Chapter 10: Precommercial Thinning in California Forests

Martin W. Ritchie, USFS Pacific Southwest Research Station, Redding CA

John-Pascal Berrill, Humboldt State University, Arcata CA

Table of Contents

Introduction

Precommercial thinning (PCT) can be defined as "*the removal of trees not for immediate financial return but to reduce stocking to concentrate growth on more desirable trees*" (Helms 1998). PCT plays an important part in the reforestation process. It is typically applied between stand establishment and the first commercial thin (CT) or harvest. In addition to altering planting density and competition from non-crop vegetation, selection of which trees remain after PCT affects the timing and average tree size attainable at the next harvest. A higher intensity PCT will shorten the time to grow trees large enough to produce commercial products but will also reduce the total amount of wood fiber (but not necessarily the wood value) available for removal in the first CT.

The decision space for PCT involves:

- Timing (early vs. late PCT)
- Intensity (heavy vs. light PCT)
- Thinning method (selecting favorable trees for retention)
- Implementation (tools and equipment used).

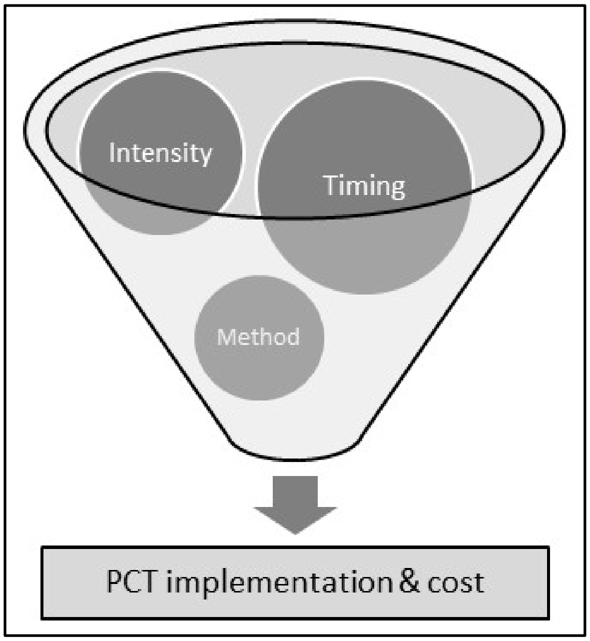

Figure 10.1 PCT timing, intensity, and method affect how it can be implemented and the cost.

PCT influences the risks associated with disturbances such as wildfire (Pollet and Omi 2002), bark beetles (Fettig et al. 2007), windthrow, snow damage (Powers and Oliver 1970) and bear damage. These risks change over time, before/after or with/without PCT. There are occasions where PCT has a role in naturally-regenerated even-aged and multiaged stands, and it is commonly applied in young artificially regenerated (planted) even-aged conifer forests in California.

PCT Outcomes

The decision to conduct PCT comes with the expectation of some outcomes (both positive and negative) for the treatment. We review possible outcomes and how these outcomes are influenced by choices made at the time of PCT implementation.

Enhanced Growth

Thinning results in the redistribution of tree growth to fewer stems, thus increasing growth rates of remaining trees (Ashton and Kelty 2018, p. 395). By accelerating growth rates on residual trees, the time until the retained trees are of a harvestable size is shortened. The increase in tree growth is achieved at some loss to overall stand volume growth per acre and will delay the culmination of mean annual increment (Curtis 1994, 1995).

Growing Stock Improvement

PCT can be a means to improve growing stock. Unhealthy or damaged trees and trees with low vigor or value can be removed. Sometimes the largest trees have poor form and heavy branching. Failure to remove malformed trees at PCT preserves trees that will continue to increase in size but perhaps little in value if logs are defective or become downgraded by large knots.

Growing stock may also be improved by removing species that do not meet management goals. Note that these goals need not be guided by optimal growth. For example, PCT prescriptions could be tailored to maintain and promote trees that provide critical wildlife habitat, like black oak (*Quercus kellogii*). On the other hand, a management goal of maximizing conifer growth and yield would necessarily remove most hardwoods.

Impact on Wood Quality

It is difficult to generalize about the impacts of PCT on wood quality because of differences among species, their end-uses, and innovations in sawmill technology. Maintaining lower stand density will likely produce some degree of reduction in wood quality. Trees with wider spacing can keep low branches alive and growing longer, resulting in low crown base height, larger branch size and knots, lower height-to-diameter ratio and more conical form than trees grown under higher densities (Maguire et al. 1991; Weiskittel et al. 2009; Briggs et al. 2008). These attributes can lead to problems such as downgrading of logs with excessive knot size or reduced recovery of sawn timber from tapered logs. Conversely, postponing PCT keeps lower branches in the shade longer, where they grow slowly or die, and being smaller, these low branches may fall sooner to allow for production of more knot-free clearwood. However, species producing decay-resistant heartwood may be more valuable if they grow rapidly and attain larger log sizes containing more heartwood, while maintaining live lower branches producing inter-grown knots to preserve the integrity of sawn timber for exterior applications (Ashton and Kelty 2018, p. 424). The problem of branches growing unabated into large openings can be mitigated by maintaining evenness of spacing after PCT and reducing the amount of stand edge versus interior stand area where branch size is controlled by contact with neighbor trees.

Enhanced growth after thinning has been linked to changes in wood anatomy and wood product performance in service of some species, but not others. Markstrom et al. (1983) found no impact of growing stock levels in ponderosa pine (*Pinus ponderosa*) on factors linked with performance of structural lumber: specific gravity, latewood percentage, tracheid length or microfibril angle. Rapid diameter growth produces wider annual rings that some consider unsightly, and can have slightly lower specific gravity in some species, e.g., Douglas-fir (*Pseudotsuga menzesii* var *menziesii*) (Jozsa and Brix 1989; Filipescu et al. 2014) and ponderosa pine (Echols 1971). However, the wide rings themselves were not the cause of performance problems. Early PCT promoting rapid diameter growth (and wide rings) at a young age tends to increase the proportion of crown wood in the butt log of conifers (Maguire et al. 1991). Crown wood typically has lower density, stability, and stiffness than outer wood that surrounds it. Therefore we expect better performance from structural lumber sawn from outer wood than from crown wood (Ashton and Kelty 2018, p. 388).

Pruning in concert with PCT can be used to improve wood quality, although the expense limits applicability in many situations. Pruning enhances wood quality and value when branches are removed over an entire log length (e.g., up to 18 feet above ground for a 16-foot log), and this is done early enough to allow clearwood to form over many years after pruning. The economics are more favorable after timely PCT on better sites where rapid *DBH* growth facilitates earlier harvest to recoup pruning costs incurred years earlier. Only a subset of crop trees designated for retention to attain large sizes should be pruned for clearwood timber production. During PCT, additional 'unpruned follower' trees should also be retained to allow for subsequent CTs of knotty sawlogs while pruned trees are allowed to continue growing larger to produce enough clearwood for adequate recovery of knot-free lumber during milling (Ashton and Kelty 2018, p. 432). Pruning can also be done to reduce risk of white pine blister rust (caused by fungus *Cronartium ribicola*) entering lower branches of young pines (O'Hara et al. 2010), or to reduce ladder fuels and facilitate fire suppression efforts in locations such as fuel breaks, high value landscapes, and buffers along main roads. Pruning for forest health or fuels and fire hazard reduction can be restricted to 8-10 feet up from the ground to limit cost, but this restricts clearwood production to an unusually short butt log that may not be saleable at a premium (O'Hara et al. 1995). Pruning for fire hazard reduction is commonly applied strategically within 100 to 200 feet of main roads.

To improve operational efficiency and reduce fuel loading, pruning can be done in 2-3 separate operations or "lifts" conducted a few years apart, leaving 40-50% live crown upon completion of each lift. Pruning heals over better when done on live limbs and not dead limbs, when branches are smaller (smaller wounds) and when trees are growing rapidly (stem encapsulates wound faster). The timing and intensity of PCT and pruning should both be considered when fuel loading is a concern, when the species can suffer from thinning shock (e.g., Douglas-fir and white fir: after PCT, consider delaying pruning), or when the species responds to PCT and/or more severe pruning with epicormic branching that negates benefits of pruning (e.g., coast redwood: leave shade on pruned stem by delaying PCT; O'Hara and Berrill 2009). Timing may be better during the growing season to limit epicormic sprouting (O'Hara et al. 2008), or during the fall and winter to avoid insect attack in some species. A contractor selected for pruning should have the appropriate tools and experience to achieve the desired results.

Insect and Disease Impacts

Density management can also reduce the likelihood of mortality from bark beetles. Low tree vigor is related to bark beetle attacks (Larsson et al. 1983) and thinning has long been proposed as a method to reduce risk of bark beetle attack (Sartwell 1971; Sartwell and Stephens 1975). The primary long-term concern in California will be with *Dendroctonus* species (Table 10.1). While many trees are too small at the time of PCT to be susceptible to *Dendroctonus*, an increase in tree vigor is expected to limit the mortality from bark beetles over time as the trees approach a size where commercial thinning may be considered (Oliver 1995; Fettig et al. 2006, 2007; Egan et al. 2010).

Table 10.1 *Dentroctonus* species of concern for California native conifers

Insect Species	Host Species	Impact
D. brevicomis, Western pine beetle	*P. ponderosa,* *P. coulteri*	Usually attacking trees > 6 inches *DBH*
D. jeffreyi, Jeffrey pine beetle	*P. jeffreyi*	Usually attacks where bole is > 12 inches *DBH*
D. ponderosae, Mountain pine beetle	*P. ponderosa* *P. contorta* *P. lambertiana* *P. monticola* *P. coulteri* *P. flexilis* *P. balfouriana* *P. monophylla* *P. longaeva*	Usually attacks trees > 5 inches *DBH*
D. pseudotsugae, Douglas-fir beetle	*P. menziesii* *P. macrocarpa*	Will infest recent mortality or windthrown trees; can spread to living trees.
D. valens, Red turpentine beetle	*P. ponderosa* *P. contorta* *P. lambertiana* *P. monticola* *P. jeffreyi*	Usually not a tree killer in California, but it may weaken trees; is often active after fire.

Another group of bark beetles that can be a more immediate concern to managers conducting PCT are *Ips* species (Sartwell 1970). The primary species of concern in California are pine engraver (*Ips pini*) and California five-spine ips (*Ips paraconfusus*). Hosts include most pines found in California. Both of these species of *Ips* will readily infect green logging slash, so season of PCT and distribution and amount of slash generated is a concern. Lower levels of slash and more widely scattered slash that dries quickly will tend to inhibit populations of *Ips*. Lopping felled trees may facilitate drying but can be cost prohibitive (cost increases in excess of 50%). In some instances foresters may choose to accelerate drying of felled trees by delimbing the top side to let direct sunlight reach the stem, or leaving the cut tree intact with hope that transpiration via foliage helps purge moisture from inside the stem and branches (Mark Gray, personal communication). Some have suggested that thinning pine in late summer or early fall may also inhibit population growth of *Ips* (Kegley et al. 1997). *Ips* will produce several generations per year and with high levels of slash emerging adults can attack small green trees and the tops of larger trees.

While PCT may improve tree vigor in relation to beetles, it may also exacerbate problems with other insects such as shoot borers (Robertson and Dewey 1983, Ferguson et al. 2011). This problem is most pronounced with heavy thinning removing more than half of the standing trees (Mark Gray, personal communication). Disturbance may also create an environment favoring some root bark beetles, such as *Hylastes nigrinus*, and these beetles can vector black stain root disease (Goheen and Hansen 1993; Hessburg et al. 2001). There is some evidence that host tree species can have different interactions between thinning and root disease. In ponderosa and Jeffrey pine forests, thinning has been observed to reduce occurrence of black stain (Woodruff et al. 2019), whereas thinning in Douglas-fir plantations appears to increase the spread of the pathogen (Harrington et al. 1983; Hessburg et al. 2001).

More generally, the presence of root disease in plantations is not necessarily an impediment to thinning (Filip and Goheen 1995; Filip et al. 2009, 2015). General guidelines for thinning with regard to pathogens are to thin favoring species that are less susceptible to the disease and minimize soil disturbance. Furthermore, care should be taken to avoid spread of pathogens by washing equipment.

Fire and Fuels Management

PCT has the potential to create– through accelerated growth and increased bark thickness– trees of a size that are more resistant to fire (Ryan and Reinhardt 1988; Odhiambo et al. 2014; Zeibig-Kichas et al. 2016). However, in the short-term, trees cut and left on site elevate surface fuels that can increase fire severity. Early implementation when trees and their branches are smaller will reduce this surface load and increase the rate at which slash breaks down. Pruned limbs also become surface fuels that can be scattered or piled to avoid leaving them concentrated at the base of crop trees. Busse et al. (2009) observed that slash fuel load of small material (<7.5 cm in diameter) subsided over a 5-year period. Because of the influence of surface fuels on fire behavior, managers may consider mitigation with chipping or pile and burn treatments. Some PCT prescriptions may call for 'lop and scatter' to minimize fuel concentrations, and reduce the height of fuel beds. Contract language for lop and scatter could simply prescribe a single cut at a specified stem diameter, or prescribe a maximum fuel bed depth to be achieved by cutting fuels into progressively smaller pieces. It is more costly to achieve lower fuel bed depth, but expected benefits include mitigating extreme fire behavior due to faster decomposition of smaller pieces of fuel closer to the ground, where warmth and moisture supports decomposition (Jain et al. 2012, p. 136). However, until lopped surface fuels decompose, they pose a risk of extreme fire behavior (Stephens 1998). Keyes and O'Hara (2002) recommend an integrated strategy combining pruning, low thinning, and surface fuel management to mitigate the risk of crown fire.

Understory Vegetation Development

Lower stand density will encourage the development of understory vegetation including shrubs and herbaceous plants (McConnell and Smith 1970; Thomas et al. 1999; Dagley et al. 2018). Numerous studies show the long-term impact of shrub-competition-induced reductions in growth and yield of conifer trees (Barrett 1973; White and Newton 1988; Oliver 1990; Monleon et al. 1999; Powers and Reynolds 1999; White and Newton 1988; Zhang et al. 2006). For this reason, the growth effects of PCT will be more pronounced when done in concert with effective management of competing vegetation (Barrett 1982; Oliver 1984). For example, a masticator can be used to both thin and masticate brush simultaneously. Effective site preparation and early release treatments will tend to minimize this problem. Alternatively, delayed or repeated light PCT can mitigate this problem by reducing growing space available to understory vegetation.

Thinning Decision Space

Implementation of PCT may involve decisions on method, timing, and density of retained trees, species selection, and selection for size or vigor. In the simplest case of a single-species stand, a non-discriminatory approach such as cutting entire rows of planted trees may be under consideration. With this type of thinning, the decision space concerns only the timing and thinning intensity. However, prescriptions necessarily become more complicated with more discriminatory PCT practices requiring greater levels of understanding by the operator(s).

Timing of Thinning

PCT timing has direct and indirect impacts on cost. In general, PCT in a younger stand is easier and cheaper than culling a more mature stand. Thinning later increases the cost of thinning because trees are larger and therefore take longer to cut and result in more slash (often considered hazardous surface fuels to be dealt with at extra cost). An early PCT will reduce or eliminate the need for slash disposal (Powers et al. 2013). Figure 10.2 shows that early PCT removing 100 to 125 trees per acre when they are 2 inches diameter will generate roughly 1/20th as much biomass and new surface fuels compared to waiting until the trees are 5 inches diameter. Some foresters prefer to wait and conduct PCT when the trees are around 5 inches diameter so that trees have more time to express favorable traits such as superior growth and form. Later PCT also provides more opportunity to remove trees that sustain damage (e.g., bear damage to the stem, or shoot borer/woodrat damage causing forking). However, future dominance may be expressed quite early, allowing for early PCT focused on retaining fast-growing trees. Oliver and Powers (1971) found that ponderosa pine expressed future dominance by the time that trees reach breast height.

For coastal Douglas-fir, Reukema (1975) suggested a thinning window with tree heights between 10-15 feet and age between 10-15 years (Reukema 1975; Reukema and Bruce 1977) on high and medium quality sites. Earlier PCT when the trees are smaller is common in other areas. For example, many forest owners of mixed-conifer forests in California PCT when the stand age is between 7 and 10 years. For pine or pine/Douglas-fir mixtures that are planted at 300 TPA, expect an average site to be ready to PCT in year 7 or 8, whereas high site index areas planted to pine may be ready to thin at year 5 (Mark Gray, personal communication). The rationale for waiting until this time, instead of conducting PCT earlier, is to ensure the crop trees outsize weeds (i.e., unwanted vegetation) such that after PCT the residual trees are capable of quickly re-occupying available growing space instead of prolonging the so-called 'stand initiation phase' by ceding more growing space to weeds (Oliver and Larson 1996).

