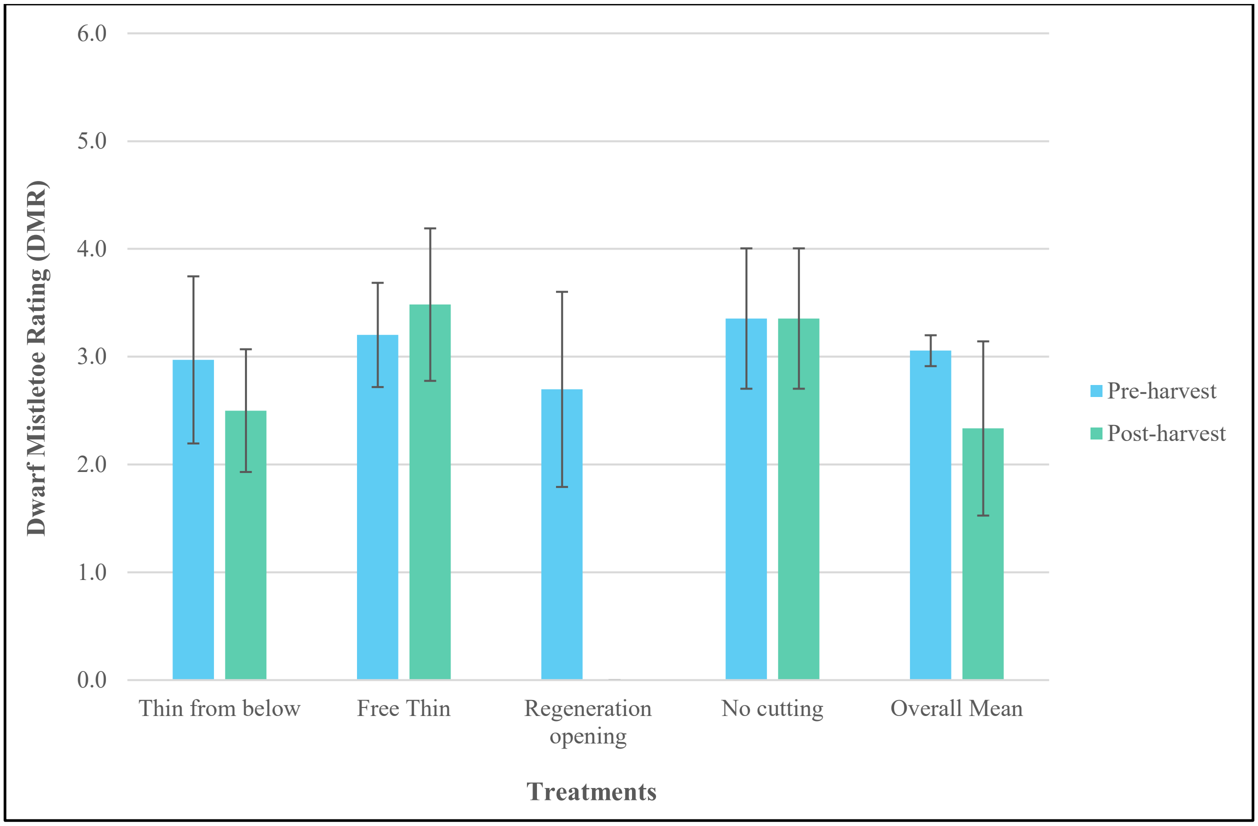


**Figure 11.** Mean dwarf mistletoe rating (DMR)—Hawksworth 6-class rating system—at the individual tree scale (only trees with >0 DMR) by treatment type and overall mean.

