

Variable-Density Thinning and a Marking Paradox: Comparing Prescription Protocols to Attain Stand Variability in Coast Redwood

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ABSTRACT

Variable-density thinning (VDT) is an emerging thinning method to enhance stand structural heterogeneity by deliberately thinning at different intensities within a stand. Subsequent stand development forms a more varied structure than is common in many even-aged forest stands. A primary difficulty with VDT treatments is systematically attaining heterogeneity. Instead, tendencies seem to be to apply a uniform treatment across a stand that enhances structural homogeneity. In coast redwood (*Sequoia sempervirens*), VDT has become the primary restoration treatment for young stands in state parks in the Humboldt and Del Norte Counties of northern coastal California. These stands are young and even-aged following clearcutting by previous industrial landowners. VDT is being used to increase structural heterogeneity, increase the proportion of redwood or other conifers, and accelerate development toward old forest structures. Six marking prescriptions have been used to date to achieve VDT objectives. These marking prescriptions were compared with regard to (1) ease of use; (2) effectiveness in achieving spatial heterogeneity; (3) capability to approach density/species composition targets; and (4) qualitative assessments of potential for bear damage, potential costs, and long-term stand development trends. Generally, prescriptions that were most complex achieved the greatest heterogeneity and vice versa. This creates a paradox with VDT: Finding simple ways to create complex structures.

Keywords: forest restoration, precommercial thinning, *Sequoia sempervirens*, stand structure heterogeneity

One of the mantras of contemporary restoration approaches in forestry is to encourage diversity through operations that create structural heterogeneity at the stand level. This is particularly true in stands established under older paradigms, where diversity was purposely reduced to promote management efficiency and predictability. In some forest types, young and even-aged stands, established under an industrial paradigm, may resemble classical stem exclusion (*sensu* Oliver 1981), where a dense, uniform single-canopy effectively excludes other vegetation on the forest floor. Precommercial thinning is often used in these stands to reduce density and favor certain trees. However, conventional precommercial thinning generally has little effect on stand structural diversity because it tends to promote a homogeneous stand of the most vigorous trees (O'Hara and Oliver 1999). Instead, what is often needed is an operation that promotes stand structural diversity in addition to reducing stand density.

Variable-density thinning (VDT) is an operation to deliberately enhance spatial heterogeneity and structural variability in a stand. By thinning at different intensities at relatively small scales within a single stand, structural heterogeneity can be enhanced (Carey 2003, Harrington et al. 2005). Because many young stands also have very high densities, the general reduction in density is also a common restoration objective. Shifting species composition may also be an objective. VDT has recently become a common restoration thinning tool in many western forests on at least an experimental basis (e.g., Carey et al. 1999, Aukema and Carey 2008, Roberts and

Harrington 2008, Comfort et al. 2010, Ares et al. 2010, O'Hara et al. 2010).

In coast redwood (*Sequoia sempervirens*), decades of conversion of private industrial land to public parks has created a great demand for restoration treatments. Prior to conversion to public parks, many of these stands were clearcut and managed for timber production, leaving legacies of even-aged stands with reduced structural diversity and sometimes with altered species compositions. For example, pre-restoration species compositions were primarily coast Douglas-fir (*Pseudotsuga menziesii* var. *menziesii*) at coastal sites and primarily hardwoods, such as tanoak (*Notholithocarpus densiflorus*) and Pacific madrone (*Arbutus menziesii*), at more interior sites. State and federal parks are therefore left with the challenge of restoring these lands to forests with greater structural diversity and a more natural species composition. An additional challenge is developing cost-efficient prescriptions given the limited financial resources of the public organizations charged with this restoration and the sometimes extensive areas needing treatment. Finally, management of young forests in this region is complicated by black bears, which damage high numbers of trees, particularly after thinning (Giusti 1990, O'Hara et al. 2010).