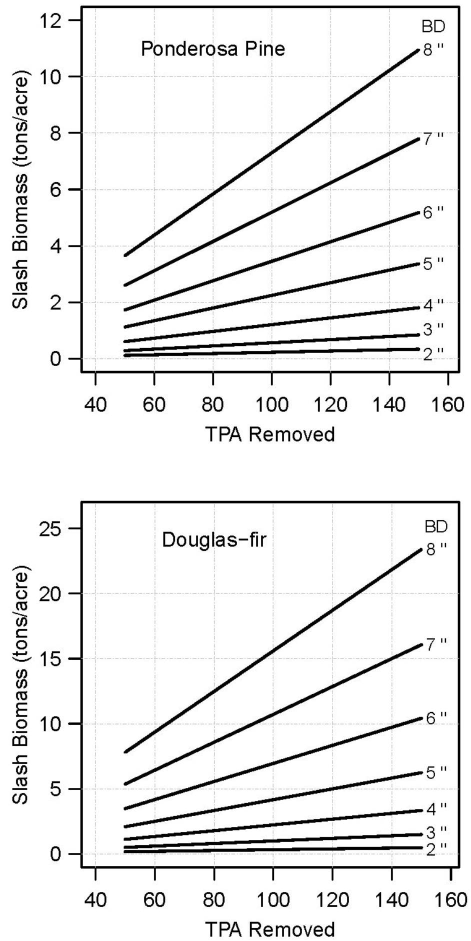

Figure 10.2 Above ground total biomass estimates in tons per acre for thinning slash as a function of average basal diameter (*BD*), at 6 inch stump, of trees removed and the number of trees per acre (*TPA*) to be removed in a precommercial thin; equations from Cochran et al. (1984) and Espinosa-Bancalari and Perry (1987).

Intensity of Thinning

The density of trees (trees acre^{-1}) retained after PCT influences the time at which a first CT may be conducted for any site quality and market. This retention level should be determined by the average tree size in terms of quadratic mean diameter (*QMD*) that a stand should exhibit at the time of CT (Reukema 1975; Webster 1997). As the target *QMD* for CT increases, the residual tree density from PCT should decrease (i.e., grow fewer larger trees). The number of trees per acre and the mean tree size determine the density threshold; density management diagrams (DMD) can guide decisions on PCT residual density for any manager's specific objectives (refer to Density Management section below).

It is a natural tendency for timberland owners and foresters to want to leave stands at higher densities; it can be difficult to cut your own trees or watch thinning crews cut trees you have planted and cared for (Mark Gray, personal communication). However, correct timing and intensity of PCT is an integral step in density management prescriptions designed to maintain the desired balance between rapid individual tree growth (at low stand densities) versus high volume production per acre per year (at higher stand densities).

One recently developed tool that may help in guiding timing and intensity decision making on early stand development of ponderosa pine is OP-Yield (Ritchie and Zhang 2018). This is a spreadsheet adaptation of the Oliver and Powers (1978) yield tables for ponderosa pine plantations (https://www.fs.fed.us/psw/publications/documents/psw_gtr259/) which allows substantial flexibility in evaluating PCT with varying establishment densities and anticipated CT targets. A web application has also been recently produced: http://3.22.183.171:3838/OP_Yield/.

Species Selection

In planted stands, natural regeneration of commercial species such as white fir (*Abies concolor*) or non-commercial species such as tanoak (*Notholithocarpus densiflorus*) can add a considerable number of trees at the point when PCT is planned. PCT provides a window of opportunity to adjust the species mix that will be available at the time of CT and final harvest. Some consideration should be given to the long term development of individual species as early status may not reliably describe future development of the stand. Consider the hypothetical case in Figure 10.3 where tree size exhibits a cross-over effect. In this situation favoring Species A because of an early size advantage may not produce the desired long-term results. For example, nine years after planting at Caspar Creek watershed in Mendocino County, Douglas-fir seedlings were shorter than redwood seedlings which were much shorter than redwood stump sprouts. However, dominant Douglas-fir were expected to overtake dominant redwood in height after a slow start (Jameson and Robards 2007).

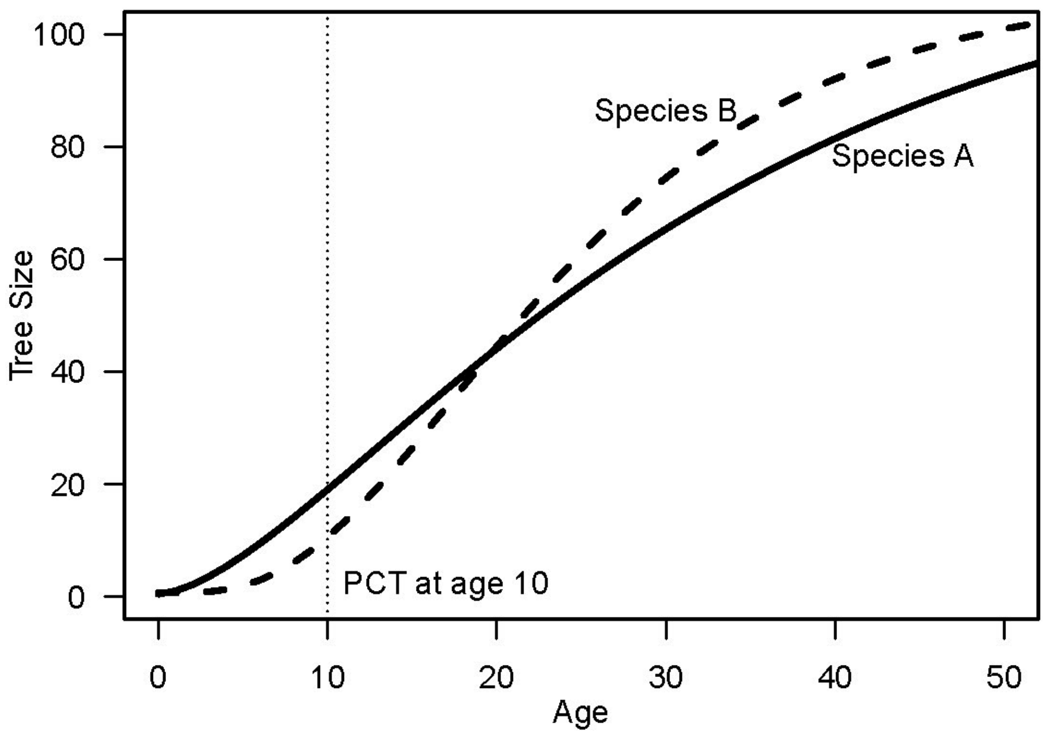

Figure 10.3 Example of different tree-growth forms with cross-over where Species A is larger than Species B at time of PCT (dotted line).

In stands managed primarily for timber production, using PCT to promote evenness of tree spacing is a high priority. Therefore PCT contractors are usually given a target average spacing to aim for, and their success in achieving this goal is assessed by foresters who count residual stems per unit area in small fixed-area plots. In mixed stands, contractors should be provided with species priority for retention, and guidelines on how small the desired species can be before it will be cut instead of a larger neighboring tree of lower species priority. The simplest example is only allowing a lower-priority species to replace a higher priority species when it is "twice as tall", or "50% taller", or some such measure that contractors are able to quickly judge. Any such prescription implies that the forester expects the smaller individual tree to be released by PCT and maintain competitiveness until the next stand entry.

Health, Vigor, Form and Defect

Typically, trees selected for retention will be the healthiest and most vigorous. The best trees may not be well distributed throughout the stand and consideration should also be given to the spatial distribution of leave trees. Variability within stands can be handled by ordering or weighting priorities for individual tree retention in the PCT prescription. For example, we might prioritize evenness of spacing, then prioritize tree vigor or size. Straightforward guidelines for contractors give priorities for retention, e.g., "#1: species choice, #2: evenness of spacing, and #3: tree growth and form". Species choice can be listed explicitly, according to individual species names or species groups e.g., "prioritize retention of redwood, then Douglas-fir, then other whitewoods, then hardwoods other than tanoak".

Thinning Methods

The thinning method defines which trees are cut according to their position within the stand, often according to relative tree crown position ranked from highest to lowest: dominant, codominant, intermediate, and suppressed/overtopped. Selecting a defined thinning method helps you refine and communicate your PCT prescription using professional terminology:

- Row thin (also called geometric or mechanical thin; no discrimination based on size; trees from all diameter classes are cut to maintain the same tree diameter distribution),
- Low thin (also called thin from below; focus cutting on smaller trees),
- Crown thin (focus cutting mainly on codominant trees to keep larger trees while also releasing smaller trees with desirable properties),
- Selection thin (also called thin from above or dominant thin; focus cutting on largest trees, which is only acceptable when cut trees were unhealthy or undesirable in terms of species or form),
- Variable-density thin (VDT; cut patches to different spacing, creating a mosaic of different densities throughout the stand, for objectives other than timber production),
- Crop-tree release (CTR; also called localized release; only cut trees in the vicinity of crop trees selected for retention and release from competition), and
- Free-form thinning (situations when any of the thinning methods listed above are deliberately combined for specific objectives).

Row thinning is simple and economical. By felling trees in one direction along a row of plantation trees, row thinning facilitates efficient felling of trees that could otherwise hang up. In dense naturally-regenerated stands, cutting or crushing strips of trees will be simpler and less costly to implement than most other PCT approaches. Row thinning is typically the first thinning in a sequence of planned thinnings (i.e., row thin PCT followed by CTs using more sophisticated thinning methods.

Low thinning reallocates growing space to the largest, most vigorous, and windfirm trees. It preempts natural mortality of weaker trees, but cutting only the smaller trees requires that many trees be cut to achieve the desired release from competition among crop trees. Application in mixed stands can be detrimental when slower-growing species are inadvertently targeted. The small cut trees should decompose more rapidly than relatively larger trees cut during selection or crown thinning.

Crown thinning involves thinning in the middle and upper canopy to create space for promising crop trees of any size. Removing neighboring trees with crowns interfering with crop tree development usually involves cutting codominants, but cutting some dominants or intermediates may also be needed. Crown thinning requires cutting of fewer (larger) trees than low thinning, so it may be more economical and hazardous fuel beds are not as uniform or continuous. In a stand with trees approaching merchantable size, a crown thinning CT could be performed in lieu of a low thinning PCT of the smaller non-merchantable trees.

Selection thinning is used to remove dominant trees of poor health, form, or value such as pioneer species overtopping the desired crop or trees with form problems. Unfavorable genetics may predispose a vigorous tree to form problems such as heavy branching and forking. Also common is stem or leader damage caused by pests damaging the most vigorous trees. Timely PCT that applies selection thinning culls such trees before they overtop desirable crop trees.

Variable-density thinning enhances variability of tree spacing which leads to differences in crown size, growth rate, and tree form within stands. Trees in uncut ‘reserve’ patches grow slowly while other trees grow rapidly at wide spacing and adjacent to patch cuts. This medley of densities is expected to promote development of heterogeneity and complexity characteristic of older forests. VDT is not recommended for timber production because of inefficiencies related to the range of tree sizes and form problems such as heavy branching and crown asymmetry.

Crop-tree release only requires cutting a few large trees with crowns in direct contact with each crop tree. Smaller trees overtopped by the crop tree remain as trainers restricting lower branch growth of crop trees. CTR usually removes crown competition on all four sides of each crop tree, but “3-sided release” can be used to reduce cost albeit at reduced benefit in terms of crop tree growth (Dagley et al. 2018). After localized release of well-formed, desirable trees, much of the stand remains unthinned making the CTR method cost-efficient, especially in dense stands and when low retention densities are prescribed (Leonard et al. 2017).

Free-form thinning combines any two or more thinning methods. Within a plantation, row thinning can efficiently removing entire rows in combination with low thinning along adjacent rows of retention trees to leave a well-spaced stand of superior trees. Free-form thinning is also useful in stands with irregular species composition and structure. Here, the PCT prescription could list different localized conditions matched with the desired thinning method(s). For example, patches of desirable/valuable hardwood or tolerant conifers could receive crown thinning to release them, while areas dominated by intolerant conifers receive low thinning.

For more detail and examples of thinning methods, see Ashton and Kelty (2018, p. 461-485).

Implementation Methods

The options for implementing PCTs include hand treatments, mechanical treatments, chemical treatments, and prescribed fire. Hand treatments (chainsaw, brush-saw or loppers) offer the potential to be very selective but can be slow (and therefore more costly), particularly in stands of advanced age or those with dense competing vegetation. Hand felling allows the land manager to be very specific about which trees to remove and which to leave, enabling the treatment to target problems with disease, insects, mechanical damage or ingrowth of undesirable species. By the same token, this type of PCT can be used to retain and protect or promote growth of critical habitat elements such as snags, mast-producing hardwoods, and trees with features offering habitat value. If possible, the stem should be completely severed below the lowest live branch or foliage, otherwise this foliage may survive and turn upwards to become a replacement stem. The same applies to trees pushed over by other falling trees; the down tree should be cut otherwise its branches may grow upwards as new tree stems that are unstable.

Tree size affects choice of PCT tool. Loppers may be employed for very small diameter trees but often tree size will be prohibitive. Another option for small diameter material (< ~3 inches basal diameter) is a brush-saw or clearing saw. This motorized tool has a blade mounted on a pole, similar to a string trimmer but with a circular saw blade on the cutting end. A clearing saw will not work well for larger trees that require a face-cut, but may prove effective for dealing with dense pockets of natural regeneration. The backpack chainsaw is ergonomically designed specifically for PCT of smaller saplings, with backpack powerhead running a chainsaw bar and chain mounted to the end of a handheld pole. Keyes et al. (2008) reported that when thinning crowded redwood sprout clumps, smaller chainsaws performed adequately and represented a balance between less operator-fatigue from using a larger saw that was slightly faster. Brush-saws and hedge trimmers were not effective because they could not cut larger, older stems (Keyes et al. 2008). Common chainsaw sizes used for PCT are 60-70 cc and power output of 3.5-4.0 kW or 4.7-5.4 hp (Mark Gray, personal communication). Professional grade chainsaws have slightly higher power-to-weight ratio that can reduce fatigue.

Chemical thinning is using herbicides to kill trees selected to be thinned. A common application is to spray unwanted trees that have resulted by seeding in to a planted stand or to spray unwanted species that result from post plant germination of serotinous species such as knobcone pine or lodgepole pine. Spraying can be a useful tool for these young stands, but as the stand grows, spraying is less effective. Hack and squirt application or stem injection of herbicide has been used to thin when the plantation trees reach appropriate thinning age and beyond. With hack and squirt, a small quantity of herbicide is injected/sprayed into cuts (frills) that go through the bark and into the cambium of a target tree.

While most conifer stumps will not resprout after cutting, redwood and most hardwood stumps (Roy 1955) can sprout vigorously in response to thinning. This problem can be solved by spraying a small quantity of herbicide on the freshly cut stump using a handheld spray bottle. Chemical thinning will require a licensed applicator and in-depth knowledge of the best chemical and timing for application. Spring application of chemical injection may be less effective than late season application. There may be a risk of uptake or translocation of some herbicides (e.g., imazapyr) to adjacent crop trees, so testing on a small scale is advisable. Although hack and squirt is most commonly used to remove unwanted hardwoods, it may also prove useful to remove unwanted conifers. Glyphosate, imazapyr and triclopyr will kill most conifers when applied at the proper dose (Mark Gray, personal communication). There are many risks to the remaining stand associated with using herbicides for thinning. For example, imazapyr is readily translocated to adjacent trees of the same species through root grafts and will in many cases damage the tree selected to be the crop tree. Chemical application to conifers doesn't kill the treated tree rapidly, and some cases only makes the tree decline in health over a long period of time. This can lead to insect outbreaks and increases in disease in an otherwise healthy plantation (Mark Gray, personal communication). Basal bark spraying is another chemical PCT approach where an oil-based penetrant carries the herbicide through the thin bark of young trees. Triclopyr ester is commonly used. This is an efficient way of treating multi-stemmed clumps of resprouting hardwoods quickly with a small amount of herbicide. For more information on chemical weed control, see Tu et al. (2001).

Mechanical chippers or masticators can be used for PCT (USDA Forest Service 2009). They may be boom-mounted or mounted on the front of a wheeled or tracked vehicle. These tools are well suited for row thinning, especially in extremely dense young stands, or thinning in stands of an advanced age, where hand felling will be slow. Mechanized harvesters such as feller-bunchers can cut trees and place them in bundles to be skidded to a landing where the material can be made available to firewood cutters, piled and burned, or chipped and hauled in a chip van to a co-generation plant for production of electric power. In multiaged stands, feller-bunchers can be used to quickly PCT young trees (e.g., dense patches or unwanted species) in conjunction with harvesting of merchantable trees. Operation will be limited by excessively steep or rocky terrain. For more information on mechanical treatments, see Jain et al. (2012).