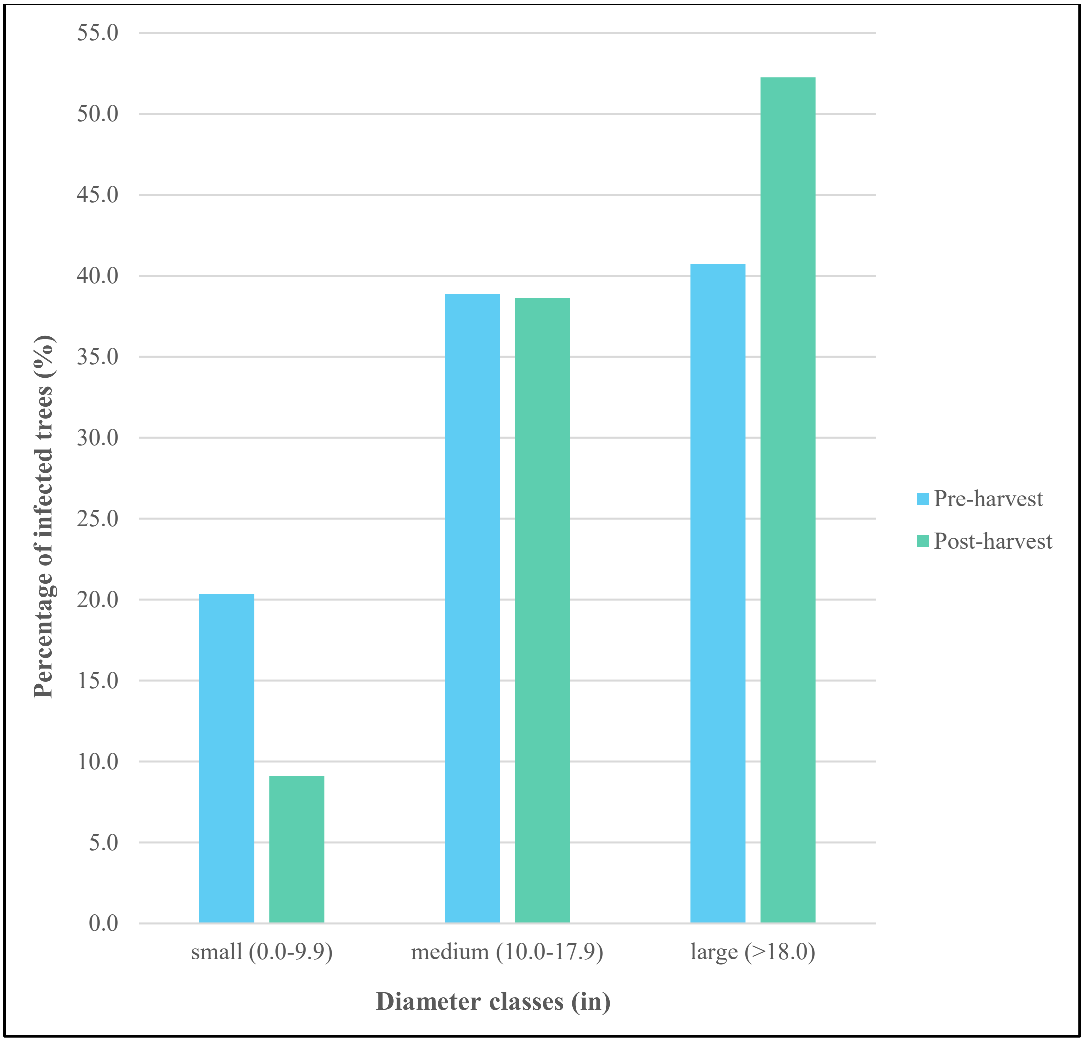

**Figure 12.** Percentage of live ponderosa pine trees infected with dwarf mistletoe by diameter class at the stand level (including trees with DMR=0), pre- and post-harvest.

