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ORIGINAL PAPER

Innovative Tree Designation Methods for a Complex Silvicultural Treatment: Costs, Efficiency and Outcomes

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Abstract

The pace and scale of ecological restoration in the US Southwest needs to increase dramatically, but conventional, paint-based tree marking has proven to be a significant bottleneck in the treatment pipeline. Alternative, paint-free tree designation strategies have been developed and introduced in the region, ranging from fully digital desktop marking to Designation by Prescription (DxP), in which harvesting operators make tree cutting decisions during implementation based on written silvicultural prescriptions. The Walker Hill Demonstration Project used five tree designation methods to implement a silvicultural prescription focused on ecological restoration. It was conducted at an operational-scale study site in northern Arizona, and the cost and effectiveness of each method was evaluated. Unsurprisingly, conventional leave-tree marking was significantly more expensive and time consuming than digital marking or unmarked DxP approaches. More notably, no statistically significant differences were observed in harvest productivity between designation methods, and most measures of silvicultural outcomes were consistent (or consistently variable) across methods.

Keywords Tablet marking · Designation by prescription · Ecological restoration · Ponderosa pine

Study Implications Alternatives to paint-based marking can be silviculturally effective, time and cost efficient, and operationally feasible for meeting ecological restoration objectives in southwestern ponderosa forests. This is especially true when harvesting is performed by an experienced, conscientious operator. In addition to meeting stand-wide silvicultural targets, designation alternatives like digital marking and DxP can support objectives related to stand structural complexity. More research is needed to assess their long-term performance across different site conditions and to identify the key factors that enable successful delegation of harvest decisions to operators. Future research should also evaluate outcomes related to ecological complexity in greater detail.

Extended author information available on the last page of the article

Introduction

Across the American Southwest, extensive restoration of degraded southwestern ponderosa pine (*Pinus ponderosa* subsp. *brachyptera*) ecosystems is urgently needed to decrease wildfire hazard, reverse habitat loss, and restore diminished ecosystem services (Reynolds et al. 2013).

Southwestern ponderosa pine forests are the dominant natural forested community over millions of hectares in Arizona, New Mexico, southern Utah and southwestern Colorado, where they are widely distributed across the elevation band from approximately 1,500–2,700 m (5,000–9,000 ft; Callaham 2013). The density, size distribution and spatial patterns of these forests have changed dramatically since late nineteenth century Euro-American settlement (Covington and Moore 1994). Historically, southwestern ponderosa pine forests were semi-open, with trees scattered in irregular patterns of small groups or clumps within a matrix of grass-forb interspaces (Sánchez Meador et al. 2011). Indigenous cultural practices and the associated frequent, low-intensity fires maintained this distinctive forest structure and supported the unique plant and wildlife communities associated with it (Covington and Moore 1994; Reynolds et al. 2013; Dewar et al. 2021). Large, old trees were dominant in these ecosystems, but a wide range of age classes were present in each stand (Moore et al. 2004; Abella et al. 2007). Many of today's southwestern ponderosa pine forests, by contrast, are densely stocked, even-aged, and spatially homogenous (Sánchez Meador et al. 2009; Reynolds et al. 2013), resulting from unregulated settlement-era logging and grazing followed by an extended period of aggressive fire suppression and exclusion (Cooper 1960; Moore et al. 1999; Dombeck et al. 2004). The present-day landscape is over-exposed to stand replacing fires, while at the same time failing to provide all of the essential habitat components crucial for biodiversity (Parks et al. 2018; Hurteau et al. 2016; Hagmann et al. 2021).

Contemporary forest management in the region is driven by the mutually compatible goals of ecosystem restoration and fire hazard mitigation. Silviculturally, these objectives are met through uneven-aged management using mechanical harvesting and prescribed burning treatments to reduce stand density and the associated fuel loads, shift the basal area distribution to larger and broader size-classes, and increase within-stand spatial heterogeneity (Reynolds et al. 2013). In northern Arizona, substantial community engagement and forest management planning in support of landscape-scale restoration was catalyzed by the Four Forests Restoration Initiative (4FRI), a collaborative restoration effort spanning one million hectares (2.4 million acres) across four National Forests (Egan and Nielsen 2014; Vosick 2016). 4FRI streamlined the planning and environmental review processes required by the National Environmental Policy Act (NEPA), overcoming a common bottleneck for projects on federal land by securing administrative approval for over 240,000 hectares (600,000 acres) of treatments through a single, consolidated Environmental Impact Statement (Fredette 2016). Other bottlenecks in the restoration pipeline have emerged, however, and the pace and scale of treatment implementation has been inadequate given the urgency and extent of restoration needs (Woolsey et al. 2024). Through FY2024, an average of only ~ 6,000 hectares (15,000 acres) per year have received mechanical treatments (USDA 2025), far short of 4FRI's ~ 20,000 hectare (50,000 acre) annual target (USDA 2017).

One significant constraint with the implementation of treatments is the time and cost required for conventional project layout, which involves manually marking individual trees with paint to designate removal or retention. Conventionally, stand-level decisions, such as residual stocking targets or group and opening size distributions, are developed through a centralized planning process and communicated to field foresters through written silvicultural prescriptions. When implementing spatially complex prescriptions, field foresters evaluate silvicultural decisions at both the ~ 0.04–0.4 hectare (0.1–1 acre) group level (e.g. decisions on where to locate an opening or retention group) and the individual-tree level (e.g. decisions on which trees to remove or retain from within a group) and communicate their decisions by marking individual trees with paint, indicating whether a tree is to be cut or kept. Not every tree needs to be marked: when "leave tree marking" (LTM) is used all unmarked trees are cut and when "cut tree marking" is used all unmarked trees are left. The choice of method is typically based on which requires less paint. If fewer trees are to be kept than cut, LTM is preferred, and vice versa. In the Southwest, LTM is the most common method of paint-based tree designation.