Another option for PCT is prescribed fire (Windell 1998), although the unpredictability of fire as a thinning tool can induce uncertainty of results. Prescribed fire has been found to be feasible in young plantations (Bellows et al. 2016) when the fire intensity is controlled. Tree mortality can be highly aggregated (Figure 10.4). If conditions are too cool or wet, the fire may not remove enough trees; if too hot and dry it may take out more than desired. Generally speaking, PCT using prescribed fire might be better suited to thinning from below in a stand with larger, older trees that are more resistant to fire.

Probability of surviving fire varies among species and according to season of burn, chances of survival may be slightly enhanced by pruning and raking of fuels away from young trees (Bellows et al. 2016).

Cost Considerations with Precommercial Thinning

Cost of operation will be a key consideration for any PCT project. So, just how much will PCT cost? The problem is that even if we were to produce estimates, they would quickly become obsolete and the costs are significantly influenced by the particulars of a given project. The best approach would be to consult with professionals in your area who have had recent experience with PCT contracting. However, there are some key factors to consider.

The larger the size of the material being cut, the more it will cost (Webster 1997). More so if the contractor will be required to lop and scatter material. Therefore, the longer PCT is delayed, the higher the cost.

The more trees to be cut per acre, the higher the cost of thinning. Thus overplanting a site not only costs you at the time of planting, it will increase the cost of PCT as well. Since it will be decades before one can see a return on investment, this is critical. The time to think about PCT is before you plant.

The equipment used to PCT can also influence cost of operation, and choice of tools depends on size of trees being cut. For example, Jamnick (1989) compared a brushcutter with machete and chainsaw for precommercial thinning of an 8-year old mixed-conifer plantation and found that productivity was lowest with the brushcutter (which might be an efficient tool cutting smaller trees).

Access is another important factor. Is there easy access or will workers have difficulty getting to the site? Any time crews have to walk some distance that will add cost. In like manner, steep slopes will slow productivity and increase costs per acre because workers and machines can generally move more effectively on flat ground. Are there other obstructions to be dealt with like high shrub cover or slash that will slow workers down? Anything that slows the rate of work will increase the cost.

Figure 10.4 Prescribed fire thinning a dense cluster of naturally regenerated ponderosa pine saplings at Blacks Mountain Experimental Forest. *Photo*: Martin Ritchie, US Forest Service.

Density Management

PCT is an important consideration for long-term density management. The ability to manipulate the number and distribution of trees in a stand over time is one of the primary tools of the silviculturist. Stand structure and growth after PCT affects timing of subsequent entries, so a consideration of the general topic of density management is warranted.

We often think about PCT prescriptions in terms of simple metrics of density such as trees per acre (*TPA*) retained. However, as stands develop over time, the metrics necessarily become more complicated and *TPA* no longer adequately describes growing space occupancy in the stand (e.g., 200 *TPA* of small trees occupy less growing space than 200 *TPA* of large trees).

Density Metrics

The generic definition of density is the number of individual trees per acre (*TPA*). For very young plantations, particularly those with fairly uniform survival and distribution, *TPA* will suffice as a descriptor of stand density. In instances where tree survival lacks uniformity as one may find with natural regeneration, *TPA* may need to be augmented with some measure of stocking (Stein 1978, 1992). Stocking reflects the amount of a stand that has been adequately regenerated, often expressed as a percentage. It may be possible to derive estimates of stocking for natural regeneration from estimates of *TPA* (Ritchie 2020).

If we wish to assess development of the stand over time it becomes necessary to incorporate the effect of tree size in any density-related metric, particularly as these expressions relate to growth and mortality. Basal area per acre (*BA*), the cross section of all trees in the stand at breast height (4.5 feet) is one such metric that has been used as a target for late-entry PCT as well as used in later commercial harvests (e.g., Oliver 1979a, 1979b). *BA* can be expressed as a function of quadratic mean diameter (the diameter of a tree of mean *BA* or mean of breast height diameter (*DBH*) squared):

$$BA = k \times TPA \times QMD^2 \qquad (1)$$

Where:

BA = Basal area in square feet per acre,

TPA = Trees per acre,

QMD = quadratic mean diameter in inches, and

$k = 0.005454154 = \frac{\pi}{576} = \frac{\pi}{144 \times 4}$, a constant needed to convert diameters measured in inches to basal area in square feet.

As an example, if *TPA* is 300 and *QMD* is 3 inches, *BA*=14.7 ft^2 $acre^{-1}$.

One of the more widely applied density metrics, certainly for forests in western North America, is Reineke's Stand Density Index (*SDI*; Reineke 1933). This metric was derived by Reineke for even-aged forests and it takes the general form of:

$$SDI = TPA\left(\frac{QMD}{10}\right)^{1.605} \qquad (2)$$

SDI is indexed to the number of trees in a stand with a *QMD* of 10 inches. The effect of indexing this metric is similar to the indexing of dominant height with site index, wherein dominant height for any given stand is indexed to that of a stand at the base age. With *SDI* values, density is indexed to *TPA* of a stand with a *QMD* of 10 inches. Therefore, if you have two stands with *QMD*s of 7 and 15 inches and both have an *SDI* of 135, both are considered to be at the same level of density in Reineke space; they both are equivalent in density to a stand with a *QMD* of 10 inches and *TPA* of 135. A re-expression of (2) yields:

$$SDI = a \times TPA \times QMD^{1.605} \qquad (3)$$

This expression (where *a*=0.0248) then has a form identical to (1), and one can see that the only important difference, is the value of the exponent on *QMD*. While the exponent of 1.605 is widely applied, it is not universal. Some studies in ponderosa pine have used a value greater than the Reineke (1933) constant of 1.605. Edminster (1988) used 1.66, and 1.7653 was used by DeMars and Barrett (1987) and Cochran (1992). Rounding this to two decimal points yields 1.77, and this has been employed for ponderosa pine as well (Oliver and Powers 1978; Cochran and Barrett 1995; Ritchie and Zhang 2018). As a result, it is important to understand which value is in use for any particular application. The example presented above, of 3 inches *QMD* and 300 *TPA*, yields an *SDI* of 43.

Because Reineke's *SDI* was developed for even-aged stands, it may not be appropriate for uneven-aged or multi-cohort stands. For this reason, some have proposed using a modified version of *SDI* using a summation method (Long and Daniel 1990). The summation form of *SDI* can be expressed as:

$$SDI_s = \sum TPA_i \times \left(\frac{DBH_i}{10}\right)^c \tag{4}$$

where DBH_i is the breast height diameter and TPA_i is the expansion factor, for the *i*th tree in the sample. The exponent, *c*, is the *SDI* exponent, again usually 1.605 although sometimes rounded to 1.6. This expression has the advantage of being additive, so the metric can be compartmentalized by individual tree, size class or species cohort. The two different expressions for *SDI*, (3) and (4) produce metrics that are very close to one another for stands with a symmetric diameter distribution (Curtis 2010; Curtis et al. 2016), as is the case in most plantations. However with multi-modal or long-tailed distributions, the value obtained for *SDI* in (4) can be substantially less than that for (3).

A case can be made for excluding very small trees by setting a minimum diameter limit for calculating (3) or (4), particularly in cases where ingrowth of natural seedlings in the understory is present (Curtis 2010). With regard to Douglas-fir in the Pacific Northwest, the recommendation of Curtis (2010) was to base this restriction on one quarter of the *QMD* of the 40 largest *TPA*, so as to exclude smaller younger trees from the *SDI* calculation. It isn't clear if this method would translate well to other species.

Density Management Diagrams

One approach to decision making with regard to PCT is to first think about an upper limit to density for a managed stand. Observed *SDI* is sometimes divided by the upper limit for that species (SDI_{UL}) to develop a relative density metric (*RD*) bounded by 0 and 1: $RD=SDI/SDI_{UL}$. A value of *RD* near 0.6 is sometimes defined as the upper limit of the management zone (*UMZ*). For example, if the SDI_{UL} is assumed to be 400 and one wishes to establish the *UMZ* at RD=0.6 then *UMZ*=0.6×400=240. Density management would be conducted in such a way as to ensure that the stand will remain below this threshold. Note that this threshold *RD* as well as the SDI_{UL} value may vary by species. The lower limit of the management zone is typically associated with the point where the stand approaches crown closure. So how does a precommercial thinning, which will generally be specified by a TPA or spacing target relate to the *UMZ*? The answer is to first assume a future QMD which will define a stand that can support a commercial entry at some time in the future. For this example, let us assume this is 11 inches. Then we would want to precommercially thin our stand to a level that would assure the stand could reach 11 inches *QMD* without exceeding the *UMZ*. Another way of saying this is that we don't want to reach the *UMZ* until we can enact our next harvest after the PCT, and that harvest should be a commercially viable timber sale. Sticking with this example this is calculated as: $TPA_{pct} = 240(11/10)^{-1.605} = 205.95$. Which is to say, you would want to leave no more than 206 *TPA* in after your precommercial thin.

In this context, density management diagrams (*DMD*) can be helpful in visualizing PCT timing and intensity. Often a *DMD* (e.g. Figure 10.5) is an expression of *SDI* with mean tree size (*QMD*) on the y-axis and *TPA* on the x-axis, both in log-log space. In addition to the lines for fixed values of *SDI*, additional isolines may be included for volume (ft^3 $acre^{-1}$) and dominant height (feet). These can be used to estimate the status of the stand in the future. By assuming a site index system, such as the Biging (1985) curves, one can then also imply the age at a given point in stand development in the DMD space. Other examples of these diagrams are presented later in this chapter.

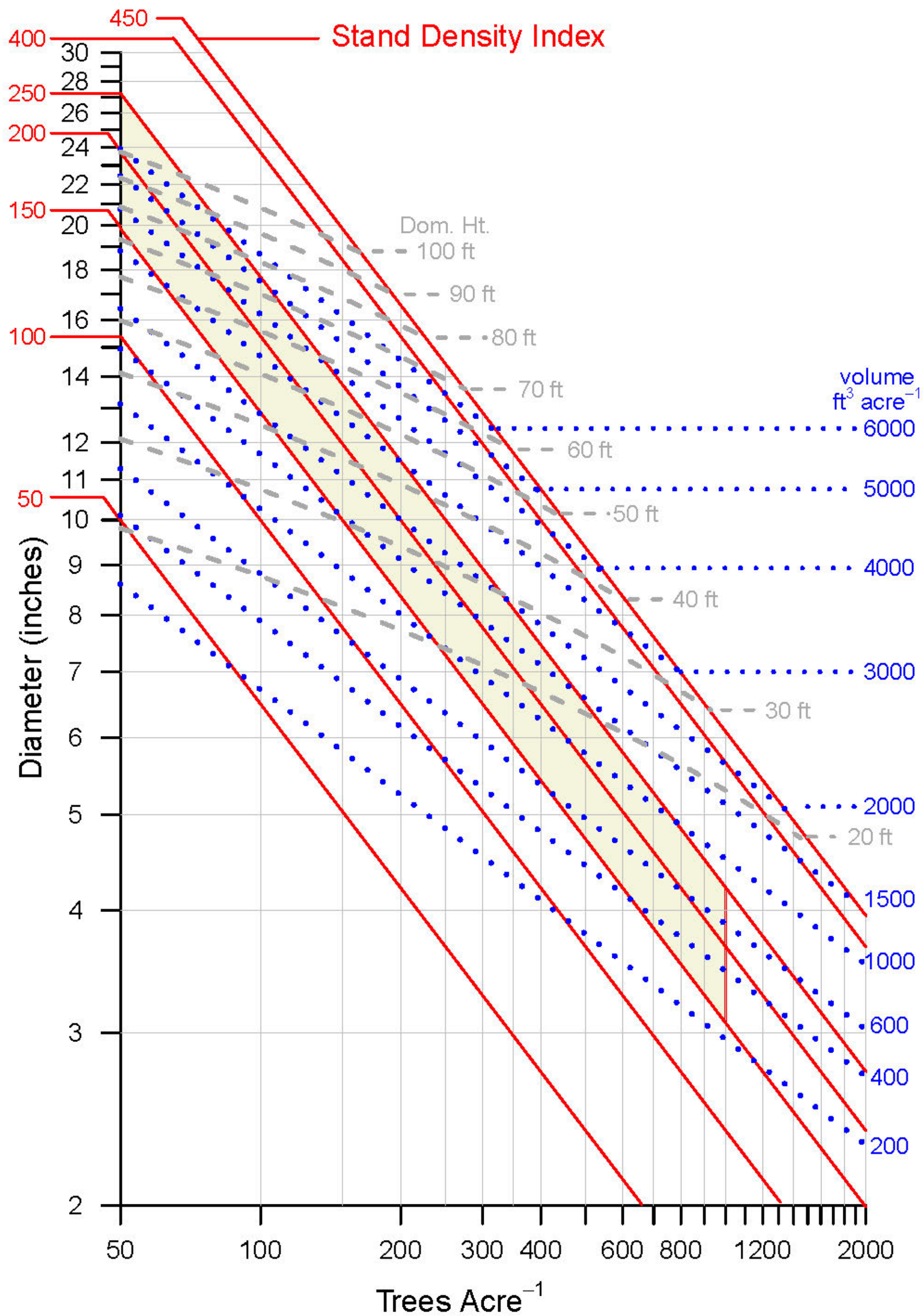

Figure 10.5 Modification of Long and Shaw (2005) density management diagram (*DMD*) with management zone from stand density index (*SDI*) 150 to 250 for ponderosa pine shaded.

Other expressions have been developed for density management. Some present average tree size as mean tree biomass (Drew and Flewelling 1977, 1979). Otherwise, this presentation is very similar. Drew and Flewelling (1979) used relative densities of 0.15 and 0.55 to bound the management zone within which they expect an acceptable compromise between lower densities (fosters individual tree growth and vigor) and higher densities (greater stand growth per acre).

Another common form of DMD employs stand *BA* (e.g. Edminster 1988; Cochran 1992). This approach uses the same technique, deriving a management zone as a proportion of a limiting *SDI*. Edminster's (1988) work on ponderosa pine in the southwestern US and the Rocky Mountains is shown in Figure 10.6.

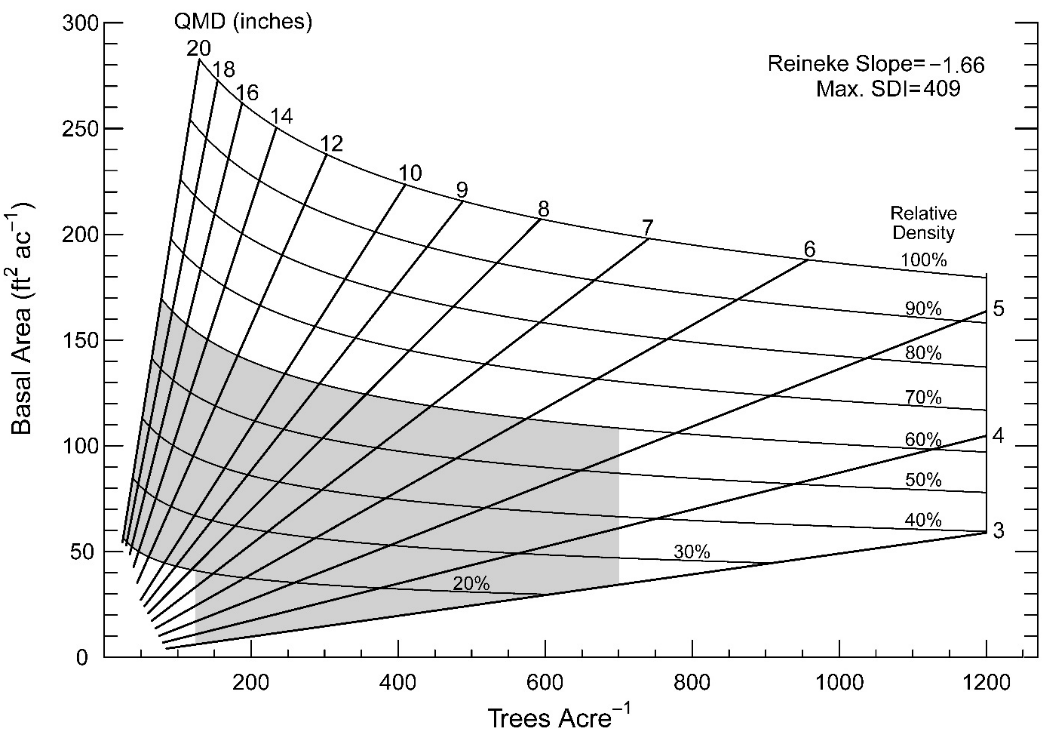

Figure 10.6 Edminster's (1988) density management diagram for ponderosa pine in the southwest and Rocky Mountains, with management zone shaded.

Both types of density management diagrams may be constructed using the *standview* R package, which can currently be accessed within the R computing environment (https://www.fs.fed.us/psw/tools/standview/). The package comes with help files and a vignette providing more detailed guidance on application. A dynamic application of the *standview*, which does not require knowledge of R, can also be found online at http://3.22.183.171:3838/SDMD_PP/.