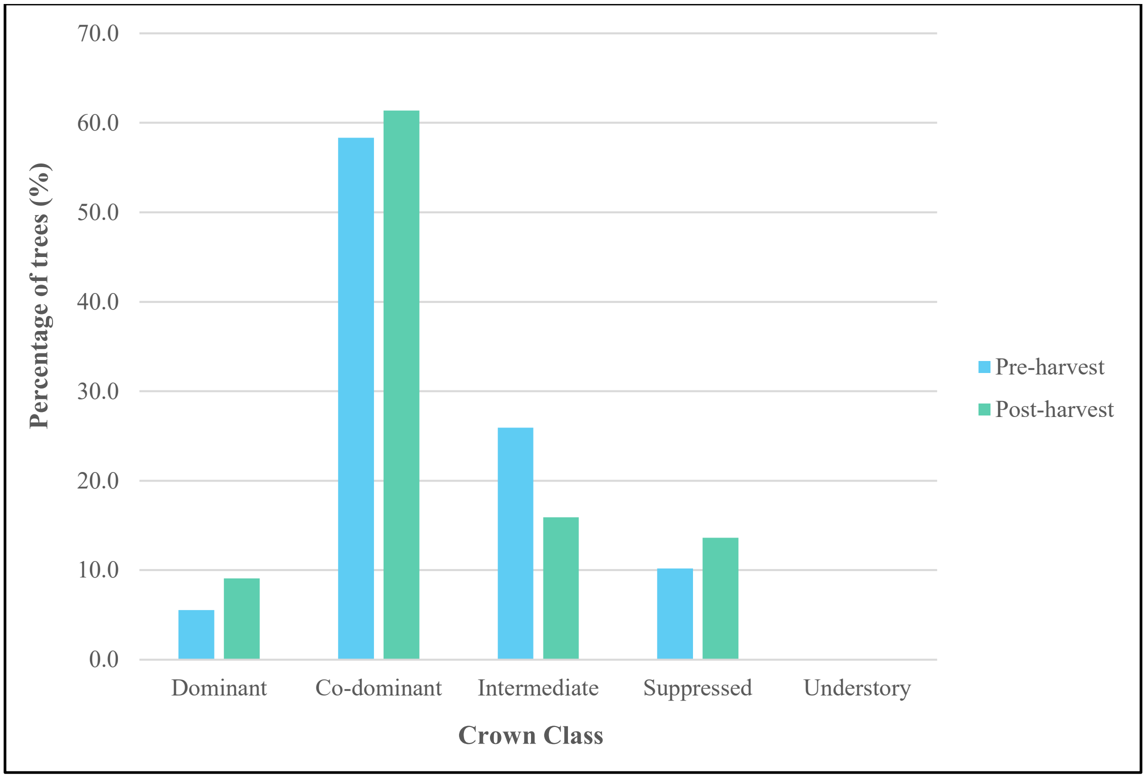


**Figure 13.** Percentage of live ponderosa pine trees infected with dwarf mistletoe by crown class at the stand level (including trees with DMR=0), pre- and post-harvest.