A range of alternatives to LTM have been developed. "Designation by prescription" (DxP) or "cutter-select" is an alternative in which harvest operators are given a silvicultural prescription and then use it to make cutting decisions themselves (Underhill et al. 2014). DxP eliminates costly and time-consuming layout but cedes control of fine-scale tree cutting decisions from the forest manager to the harvesting contractors (Dickinson and Cadry 2017; DeRose et al. 2024).

Several studies have examined the silvicultural and operational outcomes of DxP and found mixed results. In a variety of forest types, no statistically significant differences in silvicultural outcomes were observed between DxP and conventionally-marked thinning treatments (Yeo and Stewart 2000; Spinelli et al. 2016; Eberhard and Hasenauer 2021)—perhaps unsurprising given the high variability of marking patterns from one forester to another (Spinelli et al. 2016; Pommerening et al. 2018)—though significant differences were observed in the implementation of a complex prescription in Maine (Grimm 2015).

Anecdotally, DxP has been reported to affect harvest productivity, as operators are forced to slow down to engage in cognitively taxing decision making (Dickinson and Cadry 2017). No effects on operator efficiency were noted in studies of marked versus unmarked uniform thinning operations in Australia (Yeo and Stewart 2001) or Central Europe (Holzleitner et al. 2019), and mixed results were observed in a study in Finland (Pohjala et al. 2024). A study of operator efficiency in implementing a complex silvicultural prescription in Maine also found no difference between marked and unmarked operations (Grimm 2015). DxP does also present some novel administrative complications relative to paint-based marking, as the approach eliminates any opportunity for preharvest review.

New hybrid alternatives to LTM and DxP, sometimes referred to as "DxP+", have been developed for spatially-complex prescriptions. These approaches delegate tree-level decisions to harvesting operators while allowing foresters to make group-level decisions. "Tablet marking" (TM) was the first such approach and is seen as particularly promising for implementing spatially complex prescriptions (Maher et al. 2019). In TM, a forester develops a "digital prescription guide" (DPG) in the field with the help of a GPS-enabled tablet with aerial imagery or Light Detection And Ranging (LiDAR)-derived canopy height model reference basemaps. The DPG consists of GIS polygons indicating areas of different treatment types across the stand which are then conveyed to the harvesting operator through a GPS-enabled tablet in the cab of the harvesting machine. In the Southwest, where tablet marking has been applied, the DPG indicates the operational groups designated for retention and the target basal area within those groups; the operator then selects individual trees to remove from within the groups to meet the prescription targets and removes all growing stock from the interspace between groups (Camenson 2019; Rainey 2021; DeRose et al. 2024).

A further innovation, "desktop marking" (DM; also called "Heads-up Digitizing"), moves group-level decision making from the field to the office. A forester develops a DPG informed by aerial imagery, canopy LiDAR derivatives, and digital terrain models. This approach uses the same process as field-based tablet marking to convey prescription decisions to the harvesting operator, sending the DPG to an in-cab tablet (Rainey 2021; DeRose et al. 2024). Like DxP, neither TM nor DM require the use of any tree-level paint. Table 1 summarizes silvicultural decision making across different designation methods and the associated mechanisms by which information is transmitted from the point of decision to the point of execution.

These newer DPG-based designation methods have been implemented across various projects in the Southwest, but their operational implications and silvicultural outcomes have not been thoroughly studied or systematically compared with LTM and DxP. The aim of the Walker Hill Demonstration Project was to systematically examine five designation methods for implementing silvicultural prescriptions to meet ecological restoration objectives in the Southwest and to quantify the economic costs, harvest productivity, and on-the-ground silvicultural outcomes of each method.

Materials and Methods

The Walker Hill Demonstration Project is located on an operational-scale study site in the Coconino National Forest in northern Arizona (Fig. 1). The stand history in the study area was typical of that for the broader region, with extractive nineteenth century logging removing nearly all merchantable growing stock followed by delayed regeneration until a pulse regeneration event in 1919 (Pearson 1950). The resulting stand was lightly thinned thereafter, resulting in initial stand conditions across the study area that were mostly uniform, nearly even-aged, and overly dense relative to historical reference conditions (Sánchez Meador et al. 2011).

The study used a randomized complete block design. The project area was divided into three approximately 49-hectare (120-acre) blocks which were each further divided into six, eight-hectare (20-acre) units. Within each block, one of five different designation methods or an uncut control were randomly assigned to

Table 1 Locus of silvicultural decision making and mechanism for transmitting decision information, by designation method

Designation Method	Decision Maker			Decision Transmission Mechanism
	Stand-level decisions	Group-level decisions	Tree-level decision	
Leave-Tree Marking (LTM)	Office forester	Field forester	Field forester	Tree-marking paint
Tablet Marking (TM)	Office forester	Field forester	Harvesting operator	Digital Prescription Guide
Desktop Marking (DM)	Office forester	Office forester	Harvesting operator	Digital Prescription Guide
Designation by Prescription (DxP)	Office forester	Harvesting operator	Harvesting operator	Written and verbal guidance