Relationship between PCT and Establishment Density

To a large extent, planting density drives the need for PCT. High planting densities, or stands with excessive natural regeneration, put stands on a trajectory where PCT will be needed for trees to maintain health and vigor, and reach merchantable size in a reasonable timeframe. Without PCT in these stands, tree growth slows and mortality eventually ensues before reaching a point where CT is possible.

For plantations established after a regeneration harvest, the current California Forest Practice Rules (with recent changes effective January 1, 2020) require achievement of establishment stocking dependent on tree size and site class (Table 10.2). Note that these new standards are substantially lower than those in effect before 2020 and this has an impact on the need for PCT. Successful regeneration is quantified through a point count method where trees less than 4 inches DBH count as one point per acre. Thus if one is counting only small planted or natural seedlings the requisite density is equal to the point count shown in Table 10.2 (California Department of Forestry and Fire Protection 2020, page 36).

Table 10.2 Current (2020) California Forest Practice rules for minimum acceptable stocking (expressed as a point count), by district, after forest operations.

	Site Class				
District	I	II	III	IV	V
Coast	200	200	125	100	100
Northern	125	125	125	100	100
Southern	125	125	125	100	100

With these lower targets it may be possible to skip PCT and get to a CT without having to endure stand conditions that exhibit poor diameter growth and an elevated risk of mortality. Consider a ponderosa pine plantation established with 15x15 foot spacing (194 TPA) and 90% survival. This would produce a point count of about 174 if all trees are no more than 4 inches *DBH*. This would be acceptable stocking on Site III ground (Table 10.2). Without PCT or any subsequent mortality, *SDI* will be about 203 when the stand reaches a *QMD* of 11 inches. This stand remains below the recommended UMZ and therefore could be thinned or allowed to grow longer. For comparison, consider a plantation at 12x12 foot spacing with 90% survival rate. This would produce a point count of approximately 303x0.9=273 if all trees are less than or equal to 4 inches *DBH*. Theoretically, this would produce an *SDI* of 318 when the stand reaches a *QMD* of 11 inches. A site index 100 (at base age 50) stand will achieve this in about 25 years (Oliver and Powers 1978). An *SDI* of 318 is in excess of the suggested *UMZ* for ponderosa pine, indicating that PCT will be needed if one wishes to get to a *QMD* of 11 inches before conducting a CT. Furthermore, any additional natural regeneration will further elevate the *SDI*. PCT reduces *TPA* and *SDI*, allowing trees to attain larger size sooner. Table 10.3 shows the *SDI* associated with various establishment densities (or spacings) at different points of stand development expressed as *QMD*.

Table 10.3 Stand density index (*SDI*) associated with various establishment density (trees per acre; *TPA*) or average tree spacing (ft) and average tree size (quadratic mean diameter; *QMD*) combinations, assuming negligible mortality.

	QMD (inches)											
TPA	8	9	10	11	12	13	14	15	16	17	18	Spacing
50	35	42	50	58	67	76	86	96	106	117	128	29.5
75	52	63	75	87	100	114	129	144	159	176	193	24.1
100	70	84	100	117	134	152	172	192	213	234	257	20.9
125	87	106	125	146	167	190	215	240	266	293	321	18.7
150	105	127	150	175	201	229	257	288	319	352	385	17.0
175	122	148	175	204	234	267	300	335	372	410	450	15.8
200	140	169	200	233	268	305	343	383	425	469	514	14.8
225	157	190	225	262	301	343	386	431	478	527	578	13.9
250	175	211	250	291	335	381	429	479	532	586	642	13.2
275	192	232	275	320	368	419	472	527	585	644	706	12.6
300	210	253	300	350	402	457	515	575	638	703	771	12.0
325	227	274	325	379	435	495	558	623	691	762	835	11.6
350	245	296	350	408	469	533	601	671	744	820	899	11.2
375	262	317	375	437	502	571	644	719	797	879	963	10.8
400	280	338	400	466	536	609	686	767	850	937	1027	10.4
425	297	359	425	495	569	648	729	815	904	996	1092	10.1
450	315	380	450	524	603	686	772	863	957	1055	1156	9.8

As an example, for ponderosa pine at 300 *TPA* and an assumed UMZ of 250, one will reach this point at a *QMD* of about 9 inches. This stand is unlikely to produce a commercial product because the trees are too small. Thus, under earlier regulations, PCT was often not a management option but a silvicultural necessity. Planting densities following a wildfire are up to the landowner, as the California Forest Practice Rules do not dictate stocking for post-fire recovery. Planting a mix heavy to Douglas-fir on a westside stand may also raise the *UMZ* and thus delay the stand's arrival into the zone of imminent mortality (i.e., densities above 0.55-0.6 relative density; Drew and Flewelling 1979, Long 1985).

Regional Considerations

Because there are substantial differences in species and productivity across the state of California, it is important to recognize some regional considerations that may come into play when considering density management of young stands. Managers should also consider localized or emerging issues. Localized issues could include elevated risk of windthrow after heavy late PCT in exposed areas, or risk of large wildfires after creating a continuous fuel bed by conducting PCT over vast contiguous areas. Emerging issues could include elevated risk of loss due to drought in a changing climate prompting PCT to retain fewer *TPA*, or Sudden Oak Death prompting removing hardwoods. Managers may also incorporate language into contracts requiring cleaning of equipment to prevent spread of unwanted seed or fungal pathogens, or actions to be taken in presence of disease such as root rots. For example, in areas with black stain root disease, minimize tree injury during thinning operations, minimize soil compaction, minimize fuel loading, and PCT later in the year after insect flight has occurred (https://www.fs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb5187236.pdf).

PCT in California's Coast Range Forests

Coast range forests are known for their highly productive coast redwood (*Sequoia sempervirens*) forests located on alluvial flats and lower slopes with deep soils and favorable climate moderated by coastal fog. Further inland and upslope, redwood shares growing space with coast Douglas-fir, tanoak, and/or other conifer and hardwood associates eventually giving way to Douglas-fir and tanoak or true oak dominated forests characterized by climate extremes with high vapor pressure deficits. At the southern limits of its range, redwood is found in patches on cooler north-facing slopes where there is sufficient soil moisture for it to survive the hot dry summers. Many efforts to expand redwood's range by planting further inland at higher elevations have so far been successful (e.g., Dagley et al. 2017). It is still unknown whether these redwoods will reproduce by seed to become naturalized or, more likely, just re-sprout from cut stumps. High early survival in these plantations suggests they will benefit from PCT.

After harvesting in Coast Range forests, natural regeneration is usually prolific and can be dominated by less desirable conifers, advance regeneration (i.e., shade tolerant seedlings pre-dating and released by the harvest), and stump sprouts of tanoak and other hardwoods (Thornburgh et al. 2000). Redwood stumps that resprout after cutting can have over 100 sprouts (Neal 1967; Wiant and Powers 1967) that may all die in low light or self-thin when sufficient light is unavailable (O'Hara et al. 2007; O'Hara and Berrill 2010). Jameson and Robards (2007) stated *"…considering that redwoods tend to sprout when cut or destroyed, a high-density planting of redwood, coupled with the naturally high density of native sprouts, may make precommercial thinning more of a necessity than an option to avoid overcrowding and to maintain a reasonable rate of diameter increment… More recently, land managers have begun to reduce the number of trees planted, recognizing that a significant portion of the regeneration will ultimately consist of both redwood sprouts and natural fir seedlings".*

It is advisable to PCT redwood sprout clumps to promote good growth and form among the best individual sprouts (Boe 1974; Cole 1983; O'Hara et al. 2017). PCT will also provide enough space between sprouts so their stems do not grow together over time and fuse together causing deformities and making future thinning more difficult (O'Hara et al. 2015).

Time and cost of PCT increased with advancing redwood sprout clump size (Keyes et al. 2008). However, an early PCT can stimulate another regeneration event which would be counterproductive. Ingrowth comprised of sprouts arising from stumps cut during PCT as well as prolific natural seedling regeneration may counteract or lessen the benefits of thinning that was originally designed to reduce competition and promote growth of selected trees (O'Hara et al. 2015).

Leaving sprouts originating from the root collar or low down on the stump is recommended since the taller, straighter sprouts located higher on the stump may eventually separate from the decaying stump and topple over. If left unthinned, the process of self-thinning within each sprout clump will proceed, and these tall unstable sprouts will likely come to dominate. Such sprouts have been observed toppling at any age, including up to 100 years of age.

Thinning studies conducted in north coastal California on the Coast Range have included timber management-oriented studies (Oliver et al. 1994; Lindquist 2004, 2007; Webb et al. 2012, 2017; O'Hara et al. 2015) as well as research into thinning for restoration objectives such as directing stand development towards structures resembling old growth forests (e.g., O'Hara et al. 2010, 2012, Teraoka and Keyes 2011; Berrill et al. 2013; Dagley et al. 2018). A long-term study of stand development after PCT to retain 100, 150, 200, 250, 300 *TPA* with unthinned controls continues to yield data as the redwood-dominated stand surpasses a harvestable age of 50 years (Webb et al. 2017). We have learned from this most recent analysis that PCT has a lasting effect on growth in young redwood stands, but that growth is highly variable and sensitive to differences in species composition and small-scale variations in site quality (Webb et al. 2017).

Site quality varies over short distances in redwood forests. Trees in a sheltered gully can be twice as tall as trees on an adjacent ridge and have smaller or greater *DBH* depending on other site characteristics (Berrill and O'Hara 2014, 2015, 2016). Therefore, we might adjust the timing of PCT or residual stand density to best suit patches of forest with similar productivity. If the objective of management were to grow trees of uniform size for commercial harvest at the next stand entry, then in areas of poorer site quality we could PCT to lower densities (wider spacings) to promote individual tree *DBH* growth and PCT to leave higher densities on better areas where trees grow faster to foster more stand production at the expense of *DBH* growth. Similarly, multiaged redwood stands of differing site quality can be expected to have different optimal harvest return intervals, or should have different residual stand densities if the same harvested tree sizes or harvest return intervals are desired (Berrill and O'Hara 2009). PCT in the youngest cohort in multiaged stands will accelerate tree size development and therefore shorten the harvest return interval. It may also lead to harvest of larger trees, provided that sufficient growing space is made available to the understory cohort (O'Hara et al. 2007; Berrill and O'Hara 2009). Cole (1983) noted sprout mortality after early PCT (age 2 years) of redwood sprout clumps in low light; another caution against very early PCT in this forest type. PCT around stand age 10 years is common in redwood/Douglas-fir stands (Figure 10.7).

Figure 10.7 One year after PCT in redwood/Douglas-fir plantation outside of redwood's range with tanoak re-sprouting from cut stumps (above) and light branching after late PCT in pure Douglas-fir that generated deep slash layer (below). *Photo:* Christa Dagley.

Thinning Shock in Douglas-fir

Thinning shock can be a legitimate concern in Douglas-fir plantations (Staebler 1956). Thinning shock is exhibited by a period of reduced height and diameter growth after thinning. The problem seems most acute when thinning is delayed (Reukema 1975) and on poor sites (Harrington and Reukema 1983). The reductions in growth can be quite severe in the short term, but trees will generally recover, resulting in long-term growth increases in response to thinning. DeBell et al. (2002) reported very short lived thinning shock after PCT in a 10 year old plantation in southwestern Washington suggesting that application of PCT early should provide the manager with the best way to avoid it.

Usage of PCT in coastal Douglas-fir has been declining (Talbert and Marshall 2005) because a prevailing view is that Douglas-fir can often make it to CT without the need for PCT. This may be acceptable in a pure stand, but not in mixtures if more desirable species are being outcompeted or in overstocked stands. Suppressed Douglas-fir with smaller crowns are unlikely to respond well to thinning at any age (Tappeiner et al. 2007).

Density Management in Mixed Stands

Setting a goal for tree size (*QMD*) at the next harvest allows us to back-calculate how many trees to retain after PCT. Since redwood tolerates ~67% higher stand density than Douglas-fir (*SDI* upper limits of 1000 and 600, respectively; Reineke 1933), redwood can be retained at tighter spacing than Douglas-fir. In pure stands, 150 *TPA* redwood (17-foot spacing) should reach a 24 inch *QMD* when the stand reaches a *UMZ* of 0.6 relative density (600 *SDI*), but one should only retain 90 *TPA* Douglas-fir (22-foot spacing) if the goal is to reach a 24 inch *QMD* in a timely manner (i.e., when stand reaches *UMZ* of 0.6 relative density for Douglas-fir; Long 1985). Planning a commercial harvest at a lower QMD allows for retention of higher *TPA* at PCT. For example, when planning for a CT once the stand reaches 20 inch *QMD*, the PCT would leave either 120 *TPA* Douglas-fir or 200 *TPA* redwood. This translates into the following prescription for a mixed stand: PCT to leave approximately 19-foot spacing between Douglas-fir trees and 15-foot spacing between redwoods. Subsequently, if 50% of these stems were cut during CT, the remaining stems should have 30 inches *QMD* the next time relative density returns to the *UMZ* in future. Alternatively, cutting fewer than 50% of stems would allow for a shorter harvest return interval, but with smaller harvested tree sizes at the next stand entry.

Thinning in Mixed Stands with Redwood Sprout Clumps

Redwood stump sprouts use their advantage of an established root system to outcompete planted or natural seedling regeneration. Stump sprouts form dense clumps of sprouts surrounding one or more cut stumps associated with the same root system. Depending on the size of the sprouting stump(s) associated with each clump and the size of the entire clump of sprouts, a small clump might be thinned down to one sprout, whereas PCT in a large, multi-stump clump might leave two or three well-formed sprouts spaced 10 feet or more apart. Rather than considering this spacing too tight to meet our objectives for density management, we can compensate by allowing greater spacing between these sprouts and other trees in the vicinity. Our PCT prescription will dictate "spacing off" a certain distance from sprout clumps to allocate the appropriate amount of growing space to each sprout retained in the clump. This can be done by calculating the amount of growing space to be allocated to each clump. If the spacing goal was 17 feet between redwoods (17 x 17 foot = 289 ft^2 growing space), three sprouts should be allocated 867 ft^2 growing space (i.e., 30 x 30 foot square, or a 16.6 foot radius circular area). Adjacent to the growing space allocated to this sprout clump would be growing space allocated to each neighboring tree, so the distance for "spacing off" each redwood clump would depend on the growing space needs of neighbor trees selected for retention. This will depend on species, and if the neighbor is another redwood sprout clump, the number of sprouts retained in that clump.

A simpler approach is to define the tree-size goal for the subsequent stand entry (e.g., 20 inch *QMD*), then prescribe the number of sprouts to be retained per stump (e.g., average two sprouts per clump, range 1-3), and how much growing space will be allocated to each species (e.g., 50:50 redwood:Douglas-fir; note: with this growing space allocation we expect to retain more redwood than Douglas-fir on a *TPA* basis). The PCT prescription then becomes 19-foot average spacing between individual Douglas-fir trees and/or redwood clumps (averaging 2 stems per clump) giving 60 Douglas-fir and 100 redwood for a total of 160 *TPA*, where the redwoods are experiencing higher stand densities in their stump sprout pairs than the Douglas-fir which are well spaced to reach 20 inch *QMD*. Theoretically, the Douglas-fir and redwood stand components should each attain about 20 inch *DBH* and about 0.6 relative density at around the same time. This is because more growing space has been allocated to Douglas-fir versus redwood which can tolerate higher densities. PCT to 15-foot average spacing in a pure redwood stand, or PCT to 16-foot spacing in a redwood-dominated stand, should give trees enough growing space to reach a 20 inch *QMD* at the next stand entry when relative density reaches 60% *UMZ*.

In practice, densities and tree spacings are difficult to control due to the inherent variability in spatial patterns of tree locations in these mixed stands (O'Hara et al. 2015). Deviation from the prescribed spacing to retain better trees will be the norm, requiring the operator to compensate by leaving wider or narrower spacings nearby to meet the overall *TPA* goals. After PCT, higher *TPA* overall will lessen time taken to reach defined *SDI* for CT but at that future time the average tree size will be lower (i.e., harvest smaller trees sooner by retaining more trees at PCT). There is benefit to having a forester present to support contractor decision-making in these complex and variable mixed stands, and to acknowledge and accommodate the variability by prescribing a range of spacing for retention trees. One such PCT prescription accommodates variability by requiring contractors to leave the best tree every 14-20 feet, while clumps are handled differently: leave 2 stems every 10-14 feet or 1 stem every 6-10 feet within the clumps (Mike Alcorn, personal communication).