Any prescription to enhance heterogeneity is difficult when complex concepts must be transferred from the prescription writer to the marker or operator. Thinning and other intermediate operations are generally prescribed at one management level and implemented at another. The prescription must codify the marking/thinning protocol, an activity that by itself promotes simple rules or guidelines that

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are often used to treat multiple stands and thereby promote multi-scale homogeneity rather than heterogeneity. VDT prescriptions face the additional challenge of needing to create stand-level heterogeneity, where stand structures may already be homogeneous or where prescribing heterogeneity makes marking/thinning prescriptions very complex. When the VDT prescription or marking guidelines are unclear or confusing, forest workers may revert to marking or thinning stands in accordance with the more regular spacing to which they are accustomed. Even well-designed prescriptions can therefore be quickly undermined at the implementation phase. This represents a “paradox” for VDT, where a more complex, heterogeneous stand structure is the management objective but where simple marking/thinning rules are needed for clear and consistently accurate application.

We describe six different protocols for implementing VDT in young, overly dense second-growth forests in the redwood region and assess their effectiveness and efficiency for promoting stand structure heterogeneity, and we discuss their implications for future stand development. Because of the potential importance of VDT as a restoration tool in other forest types, our objectives are broadly applicable to other regions and forest types, where VDT may be used to enhance stand structural variability.

Methods

Study Site

All six VDT protocols were tested in young stands within the redwood range in Humboldt and Del Norte Counties, California. These sites are highly productive, at elevations of less than 1,700 ft, with precipitation ranging from 60–150 inches/yr, falling mostly as rain. Historically, the proportion of redwood at these sites decreased, and Douglas-fir and broadleaved species increased, with distance from the coast. Five of the sites were located in the Mill Creek drainage of Del Norte State Park and were within several miles of the coast. The sixth site, at Panther Creek, was located in Humboldt Redwoods State Park at 1,400 ft, approximately 18 miles from the coast.

VDT Prescription Protocols

Six different prescription protocols have been used or assessed in young redwood and Douglas-fir stands, where the primary goal was to place stands on a trajectory that would encourage the rapid development of old forest characteristics. Short-term objectives of all treatments were to enhance stand structural diversity, shift species composition toward preharvest conditions, promote growth in desired trees, and to maintain or improve forest health and resiliency. Because of similarities in some of these VDT protocols, we have grouped them into four types: (1) *Randomized Grid*, including low and moderate density; (2) *Dx Rule*, (3) *Spacing Thinnings*, including a 16- and 20-ft variation; and (4) *Localized Release*. The Randomized Grid protocols were developed to achieve variable spacing for a research study, where all leave trees were marked prior to operations; the other protocols were all operational thinning treatments, where thinning crews selected leave trees.

Randomized Grid

This method included a random element for achieving variability in desired numbers of residual trees. Two density targets were developed in prescriptions for thinning in the Mill Creek Watershed of the Del Norte Coast Redwoods State Park (MCW) in Del Norte

County, California (O'Hara et al. 2010). The plantations were established in cutover redwood stands with planted coast Douglas-fir seedlings and sprout-origin redwood, among other species. Plantations were 12–14 years old at the time of thinning. Sites were highly productive and ranged from an alluvial flat to moderate slopes. Two density targets were developed in conjunction with park personnel and the Save the Redwoods League. The goals were to experiment with “one-step” treatments that could direct stand development along desired pathways with one treatment and would allow for longer-termed vigorous growth and promote more structural complexity than seen in traditional thinnings. One density protocol, described as “low density,” aimed for 50 trees/ac with an additional 25 tree/ac allowance for possible mortality (75 trees/ac total). The second density protocol was for 150 trees/ac (including mortality allowance). Each of these was implemented in separate blocks and analyzed separately.

The marker was asked to visualize an area equal to the average area per tree for the two target postthinning densities, excluding the allowance for mortality (Figure 1). For the low-density treatment, that “cell” would be 1/50th ac or about 871 ft². A random number from 1 to 4 was generated with a single die and represented the number of residual trees per cell. A “4” indicated that all trees were cut. The 0–3 trees retained in each cell resulted in a mean of 1.5 trees per cell or approximately 75 and 150 trees/ac in the low- and moderate-density treatments as well as spatial variability. Methods and study site descriptions are also described in O'Hara et al. (2010).