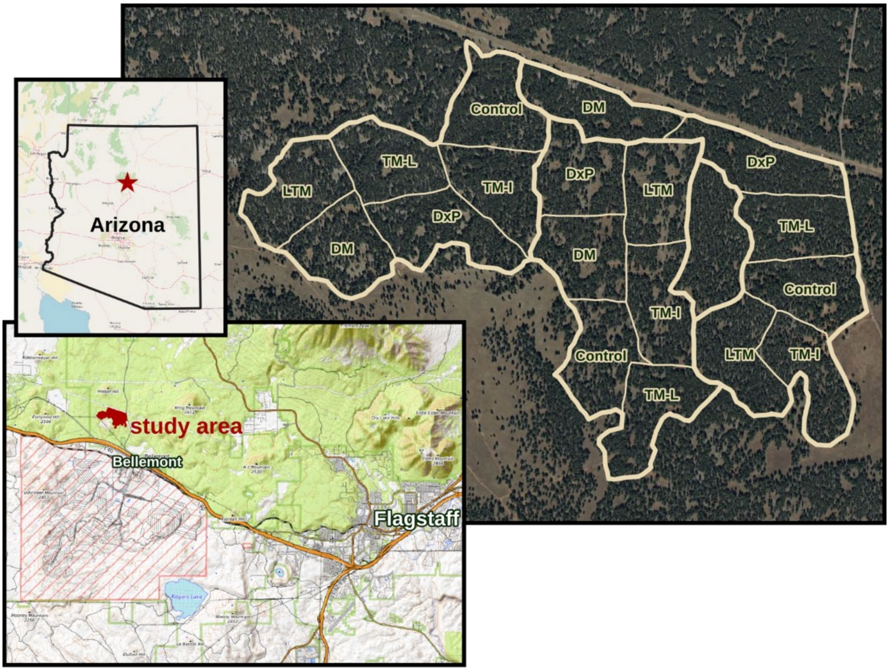

Fig. 1 Study area location and experimental design layout. Tree designation methods applied to experimental units include leave tree marking (LTM), tablet marking with satellite imagery (TM-I), tablet marking with a LiDAR-derived canopy height model (TM-L), desktop marking (DM), designation by prescription (DxP), and an untreated control

each unit. The designation methods were LTM, DxP, and three DPG-based methods: field-based TM with satellite imagery basemaps (TM-I), field-based TM with LiDAR-derived canopy height model basemaps (TM-L), and office-based DM using both imagery and LiDAR basemaps as reference (Fig. 1). The same silvicultural prescription was assigned to all treatment units in the study area. The uneven-aged prescription called for retention of groups between 0.04 and 0.4 hectare (0.1–1.0 ac) in size, 40–55% of each unit area in interspace, increases in the proportions of trees classified as “acceptable” and “desirable”, retention of older “yellow pine” ponderosa pine trees (visually distinct from the more common, younger “blackjack” pine trees), and a unit-wide target residual basal area of 11.5 m^2 ha^{-1} (50 ft^2 ac^{-1}).

Treatments implemented with LTM, TM-I, TM-L, and DM were marked in July through September of 2020. Field-based marking (i.e. LTM, TM-I, and TM-L) was performed by USDA Forest Service (Forest Service) seasonal field foresters and office-based DM was performed by an experienced Forest Service permanent employee and certified silviculturist. No specialized software or hardware were required for desktop or tablet marking methods other than standard-issue computers and tablets, and the GIS software and applications already used by the Forest Service for silvicultural planning and timber sale preparation. Work hours and paint usage (for LTM) were recorded by unit. For analysis, paint costs and wage rates were inflated to 2024 values using 2024 Forest Service employee daily rates (inclusive of benefits) and observed 2024 paint rates. Applied paint costs were \$15.93 l^{-1} (\$15.08 qt^{-1}) plus \$1.15 l^{-1} (\$1.09 qt^{-1}) shipping and wages were \$18.75 h^{-1} and \$61.00 h^{-1} for the seasonal (GS-5) and permanent (GS-11) employees, respectively. Work hours were translated to layout productivity rates (area marked per day) for analysis.

Harvest operations were conducted from January through May, 2023 by a contractor operating a mechanized, ground-based harvesting system typical for the region (i.e. a wheeled feller-buncher and rubber-tired grapple skidders). The contractor had prior experience implementing DxP and DPG-based prescriptions similar to those used in this study and had already equipped harvesting machines with GPS-enabled tablets. Machine hours were tracked by unit using cab-mounted GPS receivers and operator time logs to assess harvest productivity rate (area harvested per hour). Air temperatures, snow depths, and qualitative ground conditions were also recorded. Figure 2 illustrates a DPG drawn over a portion of a treatment unit (TM-L, Block 3) overlaid on pre- and post-harvest satellite imagery.

Silvicultural outcomes were assessed using pre- and post-harvest inventory plot data and post-harvest remote sensing data. Plot data were used to assess post-harvest basal area, yellow pine retention, retention of large trees over 46 cm (18 in) diameter at breast height (DBH), retention of standing dead trees, and changes to the proportion of acceptable and desirable trees. Remote sensing data were used to assess spatial outcomes.

For plot data, experimental units with concentrations of yellow pine trees were stratified to ensure that the yellow pine areas were adequately sampled. Yellow pine areas were manually identified from a LiDAR-derived canopy height model using visible crown heights averaging greater than 21 m (70 ft), open canopy conditions, and the presence of advance regeneration (see, for example Fulé et al. 1997; Moore et al. 2004). A systematic sample of 0.04 ha (0.1 ac) fixed-radius circular plots was taken in each stratum, such that each stratum had a minimum of two plots and each experimental unit had a total of ten plots. Plots were installed in 2020 and monumented with witness trees so they could be relocated after harvesting. At each plot, DBH was recorded for all live and standing dead trees over 12.7 cm (5 in) DBH, along with stem quality assessments to track the percentages of acceptable and desirable trees, and yellow pine/blackjack pine classifications for individual trees following Thompson (1940). Between May and July 2023, plots were resampled,

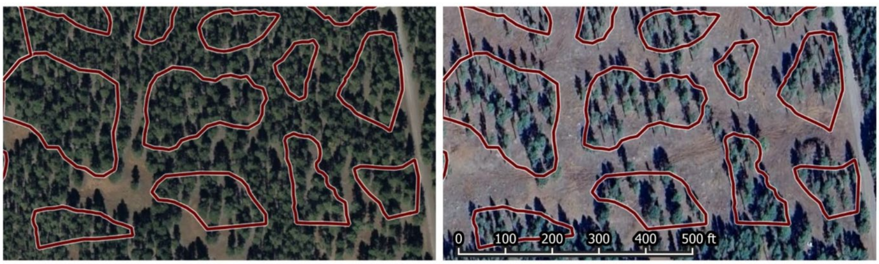

Fig. 2 Digital prescription guides (red lines) on a portion of one treatment unit, overlaid on pre- and post-harvest satellite imagery

and each previously measured tree was classified as having been cut, died naturally, or still alive. Plot data were summarized to estimate pre- and post-harvest average basal areas, numbers of large trees, yellow pines and standing dead trees, and percentages of acceptable and desirable trees for each experimental unit.