Reducing Competing Tanoak

Tanoak nuts are an important source of food for wildlife, but tanoak have low to no commercial value so retaining many tanoak per acre may not be advisable. Tanoak compete with conifers and impact their development (Harrington and Tappeiner 2009; Berrill and O'Hara 2014, 2016). Ideally we would treat the tanoak as soon as possible. However, if they are not overtopping the commercial conifers, it may be more efficient and economically advantageous to wait until PCT to remove tanoak. Tanoak also competes with planted and naturally-regenerated young conifers after variable retention and selection harvests (Berrill et al. 2018a, 2018b). Berrill and Han (2017) showed that PCT in group selection openings 10 years after harvest enhanced future growth and yield of merchantable conifers in these openings. The PCT focused on removing hardwood and retaining Douglas-fir and redwood. Berrill and Howe (2019) found that eliminating above- and belowground competition by killing tanoak with herbicide resulted in a major *DBH* growth response in neighboring redwood. Treating tanoak by stem injection, or by spot spraying smaller individuals and clumps, leaves dead wood standing for a time (Krieger et al. 2020). This is generally considered beneficial to mitigate fire hazard as opposed to cutting unwanted hardwoods and leaving the cut biomass as surface fuels (Valachovic et al. 2011). PCT at Headwaters Forest Reserve changed forest structure and fire hazard by increased surface fuel loading and altering the microclimate at the forest floor, resulting in relative humidity lower by 4.6%, and air temperature higher by 1.6°C (Glebocki 2015). The low cost of chemical thinning relative to cutting or girdling makes it an attractive option for a wide range of cull tree sizes.

Thinning Intensity and Bear Damage

Bear damage to conifers is widespread in Del Norte and Humboldt Counties and has been noted further south. Bears strip bark from the tree to feed on sugars in the cambial layer located immediately inside the bark. Perry et al. (2016) found that PCT results in high incidences of bear damage compared to neighboring unthinned stands. Generally, more redwood sustained damage than Douglas-fir. Damage is typically concentrated on larger fast-growing trees (O'Hara et al. 2010; Perry et al. 2016; Berrill et al. 2017; Dagley et al. 2018). Redwoods near forest roads were a little more likely to be damaged than redwoods further inside (Giusti 1990; Hosack and Fulgham 1998; Perry et al. 2016). In light of these results, we might refrain from PCT alongside forest roads, retain higher densities in anticipation of damage, thin small parts of a landscape progressively instead of thinning large areas in hopes that we escape the attention of bears, and/or implement a series of lighter thinnings instead of one heavy PCT that promotes rapid *DBH* growth. When bears damage the young stand before PCT, the PCT prescription should take account for how to prioritize culling trees that sustained damage.

Wood Quality

Heavy PCT encourages branch development, especially on better sites along the Coast Range, as tree crowns quickly expand to re-occupy growing space liberated by thinning. Douglas-fir branches were larger after PCT in Oregon and Washington (Weiskittel et al. 2007), with the largest increase in branch size following low thinning (Maguire et al. 1991). Low thinning removes smaller trees, which often have smaller branches, leaving larger trees with larger branches to re-occupy the growing space. In Mendocino County, branches of overstory trees in multiaged stands responded to partial harvesting (commercial harvest, not PCT) with greater branch basal diameter growth response than after chemical thinning of neighboring tanoak trees, and branch growth response was greater in Douglas-fir than redwood (Kirk and Berrill 2016).

The size, taper, and slenderness of a cut tree influence the number of logs it yields and the size and value of each log. More logs can usually be cut from taller trees. In general, redwood tree height-diameter ratios are lower than Douglas-fir, so Douglas-fir will be taller than redwood of similar *DBH* (Berrill et al. 2012). However, redwoods have a plastic physiology where they can alter their allocation of resources to height growth or diameter growth depending on conditions (Berrill and O'Hara 2016). There is some evidence that taller Douglas-fir encourage neighboring redwood from the same age class to allocate more resources to height growth, presumably to 'keep up with' Douglas-fir or because less *DBH* growth is needed when redwood is sheltered (Berrill and O'Hara 2016). This suggests that frequent light thinning would promote a steadier *DBH* growth rate in redwood when compared against a single heavy PCT that would have long treatment longevity (time until next stand entry) but promote rapid branch growth and *DBH* development.

The timing of thinning influences residual tree growth and form. Over the first five years after PCT at age 2 years in redwood sprout clumps, *DBH* growth but not height growth was enhanced by thinning more intensely (Boe 1974). After this time, both height and *DBH* development were enhanced by the early PCT, but no further benefit was detected after a second PCT at age 15 years (Cole 1983). An alternative to frequent light thinnings or heavy early PCT is to delay the PCT until branches in the first 1-2 logs have become suppressed. Delaying PCT adds to the cost because larger trees are being felled and will tend to hang up, but in the meantime lower branches remain small and many die and fall or break off during the late PCT operation. This may lead to production of valuable knot-free outer wood. Branches may also be removed by pruning. However, we caution that PCT timed to coincide with pruning of lower branches for clearwood production may stimulate a counterproductive epicormic branching response along the pruned bole (O'Hara and Berrill 2009; O'Hara 2012).

Dominant redwoods have higher volume growth efficiency than the lower crown classes (codominants, intermediates, suppressed trees), so cutting the largest most-efficient sprouts on a clump could reduce stand volume production (Berrill and O'Hara 2007). However, this effect may be offset by also cutting the smallest, least-efficient intermediate and suppressed redwoods. Future growth will then be concentrated on well-formed codominant stems adding more valuable wood than small trees with low recovery of sawn timber or on rough large trees with large branches and knots (Plummer et al. 2012; Kirk and Berrill 2016).

Developing a DMD for redwood is problematic due to a lack of data. Reineke (1933) showed a limiting SDI of 1000, although a limit of 774 and an upper management bound of about 550 has been suggested for young stands (Dan Opalach, personal communication). Figure 10.8 shows a DMD for coast redwood with management zone bounded by *RD* of 0.15 and 0.55 (Drew and Flewelling (1979) with an assumed SDI maximum of 1000. When thinning redwood, a narrower density management zone is probably advisable in most cases because thinning from 0.55 to 0.15 *RD* involves removing 73% of the growing stock. This intensity of treatment leaves ample growing space available for brush and is expected to result in transformation to multiaged silviculture by regenerating a vigorous new age class of redwood (Berrill and O'Hara 2009; Berrill et al. 2018b).

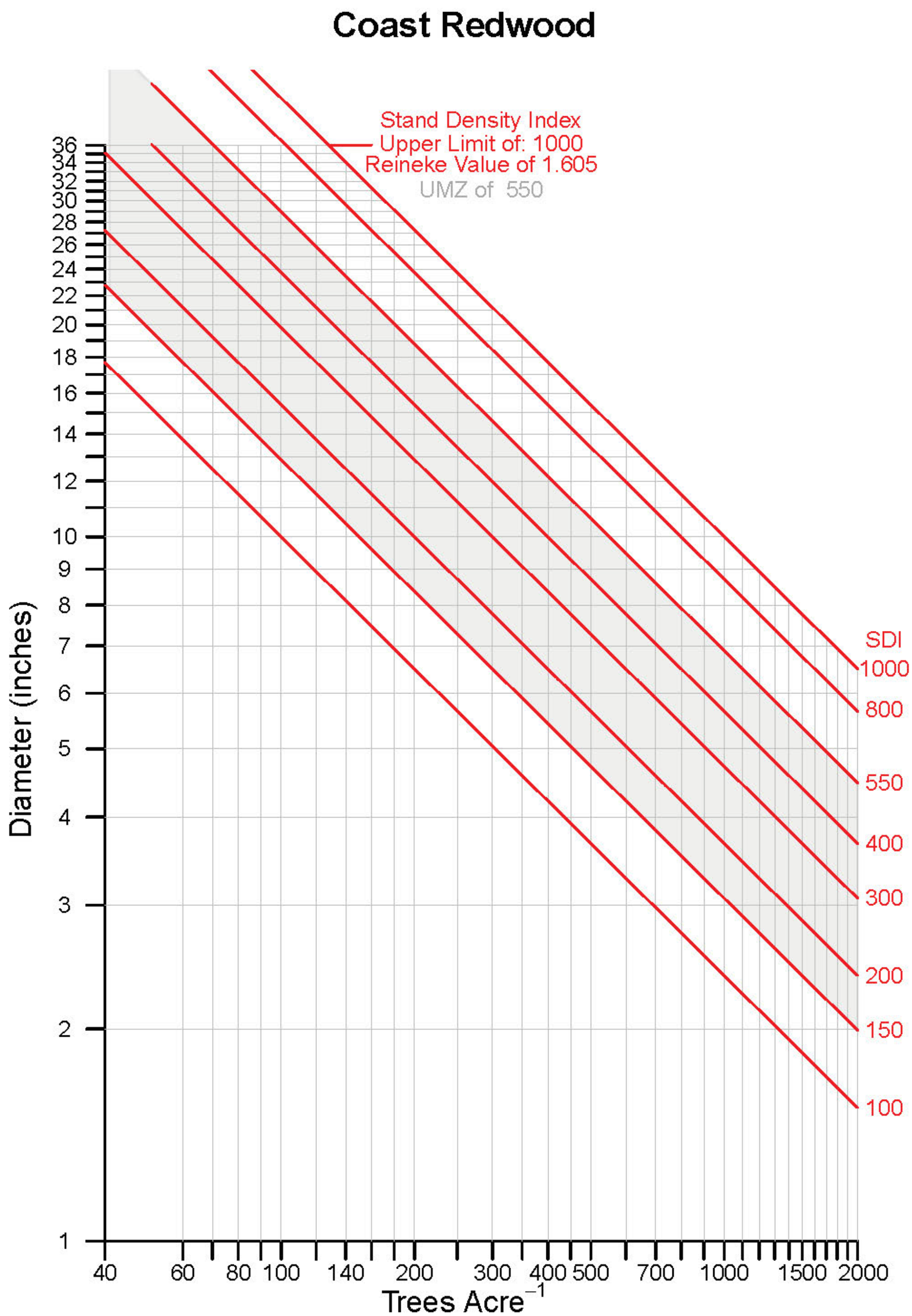

Figure 10.8 Density management diagram for coast redwood forests derived from Reineke (1933) with management zone from Drew and Flewelling (1979).

PCT in California's Eastside Forests

Forests east of the crest of the Cascades or Sierras are drier and colder than westside forests. These eastside forests generally have less than 25 inches total precipitation per year. Due to shorter growing seasons and limited water, forests are less productive than those found in other regions of the state. In an investigation of site classification (Dunning 1942), about 75% of the eastside forests were classified as low in site quality, and average net growth was 104 BF Scribner per acre per year (Bolsinger 1983).

One consideration for precommercial thinning is that rates of slash decomposition are generally slower than those on warmer, wetter sites in California. Thus slash loading is a pressing concern because elevated slash levels will reside longer, producing elevated fire hazard for a longer period of time. Delays in precommercial thinning activity should be avoided so as to minimize the amount of slash and the size of material to be left after PCT. Should PCT be delayed for some reason, it may be necessary to consider slash mitigation measures.

Existing guidelines for PCT in eastside forests dominated by ponderosa pine are few and dated to a period when planting densities tended to be higher. Barrett (1979) reported that even heavy PCT (reduction of 65% *BA*) produced remarkably high volume growth compared to much lighter thinning in central Oregon. Cochran (1983) recommended PCT to 120 *TPA* on a low quality site. Oliver and Trask (1983) found that ponderosa pine responded well after thinning even in stagnated stands. Cochran and Barrett (1999a) in evaluating a spacing study in central Oregon, suggested *TPA* less than 246 for an assumed upper limit of *SDI*=270. This guideline was recommended to minimize long-term risk of mountain pine beetle mortality whereas Cochran and Barrett (1999b) suggested *TPA*=134 (18-foot spacing) for maximizing tree diameter growth.

Density Management of Eastside Forests

Commonly on these dry eastside forests, management efforts focus on ponderosa and Jeffrey pine. Guidelines for management of stand density can vary. Differences among published values for the ponderosa pine *UMZ* (e.g. Table 10.4) serve as a reminder that the *UMZ* is an estimated guideline, not an exact rule; it may also vary dependent on specific management objectives.

Table 10.4 Published upper limit of the management zone for ponderosa pine, with exponent rounded to two decimal places; note some of these are site index (*SI*) dependent with lower SI_{100} (base age 100 years) having a lower stand density index (*SDI*) limit for management; *SI* from Barrett (1978).

Citation	*SDI* Management Limit	Exponent
Oliver (1995)	230	1.77
Edminster (1988)	270	1.66
Long and Shaw (2005)	250	1.60
Cochran et al. (1994)	124 at SI_{100}=70	1.77
Cochran et al. (1994)	161 at SI_{100}=80	1.77
Cochran et al. (1994)	197 at SI_{100}=90	1.77
Cochran et al. (1994)	234 at SI_{100}=100	1.77
Cochran et al. (1994)	270 at SI_{100}=110+	1.77
Cochran and Barrett (1999a)	240-270 at SI_{100}=110	1.77

Cochran et al. (1994) suggest that for poor sites the UMZ should be adjusted as a function of site index, with lower site index being associated with lower target values for the management zone. Consideration of this would necessarily lead one to adjust precommercial thinnings as well because the value assumed for the *UMZ* influences tree retention at PCT. These adjustments of density as a function of site are related to concepts of stockability on marginally productive sites.

As an example application of this figure, suppose that a stand with 300 *TPA* has a PCT at a *QMD* of 3 inches removing 165 *TPA* resulting in an increase in the *QMD* to 3.5 inches (Figure 10.9). This is then followed by a commercial entry when the stand reaches 15 inches (at a dominant height of about 60 feet). At this point the stand will have reached a *UMZ* of 250. The thinning at this point takes the stand back to 79 *TPA* and increases *QMD* to 17 inches, removing approximately 1000 ft^3 $acre^{-1}$ (from 4000 to 3000). Now this thinning from below means that the smaller trees removed will primarily be smaller than the *QMD* of 15 inches. If future market conditions are not favorable or if these trees are too small for a CT, then the landowner will need to wait for a period of time during which some density-related mortality may be experienced as the stand grows past the *UMZ*. Alternatively, a lighter PCT taking the stand back to 200 *TPA* instead of 135 would require a much earlier CT at a smaller *QMD*. A heavier PCT would leave fewer trees that could grow larger before needing to be harvested or becoming overcrowded if *SDI* exceeds the *UMZ*.

In drier, less productive, stands the time between PCT and the first commercial entry will be considerably longer than would be encountered on more productive sites meaning that the return on investment expressed as a net present value is reduced. This means decisions about PCT, or any early cultural treatments during stand establishment can have great impact on profitability. So cost saving efforts early are critical. So on low productive sites, lower planting densities that reduce or eliminate PCT costs should be seriously considered.

It is worth noting that planning based on future CT requires assumptions about the *QMD* associated with a commercially viable timber sale. The assumption of a target tree size comes with some uncertainty. For example, Webster and Fredrickson (2005) recommended a minimum *QMD* of 14 inches for a CT in ponderosa pine. However, fluctuations in market conditions, improvements in milling technology, or even changes in the regulatory environment, could move the minimum tree size that defines a commercial thin.