Dx Rule

The *Dx Rule* attempted to decrease the component of broadleaved trees in favor of the underrepresented Douglas-fir component. The study site was in the Panther Creek drainage of Humboldt Redwoods State Park—in Humboldt County, California—in young second-growth stands that had replaced the mature Douglas-fir dominated stands that were cut in about 1959. The site had naturally regenerated and before the VDT treatment included about 160 ft²/ac basal area and 275 trees/ac. Broadleaved trees, primarily tanoak and Pacific madrone, represented over 50% of trees/ac before treatment, with a Douglas-fir component that varied spatially. The Panther Creek drainage is steep and deeply dissected by small watercourses. VDT treatments were applied to both sides of the drainage (northerly and southerly aspects) during sequential years. The objective of the protocol was to reduce the overall density and increase the relative proportion of Douglas-fir, while enhancing the spatial variability of within-stand densities.

The *Dx Rule* used a diameter-based multiplier to designate gaps around targeted residual trees proportional to their current size. Rather than being arbitrarily determined, the thinning intensity varied throughout the stand as a function of existing inequalities in growing space that were manifested in differential tree sizes. The thinning was intended to remove trees in the 5 to 15 in. dbh class. The operator identified a Douglas-fir or redwood larger than 5 in. dbh as a retention tree, multiplied the dbh by a constant (in this case, two) and removed trees in a radius equal to that many feet, up to a maximum of 20 ft (Figure 1). Within the *Dx Rule* cutting radius, cutting restrictions precluded cutting any trees less than 5 in. dbh (for efficiency), conifers greater than 10 in. dbh, or broadleaves greater than 15 in. dbh. The operator then moved to the next retention tree regardless of distance from previous retention tree and repeated the process. More detail on this protocol is available in Keyes et al. (2010).