A canopy cover map was derived from National Agriculture Imagery Program (NAIP) aerial imagery collected in the summer of 2023, using vegetation indices. Normalized difference vegetation indices (NDVI) are provided by NAIP and classify areas of vegetation by the reflectance of near infrared light. These indices include grasses and shrubs in addition to trees (Xue and Su 2017), so are insufficient for tree canopy classification on their own. We supplemented NVDI data with visible difference vegetation index (VDVI) data that we derived from NAIP imagery, to filter out areas of grass and shrubs. The VDVI model identifies tree canopies based on their visible color and is much less likely than NDVI to classify ground vegetation as tree canopy. However, VDVI can misclassify shadows as tree canopies, which the NVDI typically does not. By identifying overlapping areas between the VDVI and NDVI models, we generated a canopy cover map that excluded the shadows from the VDVI model and the ground cover from the NDVI model. We compared our canopy cover map to an accurate but outdated canopy map derived from pre-harvest LiDAR data, to ensure that the remaining tree canopies in the new map aligned with the corresponding canopy area from the older map.

The post-harvest canopy cover map was further processed to remove landings and haul roads. Tree groups and interspaces were then mapped by grouping canopy cover polygons using a concave hull algorithm. Both functional groups and operational groups were mapped. Functional groups are clusters of trees with interlocking or near interlocking crowns that form cohesive canopy areas, while operational groups are often larger, "microstands" in which the tree stocking is broadly uniform. In the context of ponderosa restoration, operational groups can be thought of as collections of functional groups. A functional group was defined as one or more trees whose canopies were within 4.6 m (15 feet) of one another and with a total canopy area of greater than 0.004 ha (0.01 ac), based on the authors' experience and on restoration prescriptions developed by the Forest Service. Separately, operational groups were defined using a similar approach but aggregating canopies within a 9.1-m (30-foot) separation buffer.

Multiple measures of spatial structure were assessed across treatment units. Canopy cover percentage, area in functional groups, and area in operational groups were calculated at the unit level as well as within units across a rasterized, 0.04 ha (0.1 ac) square grid. Functional and operational group size distributions were assessed across treatment units.

Analysis of variance was used to test for significant differences between tree designation methods, related to marking and layout costs, layout and harvest productivity rates, and numerous silvicultural outcomes. When significant differences were observed for any given outcome ($\alpha = 0.05$), pre-planned, nested contrasts were used to parse the differences. For silvicultural outcomes five contrasts were tested: (1) control vs. cutting treatments, (2) non-paint-based designation methods vs. LTM, (3) DPG-based methods vs. DxP, (4) TM methods vs. DM, and (5) TM-I vs. TM-L. Harvesting productivity outcomes did not apply to the control so only contrasts (2), (3), (4), and (5) were tested. Similarly, layout cost outcomes did not apply to the control or DxP treatments, so contrast (2) was modified to exclude DxP and contrasts (4) and (5) were also tested.

Results

Economic Cost and Harvest Productivity Assessment

We found significant savings of time and money in DPG-based methods when compared to LTM, and failed to observe any significant differences in harvest productivity between designation methods.

Table 2 presents tree-marking costs and layout and harvest productivity across designation methods. Total designation costs per unit area for LTM were higher than the average of DPG-based methods by an estimated \$140.63 ha^{-1} (\$56.91 ac^{-1}) ($p < 0.001$). Average designation costs for DPG-based methods were an estimated \$12.85 ha^{-1} (\$5.20 ac^{-1}) higher than for DxP, where tree-marking layout costs were \$0 ha^{-1}. Among digital methods, the difference in designation costs between tablet-based methods and DM were statistically significant ($p = 0.048$) but averaged only \$3.34 ha^{-1} (\$1.35 ac^{-1}) higher.

Savings in both time and materials (i.e. paint) explain the substantial cost advantage of digital methods over paint-based marking (Table 2), though the specific drivers of cost savings varied among DPG-based methods. The daily layout productivity rate was four or four and a half times higher for DM than for TM-L or TM-I methods, respectively, but cost savings from the faster pace of "marking" were mostly offset by the higher wage rate required for a more experienced forester.

Harvest productivity rates did not differ significantly between any of the treatments in which harvesting occurred ($p = 0.612$; Table 2). We developed a linear model relating snow depth, air temperature, and ground conditions to harvest productivity rates. None of the estimated coefficients were statistically significant (results omitted for brevity), so it is unlikely those factors obscured any otherwise significant effects of designation method.