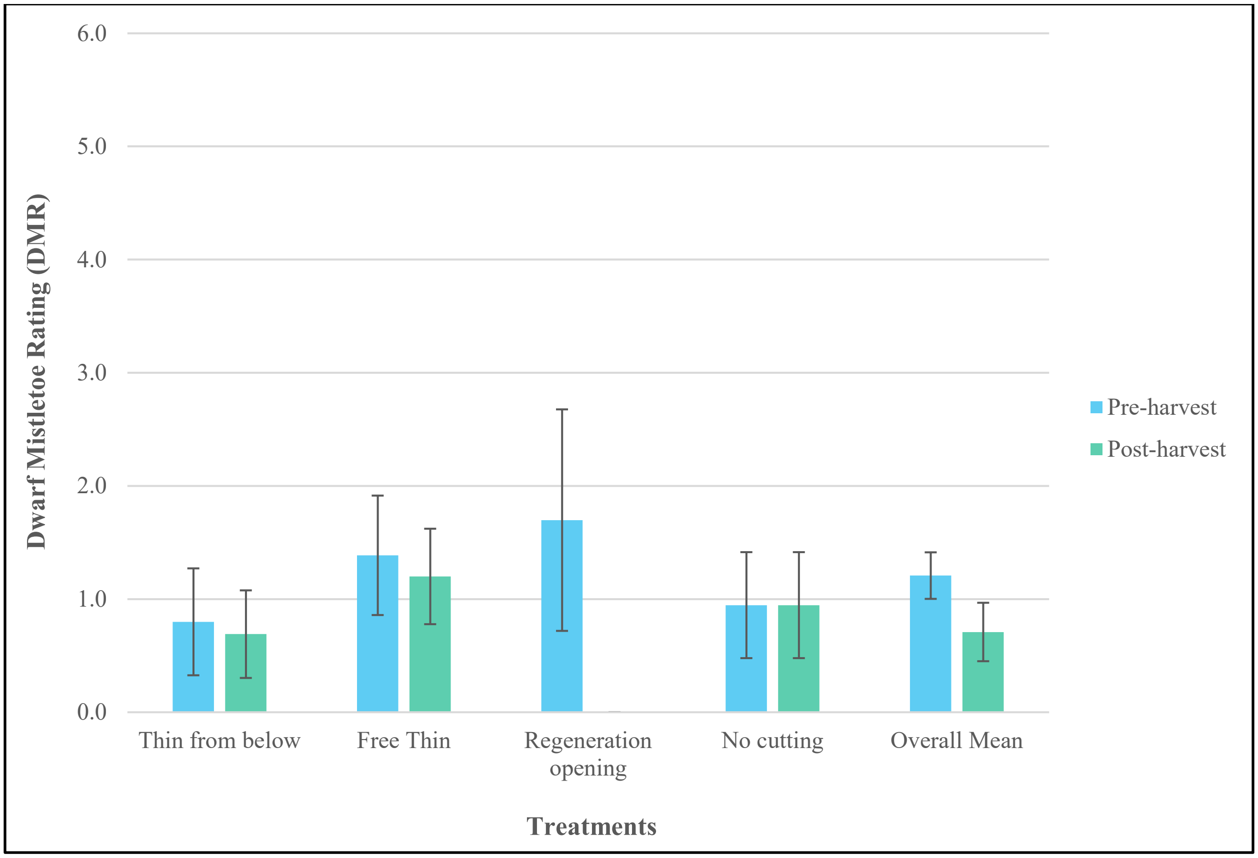


**Figure 14.** Mean dwarf mistletoe rating (DMR)—Hawksworth 6-class rating system—at the stand level (including trees that had DMR=0) by treatment type and the overall mean.

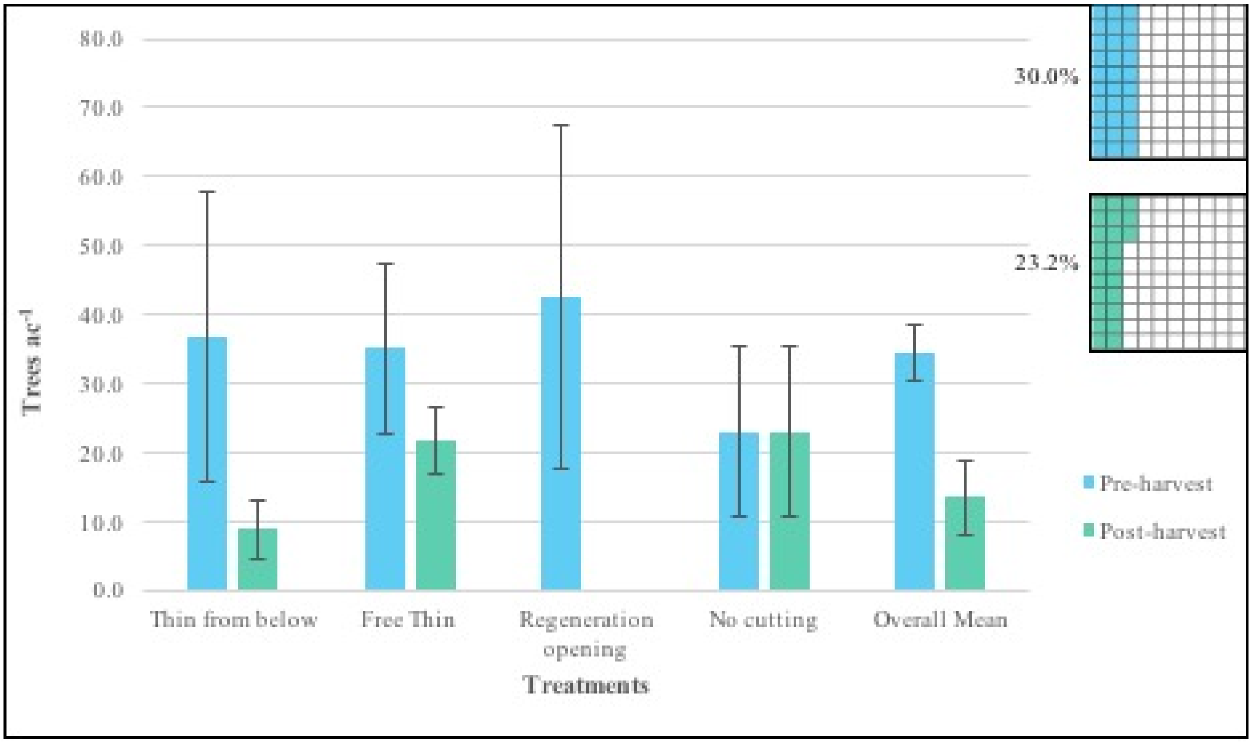


**Figure 15**. a) Mean dwarf mistletoe infected trees ac$^{-1}$ at the stand level by treatment type. b) Colored squares represent trees infected with dwarf mistletoe out of 100 percent possible.