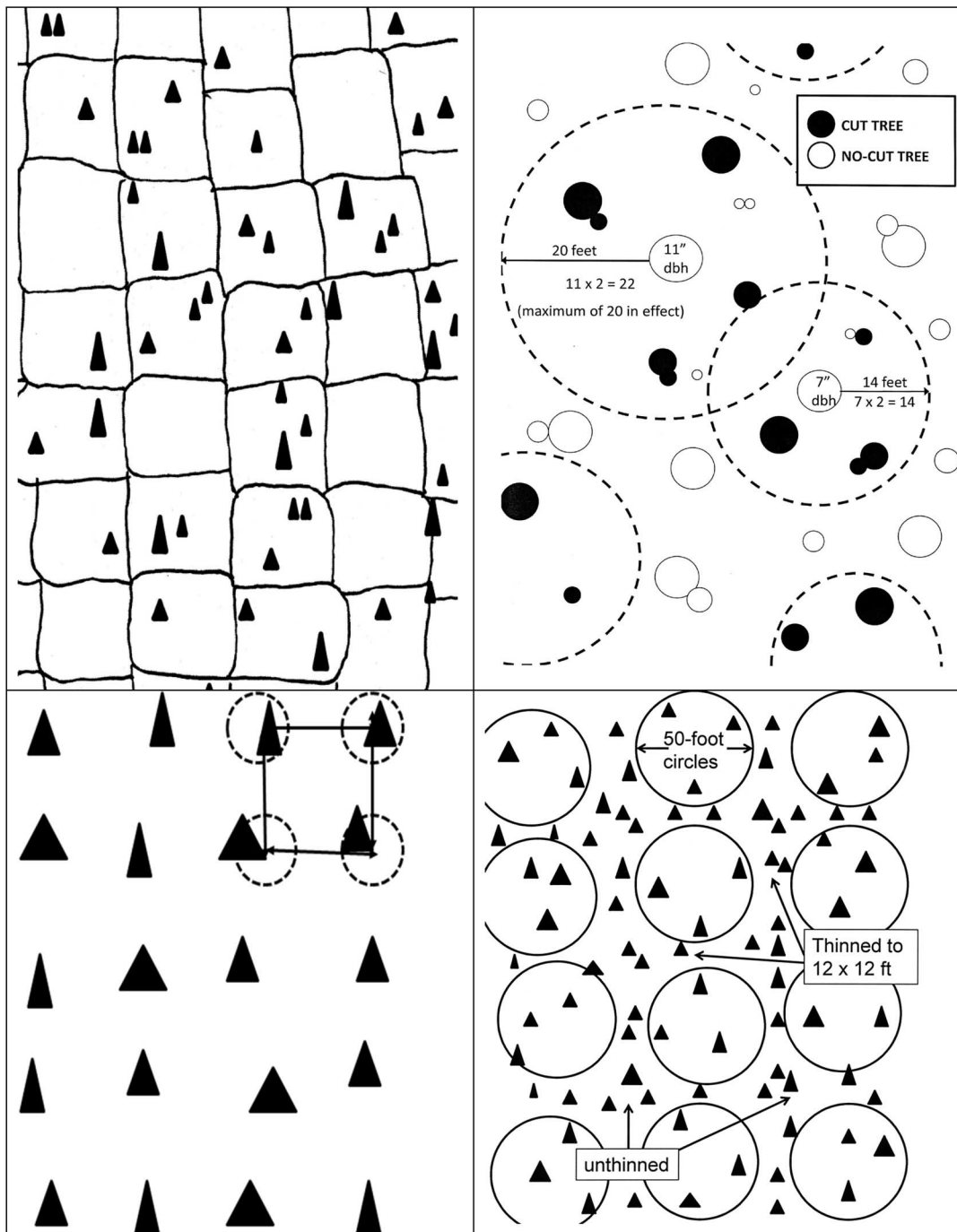


Figure 1. Schematic diagrams of VDT protocols. Upper left is the *Randomized Grid* method where cells are shown with 0 to 4 residual trees. Upper right is the *Dx Rule* where shaded circles show the zone where all trees over 5" dbh were removed. Circle radius was determined as $\text{dbh} \times 2$ and converted to ft. Lower left is the *Spacing Thinning* where trees were selected on a 16×16 or 20×20 -ft grid. Circles represent the 4 ft allowance for selecting the best tree. Lower right is *Localized Release* protocol where 3 residual trees were retained in each 50-ft circle. Areas between circles were thinned to 12×12 ft and the areas between 4 circles were unthinned. Figures are not to scale.

Spacing Thinnings

Two treatment protocols used in the MCW were based on spacing grids (16×16 ft and 20×20 ft). These two treatments attempted to find suitable retention trees on the prescribed grid with a 4-ft margin for finding the best tree for retention (Figure 1). The "best" tree had to be at least 3" dbh and was chosen based on species with redwoods as the most desirable followed by less-common co-

nifers, Douglas-firs, and finally tanoaks. The largest, healthiest trees were retained when choosing between trees of the same species and redwood stump clumps were not thinned. Prescriptions were designed to be similar to precommercial thinning conducted in the area (often 14×14 ft) for ease of implementation but were developed to allow prolonged growth and greater flexibility in spacing than desired for industrial lands. Site productivity was high, stand

Table 1. Trees/ac by protocol for VDT in young, dense second-growth stands in the coast redwood region.

Protocol	Location	Pretreatment trees/ac	Target trees/ac	Posttreatment trees/ac	Pretreatment species composition	Posttreatment species composition
Randomized grid moderate density	Mill Creek	1,126	75	77 to 134	59.2 Douglas-fir	28.9 Douglas-fir 64.4 redwood
Randomized grid low density	Mill Creek		150	140 to 226	22.8 redwood	43.6 Douglas-fir 47.4 redwood
Dx rule	Panther Creek ^a	297		165	67.8 broadleaf 32.2 conifer	50.9 broadleaf 49.1 conifer
16 × 16 ft	Mill Creek ^b	528 (431)	170	235 (177)		53.8 Douglas-fir 37.4 redwood
20 × 20 ft	Mill Creek ^b		109	234 (150)	64.9 Douglas-fir	39.3 Douglas-fir 46.7 redwood
Localized release	Mill Creek ^b			283 (215)	25.1 redwood	51.9 Douglas-fir 39.6 redwood

Trees/ac based on variable sampling schemes between protocols. Only primary species composition categories are shown. Numbers in parentheses are counting all sprouts off a single stump as one tree.