Table 2 Mean layout costs and layout and harvest production rates, by designation method, with standard deviations shown in parentheses. See Fig. 1 caption or the text for designation method definitions

Designation Method	Labor Cost [\$ ha^{-1}]	Paint Cost [\$ ha^{-1}]	Total Cost [\$ ha^{-1}]	Layout Productivity Rate [ha day^{-1}]	Harvest Productivity Rate [ha hr^{-1}]
LTM	72.22 (4.55)	81.26 (6.10)	153.48 (1.58)	2.60 (0.17)	0.54 (0.14)
TM-I	14.69 (1.85)	–	14.69 (1.85)	12.90 (1.56)	0.50 (0.09)
TM-L	13.23 (0.52)	–	13.23 (0.52)	14.19 (0.55)	0.40 (0.06)
DM	10.63 (1.43)	–	10.63 (1.43)	58.14 (8.26)	0.49 (0.11)
DxP	–	–	–	–	0.48 (0.15)

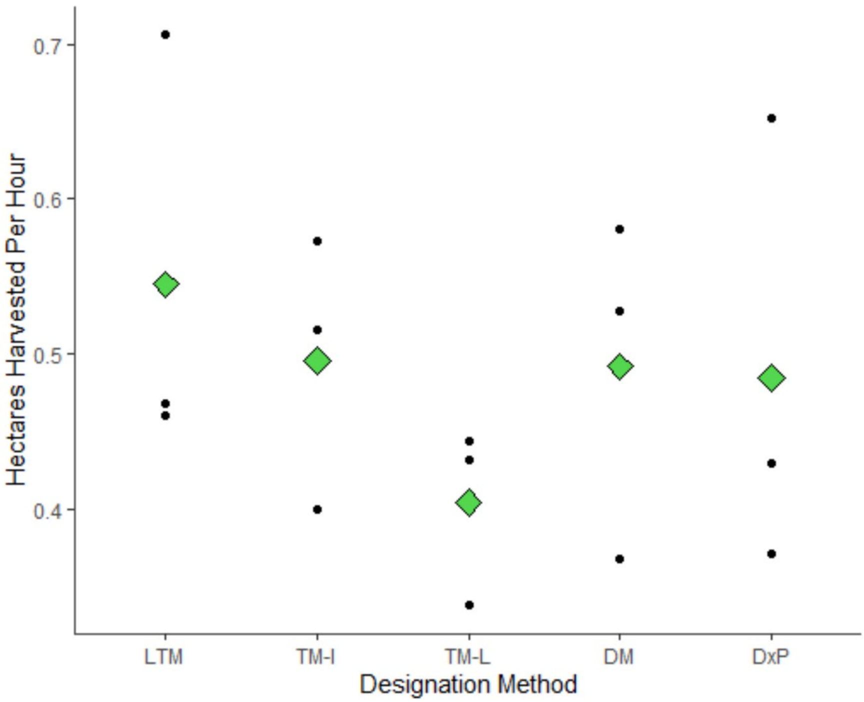

Fig. 3 Harvest productivity rate by designation method. Small black dots indicate individual-unit observations and large green diamonds represent mean values by designation method. See Fig. 1 caption or the text for designation method definitions

Harvest productivity rates varied considerably between experimental units (blocks) of the same designation method (Fig. 3). DxP methods, for example, produced the third lowest and the second highest production rates out of the 15 harvested units. Across all units, the highest recorded harvest productivity rate (0.70 ha hr^{-1} [1.78 ac hr^{-1}]) was more than double the lowest rate (0.34 ha hr^{-1} [0.86 ac hr^{-1}]).

Silvicultural Outcomes

Overall, no significant differences were found in key silvicultural outcomes between tree designation methods, and outcomes were consistent with silvicultural objectives. This was true for stand-level outcomes like residual basal area and retention of large, old, and desirable trees, as well as for outcomes related to within-stand residual spatial arrangements. Subtle differences were observed in spatial arrangement between designation methods, with LTM producing slightly larger functional groups than other methods, on average.

Non-Spatial Outcomes

No significant differences were observed between harvested treatments and the control for yellow pine retention ($p = 1.000$), large tree retention ($p = 0.555$), and standing dead tree retention ($p = 0.480$). All harvested treatments significantly increased the proportions of acceptable ($p = 0.007$) and desirable ($p = 0.006$) trees relative to the control and no significant differences were observed in post-harvest acceptable and desirable stem proportions between designation methods.

Mean residual basal areas did not differ significantly between designation methods, and did not vary significantly from the target basal area of 11.5 m^2 ha^{-1} (50 ft^2 ac^{-1}). Though not statistically significant, the residual basal areas were below the target in 10 of the 12 units where DPGs were used and above the target in two of the three units where DxP was used (Fig. 4). Total percentage of canopy cover did not differ significantly between methods (see Supplemental Information).

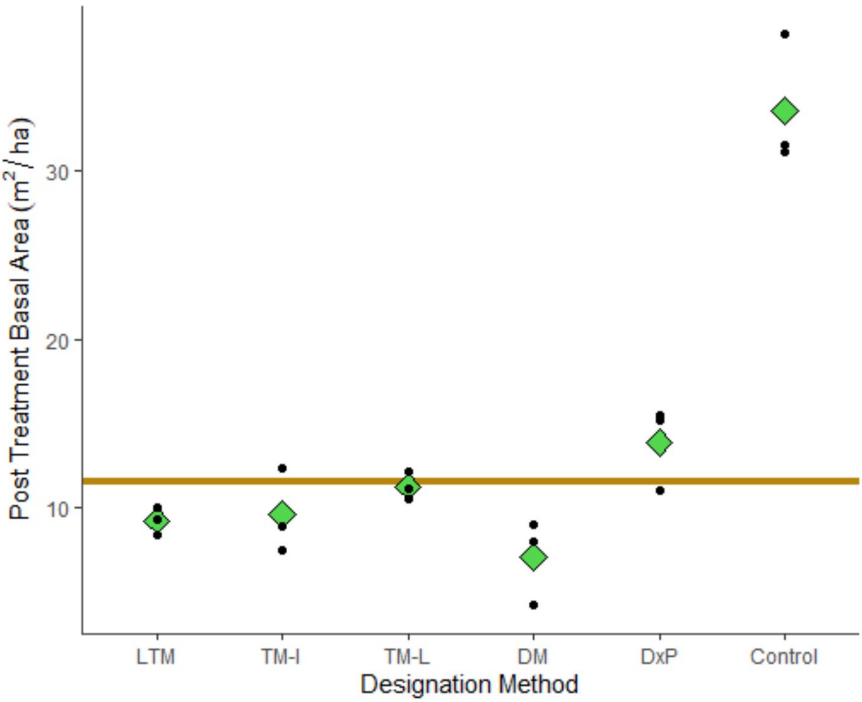

Fig. 4 Residual basal areas by designation method. Small black dots indicate individual-unit observations and large green diamonds represent mean values by designation method. The horizontal brown line shows the target residual basal area. See Fig. 1 caption or the text for designation method definitions