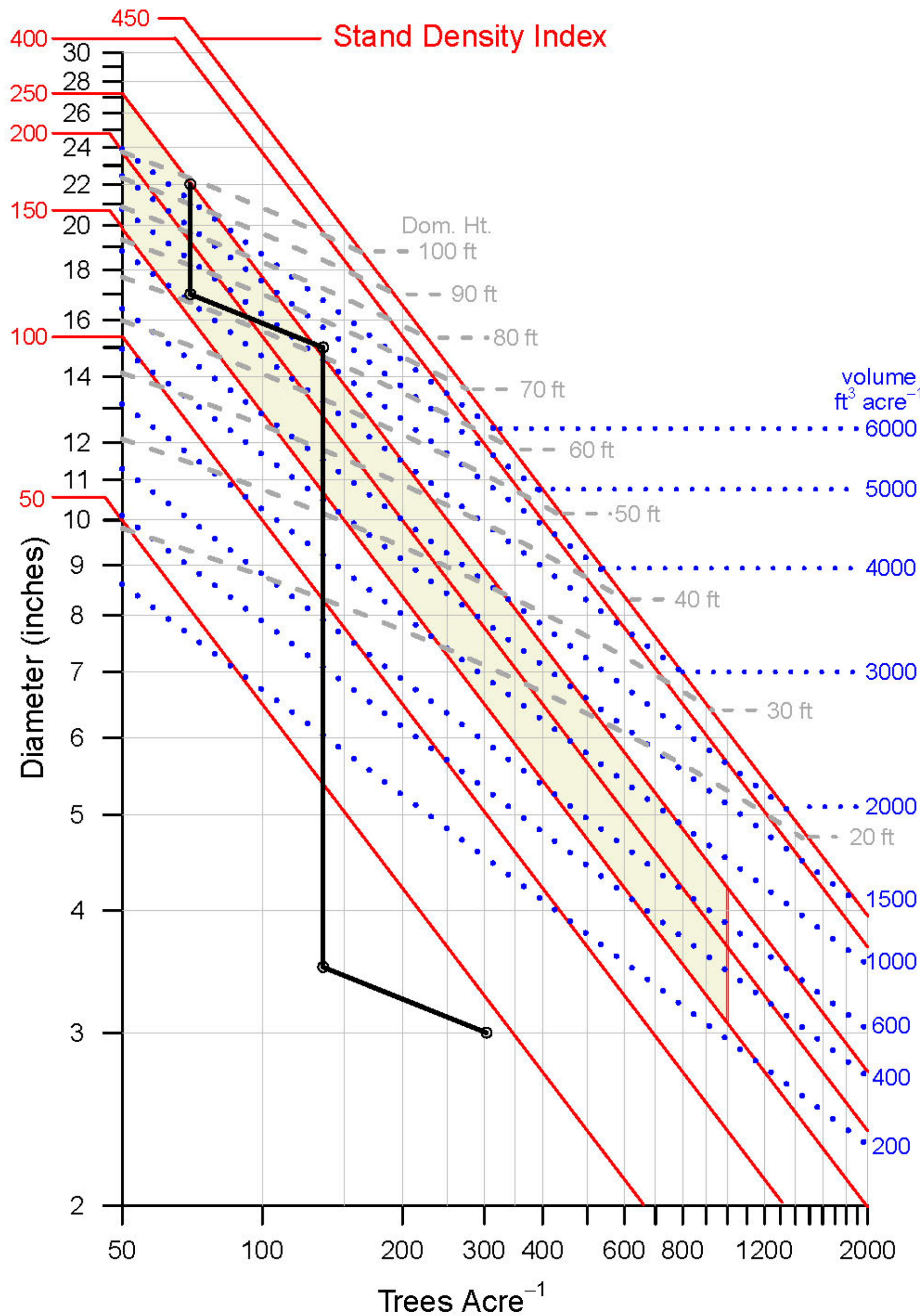

Figure 10.9 Example for ponderosa pine density management diagram from Long and Shaw (2005) with a PCT at 3 inches QMD to 135 TPA, followed by a commercial thin at QMD of 15 inches; estimated volume for commercial thin of ~1000 ft^3 ac^{-1}.

PCT in California's Sierra Nevada and Southern Cascades

In contrast to eastside forests, the mixed conifer forests west of the crest are generally more productive and have greater conifer diversity. Because of greater species diversity, considerations of optimal species mix for planting and retention with PCT become more important.

Managed stands in this range are often comprised of a mix of conifers and hardwoods, most notably black oak (*Quercus kelloggii*) with older plantations dominated by ponderosa pine and Douglas-fir. More recent plantations may include other conifer species in the mix (sugar pine (*Pinus lambertiana*), incense-cedar (*Calocedrus decurrens*), white fir and occasionally giant sequoia (*Sequoiadendron giganteum*), as management philosophy has shifted over time.

Research focused on precommercial thinning in the region is sparse. Some recent research has focused on the role of fire in young plantations (Bellows et al. 2016) and plant diversity (Thomas et al. 1999). Zhang et al. (2013) observed reduced mortality of pine plantations in response to thinning.

Planting practice in the California Sierra Nevada for some time has called for square spacing ranging from 12 to 14 feet, with lower planting densities sometimes used after wildfires in some areas. However, with the new California Forest Practice guidelines allowing lower stocking levels after harvest operations, this is likely to shift toward wider spacing. These wider planting densities after harvest operations on private ground will reduce or in some cases eliminate the need to thin precommercially. This will reduce costs of planting and thinning as well as reduce slash from PCT.

With improved planting stock and vegetation control, survival and growth in plantations has improved over time. This has allowed for dominance and favorable genetic characteristics to be revealed at an earlier age. In the California Sierra Nevada, plantations with heavy components of ponderosa pine are often thinned between 5 and 7 years of age; with mixed species plantations this may be slightly later. Note that there are no guidelines for post fire artificial regeneration, so PCT may not be needed after planting at wide spacing, or it may be needed early in dense patches of natural regeneration.

Density Management of Sierra-Cascades Mixed Conifers

This mix of species necessarily complicates density management since the particular species mix can vary considerably within the region and by ownership. Definition of an upper limit for *SDI* is problematic with any species mix. Reineke (1933) estimated the upper limit for *SDI* in California mixed conifer at about 750, but this value is considerably higher than the value of 550 that Long and Shaw (2012) derived empirically from an analysis of FIA data. Long and Shaw (2012) suggested that the upper limit for mixed-conifer *SDI* should vary dependent on species mix, with values ranging from 524 for a mix of ponderosa and sugar pine to a maximum of 671 for a mix of red fir (*Abies magnifica*) and white fir. Using this method, the actual upper limit for any given stand is a weighted value derived from the particular species mix expressed as a proportion of the stand (Table 10.5). Note that the presence of more shade tolerant species tends to raise the *SDI* upper limit and UMZ. As noted in the previous section this will tend to delay the need for *CT.* Thus the species mix chosen for a given plantation along with the presence of natural regeneration may influence the need for and timing of subsequent thinning.

Table 10.5 Two examples of *SDI* upper limit (*UL*), or limiting *SDI* calculation by taking a weighted mean for California mixed-conifer stands (source Long and Shaw 2012); PP=ponderosa pine, SP=sugar pine, DF=Douglas-fir, WF=white fir, IC=incense-cedar, RF=red fir.

Species	PP	SP	DF	WF	IC	RF	Weighted
UL:	446	561	570	634	576	768	UL
PP-WF	0.40	0.03	0.30	0.20	0.07	0.0	533
WF-RF	0.0	0.03	0.0	0.68	0.0	0.29	671

As previously described, thinning is typically prescribed when stands reach 0.55-0.6 relative density, equivalent to 55-60% of the *SDI* upper limit (*UMZ*). It coincides with the so-called self-thinning line, a value of *SDI* above which the onset of competition-induced mortality increases significantly.

Long and Shaw (2012) gave an example in mixed-conifer where full site occupancy was attained at *SDI* of 200 and then an upper limit for management (onset of self-thinning) was assumed to be at about *SDI* of 300 (Figure 10.10). As an example, if implementing a PCT in a stand with 400 *TPA* at a *QMD* of 3 inches, resulting in a *TPA* of 200 and 4 inches, and assuming minimal mortality thereafter, the stand will reach a *QMD* of 11 inches and *SDI* of about 230. According to this *DMD* (Figure 10.10), the dominant height is about 70 feet at this point. If the site index is 100, then this point will come at about age 35. For site index 80, that point is arrived at about age 45. So if a *QMD* of 11 inches is sufficient for a CT, then a thinning could be possible at this point. There is little risk of mortality since the stand at this point is well below the upper limit for management (300 *SDI*), however it would appear that a PCT to 200 *TPA* may too excessive (i.e., not enough *TPA* retained) if the goal were for CT at *QMD* 11 inches. More volume would be available for CT if the PCT retained 250 *TPA* and the CT could still take place at *QMD* of 11 inches without exceeding the upper limit of 300 *SDI*. If the proposed CT cut down to 150 *TPA* proportional across size-classes (i.e, non-discriminatory row or geometric thinning to leave *QMD* unchanged), then shifting the PCT from 200 to 250 *TPA* resulted in an approximate increase in CT harvest volume from 715 to 1460 ft^3/ac. Thus, CT volume would be doubled in this scenario.

These examples demonstrate how decisions on timing and intensity of PCT can influence the future growth trajectory and future commercial harvests. Site quality should also be considered because optimal PCT age is reached earlier on better sites where height and *DBH* growth is faster. A basic prescription for a Sierra Nevada conifer plantations on medium to high site ground is: plant at 13×13 ft spacing, then PCT to 18×18 at year 6-7, then CT to 28×28 at year 25-30, then let grow to final rotation or subsequent thinning entries. This prescription was developed using the G-space model (Cavallero 1990; Ritchie 1999) which derives thinning schedules using principles of stand density management described above (Mark Gray, personal communication). On poorer sites with slower growth, the thinning would be delayed while on better sites the thinning would be implemented earlier to achieve the desired goal of maximizing growth on high quality trees. Because true fir plantations can thrive at higher stocking levels, a suggested prescription using the G-space model would call for planting at 11x11 ft spacing followed by PCT to 16×16 ft at year 10, then some time later CT to 22×22 and grow to rotation or extend the time until final harvest by implementing a second CT to 31×31 ft average spacing (Mark Gray, personal communication).

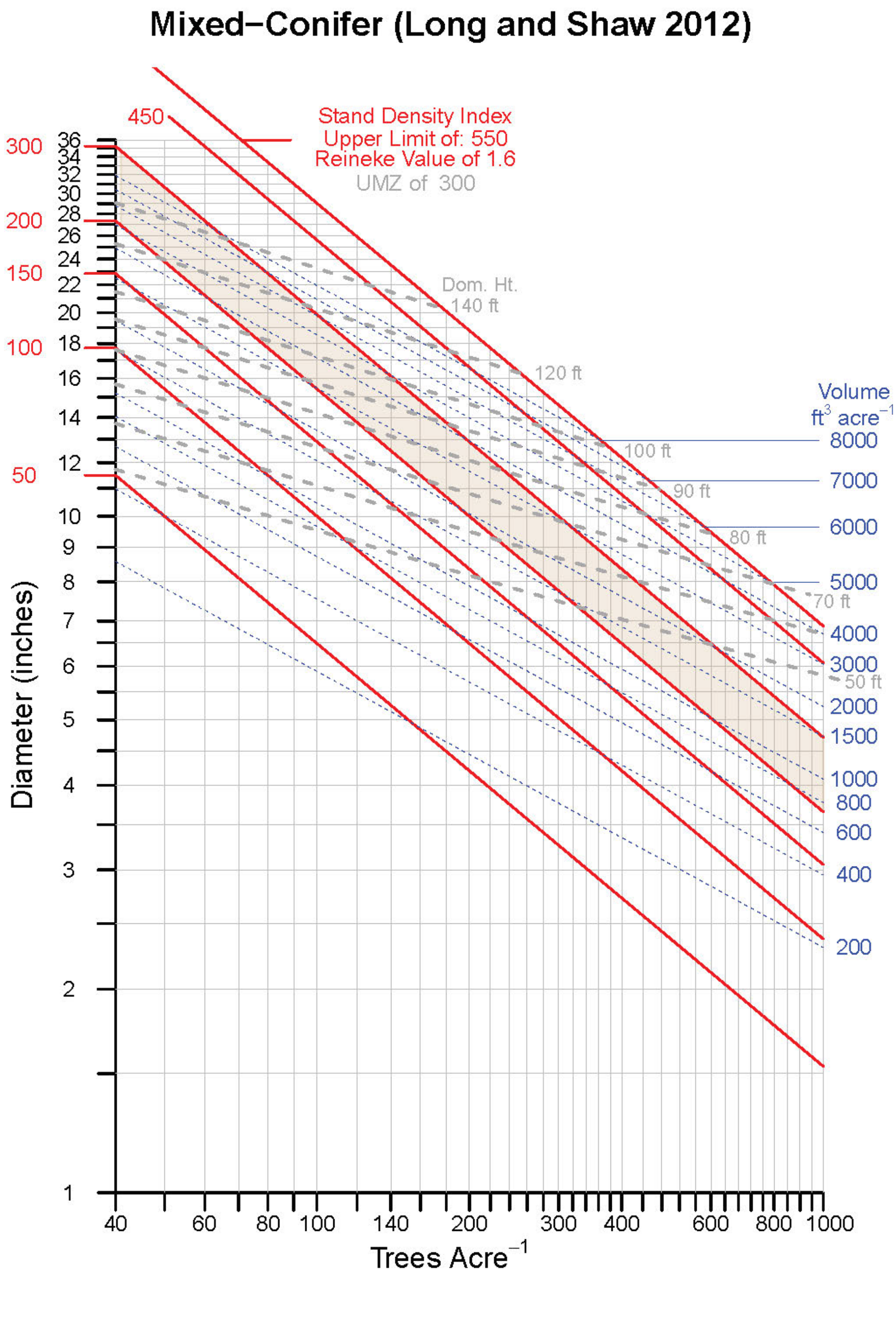

Figure 10.10 Density management diagram for California mixed-conifer forests derived from Long and Shaw (2012).

Summary

The need for PCT is driven by planting density. If we plant fewer trees, the need for PCT may be eliminated. The most current (2020) California Forest Practice rules have reduced stocking requirements and provide for greater decision space in this regard. When managing toward wider tree spacing, effective management of competing vegetation becomes even more critical, as nature will often attempt to fill that space with competing vegetation that will lower tree growth rates and increase fuel loading.

PCT leads to stand improvement by culling less desirable trees, but properly identifying favorable trees early in stand development may be problematic. Delaying PCT will increase the cost of thinning and increase fuel on the forest floor, but may be desirable in some situations, (e.g., waiting for canopy closure to shade out weeds, or where we expect bears to damage young trees growing rapidly after PCT, or in markets where lumber with narrow growth rings or smaller knots commands a premium price). We provided information and guidelines to support the manager's decision making, but these are not hard-and-fast rules. Tradeoffs abound in the manager's PCT decision space. If the objectives of management are to maintain wide spacing between trees (e.g., to reduce drought stress or fire hazard), this is achieved by adopting lower density targets (*UMZ*). Higher rates of tree growth will be sustained due to reduced competition, and the trees may better resist insect attack, but wood production on a per-acre basis will be sacrificed.

Conversely, allowing stands to surpass relative densities of 0.55-0.6 is expected to enhance wood production per acre, but with elevated tree mortality. This could prolong the time taken for trees to reach merchantable size and put the crowded stand at greater risk of stand-replacing fire, or forest health problems from reduced tree vigor; self-thinning will ensue as competition intensifies.

The environment in which thinning takes place is dynamic in many respects. Technological improvements providing for better seedling quality or tools and techniques that enhance early growth and survival of planted stands may influence the need for PCT. By the same token, changing market conditions or shifts in the regulatory environment could impact all phases of forest regeneration and it is difficult to anticipate how that may influence decisions regarding the implementation of PCT thinning in the future. Foresters need to be attentive to such changes and current research in order to make timely and effective decisions regarding density management in California forests.

Acknowledgements

The authors wish to acknowledge helpful review comments from Herb Baldwin, Mark Gray, Craig Ostergaard, Joe Sherlock, William Stewart and anonymous reviewers.

References

Ashton, M.S., and M.J. Kelty. 2018. The Practice of Silviculture: Applied Forest Ecology. 10th Edition. John Wiley & Sons. 776 p.

Barrett, J.W. 1973. Latest results from the Pringle Falls ponderosa pine spacing study. Res. Note PNW-209. USDA For. Serv. PNW For. and Range Exp. Stn. Portland OR. 22 p.

Barrett, J.W. 1978. Height growth and site index curves for managed even-aged stands of ponderosa pine in the Pacific Northwest. Res. Pap. PNW-232. USDA For. Serv. PNW For. and Range Exp. Stn. Portland OR. 14 p.

Barrett, J.W. 1979. Silviculture of ponderosa pine in the Pacific Northwest: The state of our knowledge. Gen. Tech. Rep. PNW-97. USDA For. Serv. PNW For. and Range Exp. Stn. Portland OR. 106 p.

Barrett, J.W. 1982 Twenty-year growth of ponderosa pine saplings thinned to five spacings in central Oregon. Res. Pap. PNW-301. USDA For. Serv. PNW For. and Range Exp. Stn. Portland OR. 18 p.

Bellows, R.S., A.C. Thomson, K.J. Helmstedt, R.A. York, and M.D. Potts. 2016. Damage and mortality patterns in young mixed conifer plantations following prescribed fires in the Sierra Nevada, California. For. Ecol. Manage. 376:193-204.

Berrill, J-P., and H-S. Han. 2017. Carbon, harvest yields, and residues from restoration in a mixed forest on California's Coast Range. For. Sci. 63(1):128-136.

Berrill, J-P., and R.A. Howe. 2019. Multiaged redwood responds well to partial harvest and herbicide treatments. Can. J. For. Res. 49(11):1425-1433.

Berrill, J-P., and K.L. O'Hara. 2007. Patterns of leaf area and growth efficiency in young even-aged and multiaged coast redwood stands. Can. J. For. Res. 37(3):617-626.

Berrill, J-P., and K.L. O'Hara. 2009. Simulating multiaged coast redwood stand development: Interactions between regeneration, structure, and productivity. West. J. Appl. For. 24(1):24-32.

Berrill, J-P., and K.L. O'Hara. 2014. Estimating site productivity in irregular stand structures by indexing basal area or volume increment of the dominant species. Can. J. For. Res. 44(1):92-100.