^a Includes all trees ≥ 5 in. dbh.

^b Includes all trees > 3 in. dbh.

ages ranged from 11–24 years, and species composition was predominantly Douglas-fir, with varying amounts of redwood following clearcutting. Variability was achieved by the spacing margin for finding the most desirable tree and by not treating redwood sprout clumps.

Localized Release

The *Localized Release* prescription was developed to accelerate differentiation (see O'Hara and Oliver 1999) by creating a low density of approximately 50 trees/ac intermixed with highly variable densities. Unthinned patches were retained to increase variability, reduce fuel loads, improve efficiency, and create patches in which bear damage is less likely. Windthrow may be also reduced by retaining unthinned patches as windbreaks.

Thinning operations cut 25-ft radius circles that retained the three best trees, regardless of their spatial position, within the circle (Figure 1). Choosing the best trees for retention followed the same rules as the *Spacing Thinning*. Redwood stump sprout clumps were considered a single tree thereby enhancing spatial variability. Additional circles were adjacent with space for a "row" of untreated matrix trees in between circles. These trees were thinned to a 12 × 12-ft spacing. Areas at the nexus of three or four circles were left unthinned, providing additional spatial variability. The *Localized Release* prescription was developed for the same stands as the *Spacing Thinnings*. The three prescriptions were randomly assigned to various stands to create a randomized, split-block design with five replicates.

Assessment of Protocols

The six protocols were assessed through a mixture of qualitative and quantitative means. We compared treatments by their effectiveness in achieving (1) stand-average density reduction, (2) desired changes in species composition, (3) stand-level heterogeneity, and (4) ease of implementation by stand markers/thinners. Ease of implementation was based on a qualitative assessment of the difficulty of markers/thinners to understand the protocol and achieve target posttreatment densities. Lacking spatially explicit data, we used the coefficient of variation (CV) of trees/ac to describe heterogeneity among sample plots. All six protocols included posttreatment (within one year of treatment) plot-based assessments for tree density, tree size, and species composition (Table 1). The CV was calculated from plot means within blocks. For example, in the *Ran-*

domized Grid protocol, CV was based on the SD and means from three plots each from five blocks in the moderate density treatment and three to six plots from each of nine blocks in the low-density treatment. Other protocols had similar data structures, except the *Dx* protocol, which had two treated blocks that consisted of 41 and 59 plots each (Keyes et al. 2010).

We also report production rates for thinning in the *Spacing Thinnings* and the *Localized Release* protocols and bear damage results from the *Randomized Grid* protocol. Worker production rates were calculated from log books used to record crew size and daily progress on projects implemented in 2006 and 2009. Bear damage was assessed based on percentages of damaged trees and amount of damage within sample plots four years after implementation.

Results

Posttreatment trees/ac showed substantially reduced densities, although not quite to the level of targets developed in all of the prescriptions. For example, the *Randomized Grid* protocol had targeted densities of 75 for the low and 150 trees/ac for the moderate density treatments. Postthinning densities ranged from 77 to 134 and from 140 to 226 in the low- and moderate-density treatments for the three replicates (Table 1). Results when counting redwood sprout clumps as one tree are included for the *Spacing Thinning* and *Localized Release* to allow a comparison to target tree densities. The 20 × 20-ft *Spacing Thinning* and the low-density *Randomized Grid* achieved the lowest densities but were still well above typical old forest densities, which were often less than 50 trees/ac (Lorimer et al. 2009).

Concern over species composition—primarily increasing redwood abundance at Mill Creek and increasing conifer abundance at Panther Creek—was a dominant factor for tree selection in all six protocols. A secondary concern was favoring the largest trees and reducing competition among them. Thinning could therefore be classified as more of a crown thinning than a low thinning. In second-growth stands at Redwood National Park, Teraoka and Keyes (2011) noted some deficiencies associated with low thinning and recommended more aggressive crown thinning, or a two-phase strategy, where VDT follows more traditional low or crown thinning. All six protocols appear to have been successful at meeting objectives related to species composition (Table 1). The MCW sites had been planted to Douglas-fir following clearcutting, but all five methods of VDT increased the percentage of redwood on these sites.