Spatial Complexity Outcomes

Spatial arrangements were generally similar across treatments (Table 3). One exception was for LTM, which had a significantly higher percentage of area in 0.04–0.4 ha functional groups than non-paint-based designation methods ($p = 0.018$). The median functional group size was also larger for LTM than other harvested treatments and the median operational group size was smaller. Otherwise, treatments did not differ significantly in total area covered by functional or operational groups or in the percentage of groups by size.

Analysis of stand structure in spatially complex stands can be sensitive to the scale of aggregation (Wasserman et al. 2019) but no significant differences were revealed here from changes in analytical resolution. Figure 5 shows the results of the 0.04 ha (0.1 ac) rasterized canopy cover map across the project area. As with other metrics, the distribution of canopy cover across raster cells tended to vary more between replicates of the same designation method than between designation method means (Fig. 6).

Discussion

Our findings demonstrate the potentially large cost and time savings that can result from DxP and DPG-based tree designation methods, while showing that these paint-free methods do not necessarily compromise harvest rate productivity or silvicultural outcomes. Paint-free designation methods could help to scale up ponderosa pine restoration efforts in the Southwest and elsewhere in the western US and may also be useful for implementing other kinds of complex silvicultural treatments. Our results support the conclusion that paint-free approaches to harvest layout can be operationally feasible and are worth developing and refining further.

To put the time and cost savings we observed in perspective, consider a hypothetical 2,000-hectare (5,000-acre) ponderosa pine treatment for restoration objectives. Using conventional LTM, the estimated layout costs for paint and labor over the entire area would be more than $300,000. With digital methods, the

Table 3 Group size outcomes, by designation methods, with standard deviations shown in parentheses. See Fig. 1 caption or the text for designation method definitions

Designation Method	Percentage Distribution of Functional Groups, by Size				Median Group Size (ha)	
	< 0.04 ha	0.04–0.2 ha	0.2–0.4 ha	> 0.4 ha	Functional	Operational
LTM	22.8 (21.9)	65.5 (16.6)	11.7 (20.3)	0 (0)	0.04	0.08
TM-I	51.9 (16.7)	41.4 (9.3)	6.7 (11.5)	0 (0)	0.02	0.12
TM-L	57.2 (23.8)	34.5 (13.7)	8.3 (14.4)	0 (0)	0.01	0.15
DM	37.3 (8.5)	30.1 (17.5)	32.7 (9.4)	0 (0)	0.01	0.10
DxP	47 (0.6)	53 (0.6)	0 (0)	0 (0)	0.02	0.16
Control	0.9 (0.9)	1.1 (1.5)	0 (0)	97.9 (2.4)	1.37	6.33

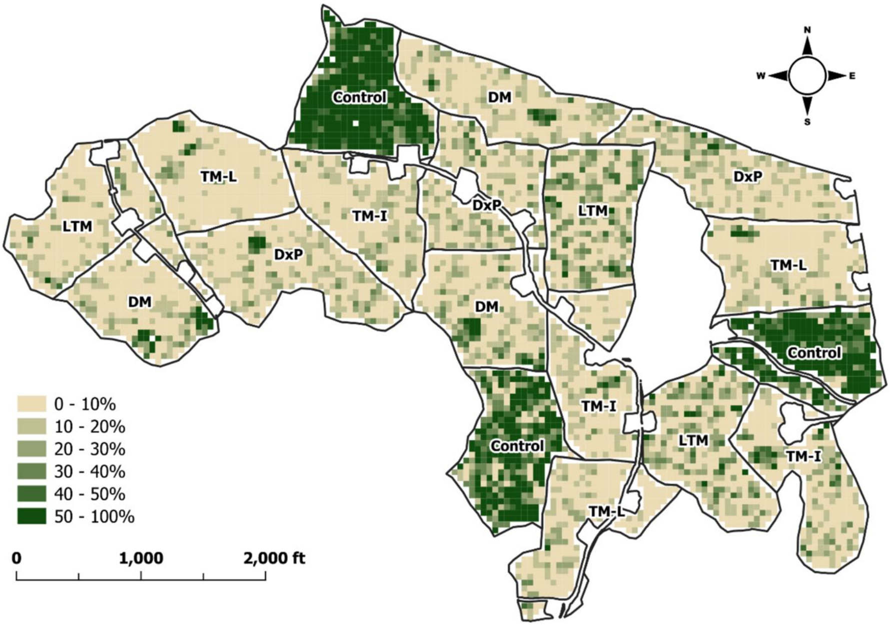

Fig. 5 Rasterized map of residual percent canopy cover across the entire study area. Grid cells are 0.04 ha. See Fig. 1 caption or the text for designation method definitions

costs would be between $20,000 and $30,000—lower by a factor of at least 10. In addition to lowering costs, digital methods could increase the pace of implementation significantly. Where paint-based marking would require personnel time of 777 workdays, tablet marking would require 149 workdays and desktop marking would require just 35 workdays. Given the extent of restoration needs in the Southwest and the resource constraints that limit the pace and scale of implementation, these advantages could translate into a more efficient use of the existing workforce and tens of thousands of additional acres treated across the landscape annually.