Berrill, J-P., and K.L. O'Hara. 2015. Spatial variation in dominant height and basal area development in a coast redwood forest: implications for inventory and modeling. J. Biodiv. Manage. and For. 4(4):1-6.

Berrill, J-P., and K.L. O'Hara. 2016. How do biophysical factors contribute to height and basal area development in a mixed multiaged coast redwood stand? Forestry 89:170–181.

Berrill, J-P., J.L. Jeffress, and J.M. Engle. 2012. Coast redwood live crown and sapwood dynamics. Pp. 473-484 in Standiford, R.B.; Weller, T.J.; Piirto, D.D.; Stuart, J.D. (Tech. Coords.). Proc. of Coast redwood forests in a changing California: a symposium for scientists and managers. Gen. Tech. Rep. PSW-GTR-238. USDA For. Serv. PSW Res. Stn. Albany, CA. 675 p.

Berrill, J-P., C.B. Beal, D.H. Lafever, and C.M. Dagley. 2013. Modeling young stand development towards the old-growth reference condition in evergreen mixed-conifer stands at Headwaters Forest Reserve, California. Forests 4(2):455–470.

Berrill, J-P., D.W. Perry, L.W. Breshears, and G.E. Gradillas. 2017. Tree size, growth, and anatomical factors associated with bear damage in young coast redwood. Pp. 326-328 *In:* Standiford, R.B., and Y. Valachovic (Tech. Coords.). Proceedings of coast redwood science symposium—2016: Past successes and future direction. Gen. Tech. Rep. PSW-GTR-258. USDA For. Serv. PSW Res. Stn. Albany, CA. 446 p.

Berrill J-P., Dagley, C.M., Gorman, A.J., Obeidy, C.S., Powell, H.K., and J.C. Wright. 2018a. Variable-density retention promotes spatial heterogeneity and structural complexity in a Douglas-fir/tanoak stand. Current Trends in Forest Research. CTFR-108 DOI: 10.29011/CTFR-108. 100008.

Berrill, J-P., Schneider, K.A., Dagley, C.M., and L.A. Webb. 2018b. Understory light predicts stump sprout growth in mixed multiaged stands in north coastal California. New Forests 49(6):815–828.

Biging, G.S. 1985. Improved estimates of site index curves using a varying-parameter model. For. Sci. 31:248-259.

Boe, K.N. 1974. Thinning promotes growth of sprouts on old-growth redwood stumps. Res. Note PSW-290. USDA For. Serv. PSW For. and Range Exp. Stn. Berkeley, CA. 5 p.

Bolsinger, C.L. 1983. An overview of forest resources and trends in the eastside pine type of California. Pp 29-38 *In*: Robson, T.F., and R.B. Standiford (Editors). Management of the eastside pine type in northeastern California. Proceedings of a Symposium June 15-17 1982. SAF-83-06, Northern California Society of American Foresters.

Briggs, D.G., R. Kantavichai, and E.C. Turnblom. 2008. Effect of precommercial thinning followed by a fertilization regime on branch diameter in coastal United States Douglas-fir plantations. Can. J. For. Res. 38:1564-1575.

Brix, H. 1981. Effects of thinning and nitrogen fertilization on branch and foliage production in Douglas-fir. Can. J. For. Res. 11:502-511.

Busse, M.D., P.H. Cochran, W.E. Hopkins, W.H. Johnson, G.M. Riegel, G.O. Fiddler, A.W. Ratcliff, and C.J. Shestak. 2009. Developing resilient ponderosa pine forests with mechanical thinning and prescribed fire in central Oregon’s pumice region. Can. J. For. Res. 39:1171-1185.

California Department of Forestry and Fire Protection. 2020. California Forest Practice Act Rules. Title 14 California Code of Regulations Chapters 4, 4.5 and 10.

Carlton, D.W., and S.G. Pickford 1982. Fuelbed changes with aging of slash from ponderosa pine thinnings. J. For. 80:91-107.

Cavallaro, J. 1990. An organismal level process model for simulating tree and stand growth responses to thinning. Pp. 207-216 *In*: Wensel, L.C., and G.S. Biging (Technical Editors). Forest simulation systems, proceedings of the IUFRO conference; 1988 November 2-5; Berkeley CA. Bulletin 1927 Division of Agriculture and Natural Resources, University of California.

Cochran, P.H. 1983. Implications of site quality for eastside ponderosa pine. Pp. 59-65 *In*: Robson, T.F., and R.B. Standiford (Editors). Management of the eastside pine type in northeastern California. Proceedings of a Symposium June 15-17 1982. SAF-83-06, Northern California Society of American Foresters.

Cochran, P.H. 1992. Stocking levels and underlying assumptions for uneven-aged ponderosa pine stands. Res. Note PNW-RN-509. USDA Forest Service PNW Res. Stn. Portland OR. 10 p.

Cochran, P.H., and J.W. Barrett. 1995. Growth and mortality of ponderosa pine poles thinned to various densities in the Blue Mountains of Oregon. Res. Pap. PNW-RP-483. USDA For. Serv. PNW Res. Stn. Portland OR. 27 p.

Cochran, P.H. and J.W. Barrett. 1999(a). Thirty-five year growth of ponderosa pine saplings in response to thinning and understory removal. Res. Pap. PNW-RP-512. USDA For. Serv. PNW Res. Stn. Portland OR. 28 p.

Cochran, P.H., and J.W. Barrett. 1999(b). Growth of ponderosa pine thinned to different stocking levels in central Oregon: 30-year results. Res. Pap. PNW-RP-508. USDA For. Serv. PNW Res. Stn. Portland, OR. 27 p.

Cochran, P.H., J.M. Geist, D.L. Clemens, R.R. Clausnitzer, and D.C. Powell. 1994. Suggested stocking levels for forest stands in northeastern Oregon and southeastern Washington. Res. Note PNW-RN-513. USDA For. Serv. PNW Res. Stn. Portland, OR. 21 p.

Cochran, P.H., J.W. Jennings, and C.T. Youngberg. 1984. Biomass estimators for thinned second-growth ponderosa pine trees. Res. Note PNW-415. USDA For. Serv. PNW Res. Stn. Portland, OR. 6 p.

Cole, D.W. 1983. Redwood sprout growth 3 decades after thinning. J. For. 81(3):148–150,157.

Curtis, R.O. 1994. Some simulation estimates of mean annual increment of Douglas-fir: Results, limitations, and implications for management. Res. Pap. PNW-RP-471. USDA For. Serv. PNW Res. Stn. Portland, OR. 27 p.

Curtis, R.O. 1995. Extended rotations and culmination of age of coast Douglas-fir: Old studies speak to current issues. Res. Pap. PNW-RP-485. USDA For. Serv. PNW Res. Stn. Portland, OR. 49 p.

Curtis, R.O. 2010. Effect of diameter limits and stand structure on relative density indices: A case study. West. J. of Appl. For. 25:169-175.

Curtis, R.O., B. Sheel, and C.A. Harrington. 2016. Relation of initial spacing and relative stand density indices to stand characteristics in a Douglas-fir plantation spacing trial. Res. Pap. PNW-RP-607. USDA For. Serv. PNW Res. Stn. Portland, OR. 27 p.

Dagley, C.M., J-P. Berrill, F.J. Johnson, and L.P. Kerhoulas. 2017. Adaptation to climate change? moving coast redwood seedlings northward and inland. Pp. 219-228 *In:* Standiford, R.B., and Y. Valachovic (Tech. Coords.). Proceedings of coast redwood science symposium—2016: Past successes and future direction. Gen. Tech. Rep. PSW-GTR-258. USDA For. Serv. PSW Res. Stn. Albany, CA. 446 p.

Dagley, C.M., J-P. Berrill, L.P. Leonard, and Y.G. Kim. 2018. Restoration thinning enhances growth and diversity in mixed redwood/Douglas-fir stands in northern California, USA. Restoration Ecol. 26(6):1170-1179.

DeBell, D.S., C.A. Harrington, and J. Shumway. 2002. Thinning shock and response to fertilizer less than expected in young Douglas-fir stand at Wind River Experimental Forest. Res. Pap. PNW-RP-547. USDA For. Serv. PNW Res. Stn. 20 p.

DeMars, D.J., and J.W. Barrett. 1987. Ponderosa pine managed-yield simulator: PPSIM users guide. Gen. Tech. Rep. PNW-GTR-203, USDA For. Serv. PNW Res. Stn. Portland, OR. 36 p.

Drew, T.J., and J.W. Flewelling. 1979. Stand density management: An alternative approach and its application to Douglas-fir plantations. For. Sci. 25:518-532.

Dunning, D. 1942. A site classification for the mixed-conifer selection forests of the Sierra Nevada. Res. Note 28. USDA For. Serv. California For. and Range Exp. Stn. Berkeley, CA. 21 p.

Echols, R.M. 1972. Patterns of wood density distribution and growth rate in ponderosa pine. Pp. H1-H15 *In:* Symposium on the effect of growth acceleration on the properties of wood. USDA For. Serv. Wood Products Laboratory. Madison WI.

Edminster, C.B. 1988. Stand density and stocking in even-aged ponderosa pine stands. P. 253-259 *In*: Baumgartner, D.M., and J.E. Lotan (Editors). Ponderosa pine the species and its management. Washington State University Cooperative Extension, Pullman WA.

Egan, J.M., W.R. Jacobi, J.F. Negron, S.L. Smith, and D.R. Cluck. 2010. Forest thinning and subsequent bark beetle-caused mortality in northeastern California. For. Ecol. Manage. 260:1832-1842.

Espinosa-Bancalari, M., and D. Perry. 1987. Distribution and increment of biomass in adjacent young Douglas-fir stands with different early growth rates. Can. J. For. Res. 17:722-730.

Ferguson, D.E., J.C. Byrne, W.R. Wykoff, B. Kummet, and T. Hensold. 2011. Response of ponderosa pine stands to precommercial thinning on Nez Perce and Spokane Tribal Forests in the inland northwest, USA. Res. Pap. RMRS-RP-88. USDA For. Serv. Rocky Mtn. Res. St. Fort Collins CO. 33 p.

Fettig, C.J., J.D. McMillin, J.A. Anhold, S.M. Hamud, R.R. Borys, C.P. Dabney, and S.J. Seybold. 2006. The effects of mechanical fuel reduction treatments on the activity of bark beetles (*Coleoptera*: *Scolytidae*) infesting ponderosa pine. For. Ecol. Manage. 230:55-68.

Fettig, C.J., K.D. Klepzig, R.F. Billings, A.S. Munson, T.E. Nebeker, J.F. Negrón, and J.T. Nowak. 2007. The effectiveness of vegetation management practices for prevention and control of bark beetle infestations in coniferous forests of the western and southern United States. For. Ecol. Manage. 238:24-53.

Filip, G.M. J.J. Bronson, K.L. Chadwick, J.B. Filip, S.J. Frankel, D.J. Goheen, E.M. Goheen, S.R. Mori, and A.L. Saavedra. 2015. Precommercial thinning in mixed-species conifer plantations affected by *Armillaria* and *Heterobasidion* root diseases in west-central Oregon and Washington: 30-year results. For. Sci. 61:914-925.

Filip, G.M., K.L. Chadwick, S.A. Fitzgerald, and T.A. Max. 2009. Thinning ponderosa pine affected by *Armillaria* root disease: 40 years of growth and mortality in central Oregon. West. J. Appl. For. 24:99-94.

Filip, G.M., and D.J. Goheen. 1995. Precommercial thinning in *Pseudotsuga*, *Tsuga* and *Abies* stands affected by armillaria root disease: 10-year results. Can. J. For Res. 25:817-823.

Filipescu, C.N., E.C. Lowell, R. Koppenaal, and A.K. Mitchell. 2014. Modeling regional and climatic variation of wood density and ring width in intensively managed Douglas-fir. Can. J. For. Res. 44:220-229.

Flewelling, J.W. and T.J. Drew. 1985. A stand density management diagram for lodgepole pine. *In:* Baumgartner, D.M., R.G. Krebill, J.T. Arnott, and G.F. Weetman (Editors). Lodgepole pine: the species and its management. Washington State University Cooperative Extension.

Giusti, G.A. 1990. Black bear feeding on second growth redwoods: A critical assessment. Pp. 214–217 *In*: Davis, L.R., and R.E. Marsh (Editors). Proceedings of the 14th vertebrate pest conference.. University of California—Davis, CA.

Glebocki, R. 2015. Fuel loading and moisture dynamics in thinned coast redwood – Douglas-fir forests in Headwaters Forest Reserve, California. M.Sc. thesis, Humboldt State University, Arcata, California. 95 p.

Goheen, D.J., and E.M. Hansen. 1993. Effects of pathogens and bark beetles on forests. Pp. 175-196 *In:* T.D. Schowalter, and G.M. Filip (Editors). Beetle-pathogen interactions in conifer forests. Academic Press, London.

Graham, R.T., A.E. Harvey, T.B. Jain, and J.R. Tonn. 1999. The effects of thinning and similar stand treatments on fire behavior in western forests. Gen. Tech. Rep. PNW-GTR-463. USDA For. Serv. PNW Res. Stn. Portland, OR. 27 p.

Harrington, C.A. and D.L. Reukema. 1983. Initial shock and long-term stand development following thinning in a Douglas-fir plantation. For. Sci. 29:33-46.

Harrington, T.C., C. Reinhart, D.A. Thornburgh, and F.W. Cobb Jr. 1983. Association of black-stain root disease with precommercial thinning of Douglas-fir. For. Sci. 29:12-14.

Harrington, T.C., and J.C. Tappeiner. 2009. Long-term effects of tanoak competition on Douglas-fir stand development. Can. J. For. Res. 39(4):765-776.

Helms, J.A. 1998. The dictionary of forestry. Society of American Foresters. Bethesda. MD. 210 p.

Hessburg, P.F., D.J. Goheen, and H. Koester. 2001. Association of black stain root disease with roads, skid trails and precommercial thinning in southwestern Oregon. West. J. Appl. For. 16:127-135.

Hosack, D.A., and K.O. Fulgham. 1998. Black bear damage to regenerating conifers in Northwestern California. J. Wildl. Res. 1(1):32-37.

Jain, T.B., M.A. Battaglia, H-S. Han, R.T. Graham, and C.R. Keyes. 2012. A comprehensive guide to fuel management practices for dry mixed conifer forests in the northwestern United States. USDA Forest Service, General Technical Report RMRS-GTR-292.

Jameson, M.J., and T.A. Robards. 2007. Coast redwood regeneration survival and growth in Mendocino County, California. West. J. Appl. For. 22(3):171–175.

Jozsa, L.A., and H. Brix. 1989. The effects of fertilization and thinning on wood quality of a 24–year-old Douglas-fir stand. Can. J. For. Res. 19:1137-1145.

Kegley, S.J., R.L. Livingston, and K.E. Gibson. 1997. Pine engraver, *Ips pini* (Say) in the western United States. Forest Insect and Disease Leaflet 122. USDA, For. Serv.

Keyes, C.R., and K.L. O'Hara. 2002. Quantifying stand targets for silvicultural prevention of crown fires. West. J. Appl. For. 17(2):101–109.

Keyes, C.R., P.J. Matzka, K.C. Wright, R. Glebocki, and H.S. Han. 2008. Early precommercial thinning of redwood sprout clumps: Evaluation of four techniques. Int. J. For. Eng. 19(2):28–36.

Kirk, C., and J-P. Berrill. 2016. Second-log branching in multiaged redwood and Douglas-fir: influence of stand, site, and silviculture. Forests 7(147):1-15.

Krieger, R.M.; Wall, B.E.; Kidd, C.W.; Berrill, J-P. 2020. Chronosequence of fuel loading and fuel depth following forest rehabilitation frill treatment of tanoak to release Douglas-fir: a case study from northern California. Forests 2020, 11(6), 691; https://doi.org/10.3390/f11060691

Larsson, S., R. Oren, R.H. Waring, and J.W. Barrett. 1983. Attacks of mountain pine beetle as related to tree vigor of ponderosa pine. For. Sci. 29:395-402.

Leonard, L.P., Berrill, J-P., and C.M. Dagley. 2017. Ecosystem responses to variable-density thinning for forest restoration in Mill Creek. P. 287-290 *In:* Standiford, R.B., and Y. Valachovic (Tech. Coords.). Proceedings of coast redwood science symposium—2016: Past successes and future direction. Gen. Tech. Rep. PSW-GTR-258. USDA For. Serv. PSW Res. Stn. Albany, CA. 446 p.

Lindquist, J.L. 2004. Precommercial stocking control of coast redwood: A seventeen-year status report (1981–1998). Calif. For. Rep. No. 2, Sacramento, CA. 24 p.

Lindquist, J. 2007. Precommercial stocking control of coast redwood at Caspar Creek, Jackson Demonstration State Forest. Pp. 295–304 *In:* Standiford, R.B., G.A. Giusti, Y. Valachovic, W.J. Zielinski, and M.J. Furniss (Editors). Proceedings of the redwood region forest. Science symposium: What does the future hold?. Gen. Tech. Rep. PSW-GTR-194. USDA For. Serv. PSW Res. Stn. Albany, CA.