Table 2. Coefficient of variation (CV) for trees/ha in treated and untreated areas.

Protocol	CV-treated	n	CV-untreated/ before treatment	n
Randomized grid moderate density	0.39	5	0.25	5
Randomized grid low density	0.43	9		
Dx rule	0.78	2	0.49	2
16 × 16 ft	0.34 (0.28)	5	0.23 (0.16)	5
20 × 20 ft	0.37 (0.26)	5		
Localized release	0.49 (0.63)	5		

Numbers in parentheses are counting all sprouts off a single stump as one tree. CV was calculated from plot means within blocks (n). Blocks generally consisted of three plots each, but the two blocks at Panther Creek included 32 and 54 plots.

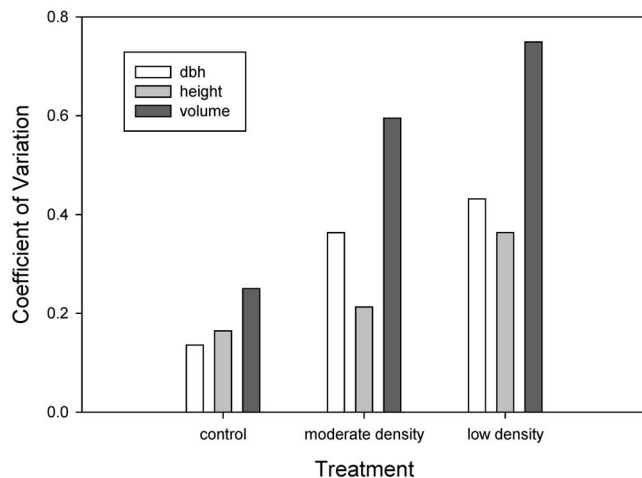


Figure 2. Coefficient of variation for dbh, height, and volume for the control, moderate density and low density *Randomized Grid* VDT treatments. These CVs are based on all trees rather than broken down by block structure as in Table 2. Adapted from O'Hara et al. (2010).

However, the most effective of the *Spacing Thinnings* and *Localized Release* methods at increasing the proportion of redwood was the 20 × 20-ft spacing, which also had the greatest reduction in density.

All six protocols enhanced spatial heterogeneity as represented by the CV of plot density (Table 2). Results inform about the changes in heterogeneity within blocks, but the numbers are not comparable between protocols (except to compare *Spacing Thinnings* and *Localized Release*) because of a highly variable number of plots, plot sizes, and differences in pretreatment stand structure. The more severe treatments generally resulted in the highest CVs (i.e., the low-density *Randomized Grid* treatment and the 20 × 20 ft *Spacing Thinning* have higher CVs than their higher-density counterparts), with the exception of the *Localized Release*, which left higher tree densities and a CV higher than either *Spacing Thinning*. The *Spacing Thinnings* did not provide much enhancement of spatial heterogeneity over pretreatment values. This was likely the result of the grid spacing being central to these protocols. The *Dx Rule* produced the largest CV (Table 2), due in part to a higher degree of structural and compositional heterogeneity before treatment.

Vertical structure was not captured by the posttreatment monitoring of any of the protocols. CVs for dbh, height, and volume distributions measured following the *Randomized Grid* VDT are shown in Figure 2. Height variation provides a representation of vertical structure because heights are indicative of crown positions. CVs of height measures responded in similar ways as dbh to VDT in

Table 3. Matrix of performance of the six VDT protocols for meeting the four assessment criteria.

Protocol	Target densities	Species composition	Stand-level heterogeneity	Ease of implementation
Randomized grid moderate density	good	good	good	difficult
Randomized grid low density	good	good	good	difficult
Dx rule	good	good	good	moderate
16 × 16 ft	moderate	poor	poor	easy
20 × 20 ft	moderate	poor	poor	easy
Localized release	moderate	moderate	good	moderate

the two randomized grid treatments. Volume, which integrates both height and dbh, also responded as did dbh and height, with a large increase in variation with the low-density treatment (Figure 2).