An important qualification to the reported layout cost savings of DxP and digital marking methods is the potentially counteracting effect of increased sale administration costs at later phases of a harvest operation. More time and attention are probably required of sale administrators to monitor performance when there is not clear evidence on the ground (in the form of painted stump marks) that the job has been harvested in compliance with the prescription. Anecdotally, administration costs have been considerably higher for DxP than conventionally marked projects, especially with operators who are less familiar with southwestern ponderosa pine silviculture for restoration objectives or DxP operations (*pers. comm.*). Speculatively, DPG-based methods could be more efficient to administer than DxP because they incorporate spatially-explicit prescriptions that are easier to monitor. A more complete assessment of the economics of DxP and digital marking methods would need to explicitly account for preharvest and postharvest administration costs.

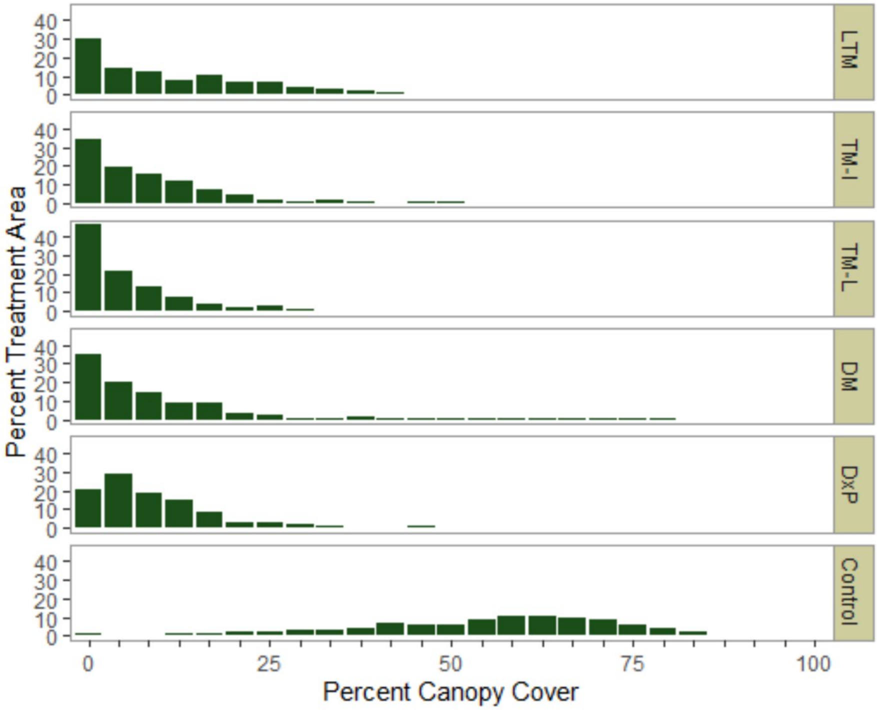

Fig. 6 Distribution of canopy cover percentage within each designation method, as calculated on 0.04 ha raster cells. See Fig. 1 caption or the text for designation method definitions

The operational results from this study are generally consistent with other research that has compared DxP and LTM (Yeo and Stewart 2001; Grimm 2015; Holzleitner et al. 2019; Pohjala et al. 2024). They also contradict the narrative (reported qualitatively by Dickinson and Cadry 2017) that DxP slows harvest operations by placing an additional burden on operators. If there was any effect of designation method on harvest productivity rate at the Walker Hill Demonstration Project, it was small enough to be lost amid the natural variability in harvest rates.

The operational feasibility of DxP appears to extend to DPG-based designation methods as well, at least in the context of complex southwestern ponderosa pine prescriptions. In addition to DPG-based methods supporting harvest rates comparable to DxP and LTM, there are now operators in the study region who report a preference for DPGs over DxP. Rather than seeing tablets as a burden, these operators have found value in having tablets in the cabs of their harvesting equipment (*Pers. Comm.* Joe Call, September 2021).

The trends we observed in operational outcomes extend to silvicultural outcomes. DPG-based methods performed as well as DxP and LTM. For most silvicultural metrics, there was greater variance within treatments than between them.

While some differences in the pattern/arrangement of residual canopy cover may be visually apparent across designation methods (Fig. 7), the total percentage of canopy cover did not differ significantly between methods. Even in this controlled study, intentionally situated in a structurally homogeneous stand, the variability in conditions from one spot to the next overwhelmed any statistically detectable signal of the silvicultural impact of different designation methods.

Despite the overall variability of the results, some subtle patterns were observed in silvicultural outcomes. DxP appeared to result in slightly higher stocking than other methods, for example (though the difference was not statistically significant).