Long, J.N. 1985. A practical approach to density management. For. Chron. 61(1):23–27.

Long, J.N., and T.W. Daniel. 1990. Assessment of growing stock in uneven-aged stands. West. J. of Appl. For. 5:93-96.

Long, J.N., and J.D. Shaw. 2005. A density management diagram for even-aged ponderosa pine stands. West. J. Appl. For. 20:205-215.

Long, J.N., and J.D. Shaw. 2012. A density management diagram for even-aged Sierra Nevada mixed-conifer stands. West. J. of Appl. For. 27:187-195.

Maguire, D.A., J.A. Kershaw, and D.W. Hann. 1991. Predicting the effects of silvicultural regime on branch size and crown wood core in Douglas-fir. For. Sci. 37:1409–1428.

Markstrom, D.C., H.E. Troxell, and C.E. Boldt. 1983. Wood properties of immature ponderosa pine after thinning. For. Prod. Journ. 33:333-36.

McCarter, J.B., and J.N. Long. 1986. A lodgepole pine density management diagram. West. J. Appl. For. 1:6-11.

McConnell, B.R., and J.G. Smith. 1970. Response of understory vegetation to ponderosa pine thinning in eastern Washington. J. Range Manage. 23:208-212.

Monleon, V.J., M. Newton, C. Hooper, and J.C. Tappeiner II. 1999. Ten-year growth response of young Douglas-fir to variable density varnishleaf ceanothus and herb competition. West. J. of Appl. For. 14:208-213.

Neal, R.L. Jr. 1967. Sprouting of old-growth redwood stumps—First year after logging. Res. Note PSW-137. USDA For. Serv. PSW For. and Range Exp. Stn. Berkeley, CA. 8 p.

Odhiambo, B., M. Meincken, and T. Seifert. 2014. The protective role of bark against fire damage: a comparative study on selected introduced and indigenous tree species in the Western Cape, South Africa. Trees 28:555-565.

O'Hara, K.L. 2012. Coast redwood responses to pruning. Pp. 529-538 *In:* Standiford, R.B., T.J. Weller, D.D. Piirto, and J.D. Stuart (Tech. Coords.). Proc. of coast redwood forests in a changing California: a symposium for scientists and managers. Gen. Tech. Rep. PSW-GTR-238. USDA For. Serv. PSW Res. Stn. Albany, CA. 675 p.

O'Hara K.L., and J-P. Berrill. 2009. Epicormic sprout development in pruned coast redwood: pruning severity, genotype, and sprouting characteristics. Annals For. Sci. 66(409):1-9.

O'Hara, K.L., and J-P. Berrill. 2010. Dynamics of coast redwood sprout clump development in variable light environments. J. For. Res. 15(2):131–139.

O'Hara, K.L., P.T. Stancioiu, and M.A. Spencer. 2007. Understory stump sprout development under variable canopy density and leaf area in coast redwood. For. Ecol. Manage. 244(1–3):76–85.

O'Hara, K.L., D.A. Larvik, N.I. Valappil. 1995. Pruning costs for four northern rocky mountain species with three equipment combinations. West. J. Appl. For. 10(2):59–65.

O'Hara, K.L., R.A. York, and R.C. Heald. 2008. Effect of pruning severity and timing of treatment on epicormic sprout development in giant sequoia. Forestry 81(1):103–110.

O'Hara, K.L., L.A. Grand, and A.A. Whitcomb. 2010. Pruning reduces blister rust in sugar pine with minimal effects on tree growth. California Ag. 64(1):31-36.

O'Hara, K.L., J.C.B. Nesmith, L. Leonard, and D.J. Porter. 2010. Restoration of old forest features in coast redwood forests using early stage variable-density thinning. Restoration Ecol. 18:125–135.

O'Hara, K.L., L.P. Leonard, and C.R. Keyes. 2012. Variable-density thinning and a marking paradox: Comparing prescription protocols to attain stand variability in coast redwood. West. J. Appl. For. 27(3):143–149.

O'Hara, K.L., L. Narayan, and K.G. Cahill. 2015. Twelve-year response of coast redwood to precommercial thinning treatments. For. Sci. 61(4):780-789.

Oliver, C.D., and B.C. Larson. 1996. Forest stand dynamics. Update edition. John Wiley and Sons, New York, NY.

Oliver, W.W., and R.F. Powers. 1971. Early height growth of ponderosa pine forecasts dominance in plantations. Res. Note PSW-250. USDA For. Serv. PSW Res. Stn. Berkeley CA. 5 p.

Oliver, W.W. 1979a. Fifteen-year growth patterns after thinning a ponderosa pine-Jeffrey pine plantation in northeastern California. Res. Pap. RP-PSW-141. USDA For. Serv. PSW Res. Stn. Berkeley, CA. 10 p.

Oliver, W.W. 1979b. Growth of planted ponderosa pine thinned to different stocking levels in Northern California. Res. Pap. RP-PSW-147. USDA For. Serv. PSW For. and Range Exp. Stn. Berkeley CA. 11 p.

Oliver, W.W. 1984. Brush reduces growth of thinned ponderosa pine in northern California. Res. Pap. PSW-172. USDA For. Serv. PSW For. and Range Exp. St. Berkeley, CA. 7 p.

Oliver, W.W. 1995. Is self-thinning in ponderosa pine ruled by *Dendroctonus* bark beetles? P 213-218 *In:* Proceedings of the 1995 National Silviculture Workshop. Gen. Tech. Rep. GTR-RM-267. USDA For. Serv. Rocky Mtn. Res. Stn. Fort Collins CO.

Oliver, W.W. 1997. Twenty-five-year growth and mortality of planted ponderosa pine repeatedly thinned to different stand densities in northern California. West. J. Appl. For. 12:122-130.

Oliver, W.W., J.L. Lindquist, and R.O. Strothmann. 1994. Young growth redwood stands respond well to various thinning intensities. West. J. Appl. For. 9(4):106 –112.

Oliver, W.W., and R.F. Powers. 1978. Growth models for ponderosa pine: I Yield of unthinned plantations in northern California. Research Paper PSW-133. USDA Forest Service Pacific Southwest Forest and Range Experiment Station. 21 p.

Oliver, W.W. and J. Trask. 1983. Responses of eastside pine to precommercial thinning. Pp 107-113 *In*: Robson, T.F., and R.B. Standiford (Editors). Management of the eastside pine type in northeastern California; Proceedings of a symposium. Susanville California, June 15-17, 1982. Northern California Society of American Foresters. 139 p.

Perry, D.W., L.W. Breshears, G.E. Gradillas, and J-P. Berrill. 2016. Thinning intensity and ease-of-access increase probability of bear damage in a young coast redwood forest. J. of Biodiv. Manage. and For. 5(3):1-7.

Plummer, J.F., C.R. Keyes, and J.M. Varner. 2012. Early-stage thinning for the restoration of young redwood—Douglas-fir forests in northern coastal California, USA. ISRN Ecol. doi:10.5402/2012/725827.

Pollet, J., and P.N. Omi. 2002. Effect of thinning and prescribed burning on crown fire severity in ponderosa pine forests. Int. J. of Wildl. Fire 11:1-10.

Powers, E.M., J.D. Marshall, J. Zhang, and L. Wei. 2013. Post-fire management regimes affect carbon sequestration and storage in a Sierra Nevada mixed-conifer forest. For. Ecol. Manage. 291:268-277.

Powers, R.F. and W.W. Oliver. 1970. Snow breakage in a pole-sized ponderosa pine plantation… more damage at high stand densities. Res. Note PSW-218. USDA For. Serv. PSW For. and Range Exp. Stn. Berkeley CA. 3 p.

Powers, R.F., and P.E. Reynolds. 1999. Ten-year responses of ponderosa pine plantations to repeated vegetation and nutrient control along an environmental gradient. Can. J. For. Res. 29:1027-1038.

Reineke, L.H. 1933. Perfecting a stand density index for even-aged forests. J. of Ag. Res. 46:627-638.

Reukema, D.L. 1975. Guidelines for precommercial thinning of Douglas-fir. Gen. Tech. Rep. PNW-30, USDA For. Serv. PNW For. and Range Exp. Stn. Portland OR. 10 p.

Reukema, D.L., and D. Bruce. 1977. Effects of thinning on yield of Douglas-fir: concepts and some estimates obtained by simulation. Gen. Tech. Rep. PNW-58. USDA For. Serv. PNW For. and Range Exp. Stn. Portland OR. 36 p.

Ritchie, M.W. 1999. A compendium of forest growth and yield simulators for the Pacific coast states. Gen. Tech. Rep. PSW-GTR-174. USDA For. Serv. PSW Res. Stn. 59 p.

Ritchie, M.W. 2020. Relating stocking and density for natural regeneration of conifers in northern California. For. Sci. fxaa005. doi:10.1093/forsci/fxaa005.

Ritchie, M.W., and J. Zhang 2018. OP-Yield Version 1.00 user's guide. Gen. Tech. Rep. PSW-GTR-259. USDA For. Serv. PSW Res. St. Albany, CA. 26 p.

Robertson, A.S., and J.E. Dewey. 1983. Determination of western pine shoot borer incidence, impact and stand hazard rating characteristics in selected Region one National Forests. Report No. 83-10. USDA For. Serv., North. Region, State and Private Forestry.

Ryan, K.C., and E.D. Reinhardt. 1988. Predicting postfire mortality of seven western conifers. Can. J. For. Res. 18:1291-1297.

Sartwell, C. 1970. *Ips pini* attack density in ponderosa pine thinning slash as related to felling date in eastern Oregon. Res. Note PNW-131, USDA For. Serv. PNW For. and Range Exp. Stn. Portland OR. 8 p.

Sartwell, C. 1971. Thinning ponderosa pine to prevent outbreaks of mountain pine beetle. P. 41-52 *In:* Baumgartner, D.M. (Editor). Precommercial thinning of coastal and intermountain forests in the Pacific Northwest. Pullman WA. Washington State University.

Sartwell, C., and R.E. Stevens. 1975. Mountain pine beetle in ponderosa pine, prospects for silvicultural control in second-growth stands. J. For. 73:136-140.

Staebler, G.R. 1956. Evidence of shock following thinning of young Douglas-fir. J. For. 54:339.

Stein, W.I. 1978. Reforestation evaluation. Pp. 205-221 *In:* Cleary, B.D., R.D. Greaves, and R.K. Hermann (Editors). Regenerating Oregon's forests, a guide for the regeneration forester. Oregon State University Extension Service, Corvallis Oregon.

Stein, W.I. 1992. Regeneration surveys and evaluation. Pp. 346-382 *In:* Hobbs, S.D., S.D. Tesch, P.W. Owston, R.E. Stewart, J.C. Tappeiner, and G.E. Wells (Editors). Reforestation practices in southwestern Oregon and northern California. Oregon State University Forestry Research Laboratory, Corvallis Oregon.

Stephens, S.L. 1998. Evaluation of the effects of silvicultural and fuels treatments on potential fire behavior in Sierra Nevada mixed-conifer forests. For. Ecol. Manage. 105(1-3):21-35.

Talbert, C., and D. Marshall. 2005. Plantation productivity in the Douglas-fir region under intensive silvicultural practices: results from research and operations. J. For. 103:65-70.

Tappeiner, J.C. II, D.A. Maguire, and T.B. Harrington. 2007. Silviculture and ecology of western U.S. forests. Oregon State University Press, Corvallis OR.

Teraoka, J.R., and C.R. Keyes. 2011. Low thinning as a forest restoration tool at Redwood National Park. West. J. Appl. For. 26(2):91–93.

Thomas, S.C., C.B. Halpern, D.A. Falk, D.A. Liguori, and K.A. Austin. 1999. Plant diversity in managed forests: understory responses to thinning and fertilization. Ecol. App. 9:864-879.

Thornburgh, D.A., R.F. Noss, D.P. Angelides, C.M. Olson, F. Euphrat, and H.H. Welsh Jr. 2000. Managing redwoods. Pp. 229–262 *In:* Noss, R.F. (Editor). The redwood forest: History, ecology, and conservation of the coast redwoods. Island Press, Washington, DC.

Tu, M., C. Hurd, and J.M. Randall. 2001. Weed control methods handbook: tools & techniques for use in natural areas. The Nature Conservancy. Last accessed May 10 2020: https://www.invasive.org/gist/handbook.html

USDA Forest Service. 2009. A user's guide to thinning with mastication equipment. USDA Forest Service Pacific Northwest Region, Okanogan-Wenatchee National Forest. 7p.

Valachovic, Y.S., C.A. Lee, H. Scanlon, J.M. Varner, R. Glebocki, B.D. Graham, and D.M. Rizzo. 2011. Sudden oak death-caused changes to surface fuel loading and potential fire behavior in Douglas-fir-tanoak forests. For. Ecol. Manage. 261(11):1973-1986.

Webb, L.A, J.L. Lindquist, E. Wahl, and A. Hubbs. 2012. Whiskey springs long-term coast redwood density management; final growth, sprout, and yield results. Pp. 571-581 *In:* Standiford, R.B., T.J. Weller, D.D. Piirto, and J.D. Stuart. (Tech. Coords.). Proc. of Coast redwood forests in a changing California: a symposium for scientists and managers. Gen. Tech. Rep. PSW-GTR-238. USDA For. Serv. PSW Res. Stn. Albany, CA. 675 p.

Webb, L., J-P. Berrill, and J. Lindquist. 2017. Long term results of early density management of a third growth redwood stand. Pp. 267-278 *In:* Standiford, R.B., and Y. Valachovic (Tech. Coords.). Proceedings of coast redwood science symposium—2016: Past successes and future direction. Gen. Tech. Rep. PSW-GTR-258. USDA For. Serv. PSW Res. Stn. Albany, CA. 446 p.

Webster, J. 1997. Pre-commercial thinning of plantations, why, when and how? An industrial perspective for interior California. Pp. 83-87 *In:* 18th Annual forest vegetation management conference. Univ. of Cal. Coop. Ext. For. Prog.

Webster, J., and E. Fredrickson. 2005. Lessons Learned on 50,000 acres of Plantation in Northern California. Pp 267-281 *In:* Ritchie, M.W., D.A. Maguire, and A. Youngblood (Tech. Coords.) Proceedings of the symposium on ponderosa pine: issues, trends, and management, 2004 October 18-21, Klamath Falls, OR. PSW-GTR-198. USDA For Serv. PSW Res. Stn. Albany, CA. 281 p.

Weiskittel, A.R., L.S. Kenefic, R.S. Seymour, and L.M. Phillips. 2009. Long-term effects of precommercial thinning on the stem dimensions, form and branch characteristics of red spruce and balsam fir crop trees in Maine, USA. Silva Fennica 43:397-409.

Weiskittel, A.R., D.A. Maguire, and R.A. Monserud. 2007. Response of branch growth and mortality to silvicultural treatments in coastal Douglas-fir plantations: Implications for predicting tree growth. For. Ecol. Manag. 251:182–194.

White, D.E., and M. Newton. 1988. Competitive interactions of whiteleaf manzanita, herbs, Douglas-fir, and ponderosa pine in southwest Oregon. Can. J. For. Res. 19:232-238.

Wiant, H.V. Jr., and R.F. Powers. 1967. Sprouting of old-growth redwood. P. 88–90 in Proc. Soc. Am. For., 1966. Society of American Foresters, Washington, DC. 232 p.

Windell, K. 1998. Understory biomass reduction: initial report to the national fuels specialists. USDA For. Serv. Tech. and Dev. Prog. Missoula Montana. 22p.

Woodruff, W., D. Greenberg, and P. Cannon. 2019. Results of a thinning study in a black stain (*Leptographium wageneri*)-infested Jeffrey/ponderosa pine forest in northern California. For. Path. 49:e12551.

Zhang, J., W.W. Oliver, and M.D. Busse. 2006. Growth and development of ponderosa pine on sites of contrasting productivities: relative importance of stand density and shrub competition effects. Can. J. For. Res. 36:2426-2438.

Zhang, J., M.W. Ritchie, and D.A. Maguire. 2013. Thinning ponderosa pine (*Pinus ponderosa*) stands reduces mortality while maintaining stand productivity. Can. J. For. Res. 43:311-320.

Zald, H.S., A.N. Gray, M. North, and R.A. Kern. 2008. Initial tree regeneration responses to fire and thinning treatments in a Sierra Nevada mixed-conifer forest, USA. For. Ecol. Manag. 256:168-179.

Zeibig-Kichas, N.E., Ardis, C.W., Berrill, J-P., and J.P. King. 2016. Bark thickness equations for mixed-conifer forest type in Klamath and Sierra Nevada mountains of California. Int. J. For. Res., Vol. 2016, ID: 1864039, 1-10.