Four years following implementation of the *Randomized Grid* treatments, bears had damaged a large number of trees in both the thinning treatments. In the low-density treatment over 38% of redwoods were damaged compared to just over 29% in the moderate-density treatment. About 25% of Douglas-fir trees were damaged in both treatments. Damage to redwoods in the control treatment averaged only about 5% and for Douglas-fir was less than 1%. In absolute numbers, damage rates were higher in the VDT treatments as well.

Worker production rates for the *Spacing Thinnings* and the *Localized Release* treatments were based on estimates of acres thinned in an eight-hour day. Production rates were lowest for the 20 × 20 ft treatment (1.32 ac/day), highest for the *Localized Release* (1.94 ac/day), and intermediate for the 16 × 16 ft treatment (1.38). These production rates correspond to residual densities in the respective treatments (Table 1) and demonstrate that a primary cost of these operations is simply cutting trees.

Discussion

The six protocols encompassed a range of complexity and ease of use (Table 3). They also demonstrated the paradox of VDT: the protocols that were easiest to implement were least effective at creating stand-level heterogeneity and vice versa. Although the two *Randomized Grid* protocols were designed as part of a research project rather than an operational thinning, they represented the most extreme form of complexity. The two *Spacing Thinning* protocols were the simplest and were least effective at enhancing variability. Although we describe a VDT “paradox”, this does not preclude finding a protocol that is both simple and effective for enhancing complexity: it only implies that we did not find one. Simple protocols are more likely to be implemented as intended in the prescription; however, they are not necessarily more efficient and may be more expensive to implement.

In this study, the protocols range from the very complex (*Randomized Grid*) to the relatively simple (*Spacing Thinnings*). The *Randomized Grid* methods required an additional marking step in the process. As research protocols, the *Randomized Grid* markings were meant to ensure consistency and achieve target densities. The marking and cutting steps could be combined to improve efficiency: otherwise these methods would seem to be of limited operational use. Kellogg et al. (1998) found individual tree marking and flagging perimeters of patches to be the greatest costs in commercial thinning in the Pacific Northwest. With our noncommercial restoration treatments, marking individual trees would contribute to even greater thinning costs.

The *Dx Rule* method resembles traditional $D + x$ thinning rules (see Smith et al. 1997, p. 125), where x is a constant added to dbh to determine average square spacing in feet or meters. For this VDT application, the constant is a multiplier that concentrates all cutting in circular zones around release trees and leaves intact any areas lacking suitable release trees. At Panther Creek, some areas with suitable release trees were left uncut because tree spacing was already greater than the multiplier thinning radius (or maximum radius of 20 ft). Other hardwood-dominated areas were left uncut because there were no suitable release trees meeting the size and species criteria.

The intensity of a thinning should be more sensitive to stand conditions when using the *Dx Rule* than with other methods. Because thinning radii are a function of release tree sizes, it was impossible to anticipate with precision the quantity of timber cut from the harvest unit; accurate harvest volume estimates would only be possible with a postmark inventory. At Panther Creek, we simulated hypothetical prescriptions during stand inventories to estimate residual tree densities and basal area reduction. Simulating hypothetical prescriptions can assist practitioners in adjusting the prescription to achieve desired results. For example, we have used the *Dx Rule* as described above to treat conifers while cutting hardwoods whose crowns are in contact with release trees in the same stand. This variation allowed for a greater reduction in hardwood density without the loss of additional conifers.

The *Spacing Thinning* methods were simple and most similar to standard thinning methods. These methods also enhanced variability but not to the extent of the *Localized Release*. Post-VDT densities were easy to predict when counting stump sprouts as one tree. But variability in spacing may also decrease as stump sprouts self-thin.