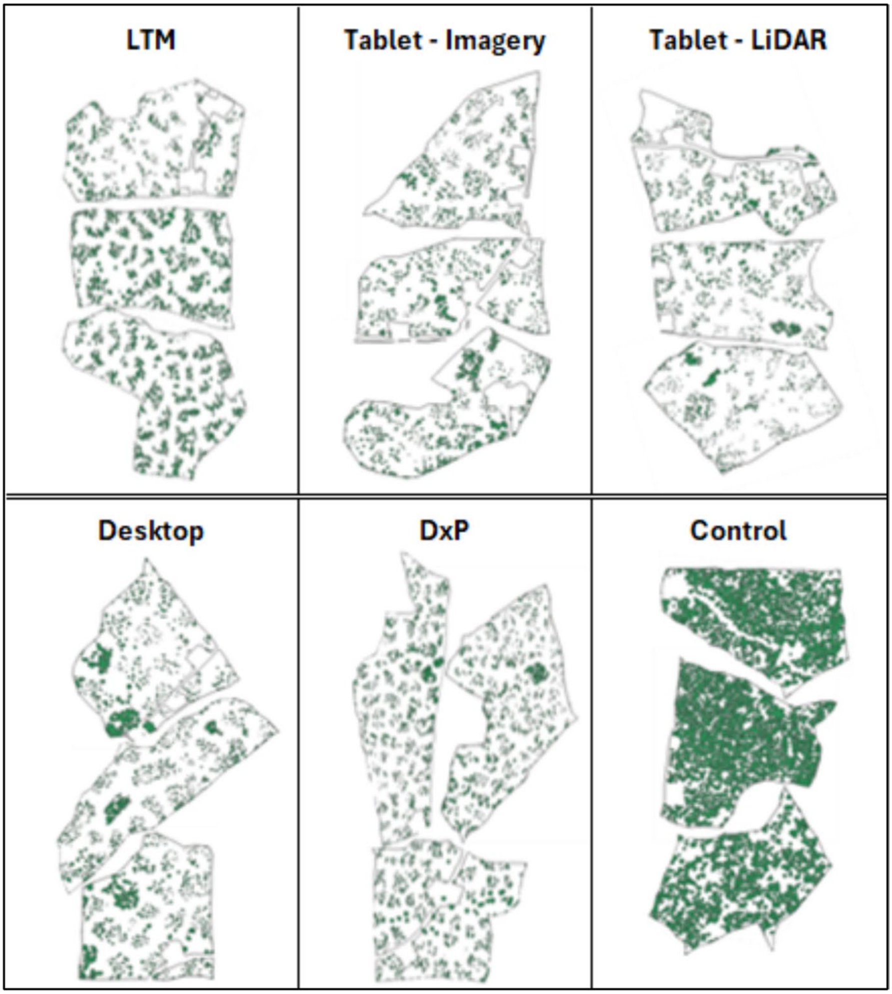

Fig. 7 Post-harvest canopy cover by treatment units. All units are shown to scale but repositioned and reoriented spatially, by tree designation method. Canopy cover was derived from intersecting normalized difference and visible difference vegetation indices. See Fig. 1 caption or the text for designation method definitions

This suggests that operators may act with caution when they are tasked with making tree selection decisions. Rather than the "greedy loggers" who some might worry will cut too aggressively if given the chance, results here match anecdotal reports of operators tending to err on the side of retention and needing a clear permission structure to feel comfortable cutting as heavily as restoration treatments require (Mottek Lucas and Kim 2016).

Qualitative evidence from this study was also consistent with the pattern, noted by the authors and others in the region, that, if left to choose for themselves, operators tend to leave trees uniformly spaced within operational groups (Mottek Lucas and Kim 2016). Clumpier distributions of residual growing stock and smaller group sizes better match historical reference conditions (Sánchez Meador et al. 2011; Reynolds et al. 2013). LTM appeared to achieve greater within-group heterogeneity than DxP or digital marking methods by multiple measures and by visual impression of the post-harvest stand conditions, although most of these differences were not statistically significant. The median size of functional groups was larger for LTM than for any of the DPG-based methods (0.04 ha versus 0.01–0.02 ha), while the median operational group size was the smallest for LTM (0.10 ha versus 0.12–0.16 ha), implying a more clustered canopy distribution with denser clumps at slightly wider or more variable spacing.

It is unclear how important subtle spatial differences like these are to the ecological functioning of restored forests, or how paint-free tree designation methods could be adapted to achieve increased stand spatial complexity. Training might improve operators' ability to create heterogeneous conditions within operational groups, but it is understandably harder for operators to feel confident about meeting basal area targets when stocking is unevenly distributed. Alternatively, DPGs could use smaller operational groups (<0.04 ha) with more varied residual stocking targets to increase structural complexity, but smaller groups may also be more difficult for operators to implement. Going forward, research is required to assess spatially complex outcomes and set appropriate silvicultural goals related to spatial complexity. Innovation may be needed to modify digital marking methods so they can be used in service of those goals. Similarly, further work would be required to evaluate the suitability of these methods in other contexts, for example in stands with greater compositional diversity or in stands with highly differentiated timber quality managed for commercial production. It seems likely that this approach, or creative variations of it, could bring value to the management complex, mixed-species stands and we hope the results from this study encourage experimentation in other forest types.

DxP and other approaches that trust operators with tree cutting decisions are highly dependent on the skill, experience, and conscientiousness of the operators, and on clear and consistent communications and training by sale administrators. How to improve the processes that develop those qualities is an open and critically important question (Häggström and Lindroos 2016). The harvesting in this study was performed by an operator who had previously carried out several successful DxP and tablet-marked projects and who had a strong working relationship with the project team. Not all DxP or digitally marked projects would have those advantages. Admittedly, then, it is misleading to report that the preparation costs for DxP methods for this project were \$0 ha^{-1}. There were real costs involved in developing the operator's skillset through attentive supervision and effective feedback over the course of multiple previous projects. High-trust relationships require time and resource investments to develop. More attention from scholars, practitioners, and industry leaders should focus on understanding the factors that facilitate the constructive working relationships and communication required for foresters to effectively delegate tree harvesting discretion to operators. Fostering these skills, alongside conventional, equipment operation-focused approaches to workforce development, will be critical in cultivating a regional workforce capable of efficiently and effectively implementing silviculture to meet ecological restoration objectives at a scale commensurate with the need across the Southwest.

Conclusion

This study found that alternatives to paint-based marking can be silviculturally effective, time and cost efficient, and operationally feasible for meeting ecological restoration objectives in southwestern ponderosa forests. Though more work could be done to further align these new approaches with desired silvicultural outcomes, these innovative methods are sufficiently well developed today to help accelerate the pace and scale of implementation of restoration treatments on federal, state, private, tribal, and community forests across the American Southwest. New iterations of these methods also have the potential for application well outside the region, wherever within-stand spatial variability and structural complexity play an important role in silviculture.

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Data Availability Project data and summarized results are available by request.

Declarations

Competing interest None to declare.

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