Localized Release was a mixed intensity thinning with designated leave areas left in between cutting circles. It achieved a high level of variability but was difficult to implement with resultant densities highly sensitive to pretreatment density and the accuracy of implementation. Predicting posttreatment density is more challenging with this prescription than any of the others. Residual densities are also likely to change more rapidly than other treatments as released trees in circles and partially released trees on the edge out-compete trees in no cut areas. If the treatment is able to expedite self-thinning, then residual tree density may be less relevant to long-term objectives, compared to how many trees are sufficiently released to achieve prolonged, vigorous growth, and how the spatial patterns of these trees compare to natural forests.

Thinning intensity is greatly dependent on how this treatment is implemented. For example, simple geometric calculations predict that circles treated on a grid would leave 22% of a stand outside of circles where light or no thinning occurs. However, the amount of area outside of the circles would increase to 30% if circles were three feet apart and decrease to 9% if circles were offset so that three circles met in a staggered grid. Implementation on such a precise pattern as this is impractical without severely slowing productivity rates. We expected variability in how circles would align and made contingencies for areas that were too small for a full circle but too large to be skipped. The best success with this and other prescriptions occurred when managers worked closely with thinning crews to help them understand desired results. Once the concepts were understood, less oversight was necessary.

Application of any of these VDT methods will require adjustments for different species, site qualities, or desired density. For example, the two *Randomized Grid* methods used two different

marking cell sizes, depending on the desired density and the *Spacing Thinnings* used two different spacings. Redwood forests may have unique spatial patterns compared to other forests. For example, old coast redwood forests form highly diverse spatial patterns (Dagley 2008) following a diverse set of disturbance regimes (Lorimer et al. 2009). The vegetative reproduction of redwood following clearcut harvests or thinnings creates unique challenges to enhancing variability and results in complex clonal patterns between trees (Rodgers 2000, Douhovnikoff et al. 2004). Redwood trees cut in thinning operations may multiply in the form of many sprouts, whose persistence is dependent on the light environment (O'Hara et al. 2007, O'Hara and Berrill 2010). Some of these characteristics of redwood may serve to enhance variability (vegetative reproduction, variable spatial patterns), whereas others may reduce it (clonal reproduction). Compared to other western conifers, these VDT prescriptions may produce substantially different results because of these unique characteristics of redwood. However, if applied in other sprouting species, these results are applicable to a wide range of forest types.

The VDT methods do appear to represent effective means of enhancing structural variability in coast redwood and Douglas-fir. Previous work with Douglas-fir in the Pacific Northwest has shown greater diversity postthinning (Harrington et al. 2005, Aukema and Carey 2008, Ares et al. 2010). All six protocols in this analysis demonstrated increased variation following treatment and enhanced diversity four years after treatment in the randomized grid protocol. Whereas we assume that heterogeneity formed in these young stands will be maintained or increase over time, this early work provides few insights into future development and changes in structural heterogeneity over time. It is therefore important to continue long-term monitoring of the development of these stands.

The extent and magnitude of black bear damage represents a major management challenge in the northern range of redwood for both restoration and other management. There, the VDT treatments enhanced structural diversity and reduce density, but they also appeared to increase the likelihood of bear damage. Although the bear damage may simply enhance structural diversity in some cases, particularly in redwood, where completely girdled trees usually resprout, O'Hara et al. (2010) concluded the damage represented an impediment to management. The treatments that lowered density to more closely approximate the restoration target experienced the most damage. Higher-density treatments had less bear damage and exceeded the target restoration density early in the study. A great challenge for VDT in these areas, where bears create problems, will be finding the appropriate posttreatment density in conjunction with the highly unpredictable effects of bear damage.

Conclusions

Variable density thinning (VDT) has been used to increase stand structure diversity and stimulate the development of old forest characteristics in a wide range of forest settings. California State Parks has used six VDT prescriptions in young, overly dense second-growth stands in the coast redwood region. All six protocols enhanced heterogeneity in tree size. However, initial results indicate more complicated protocols result in stands with greater heterogeneity. This forms a paradox where more complicated protocols achieve better results, but are more difficult to implement consistently over time and in different locations. Worker productivity is inversely related to number of trees cut. VDT in redwood forests is complicated by the unique sprouting ability of redwood as well as

broadleaved trees and potential for large scale bear damage. Application of these protocols in other regions or with other forest types will require adjustments in parameters.

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