# Management Impacts and Developmental Patterns in Mature Douglas-fir Forests of the Pacific Northwest: An Annotated Bibliography

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## Abstract

Management direction for federal lands within the range of the northern spotted owl (*Strix occidentalis*) currently is derived from the Northwest Forest Plan Record of Decision for Amendments to Forest Service and Bureau of Land Management Planning Documents Within the Range of the Northern Spotted Owl (USDA and USDI 1994a) and Standards and Guidelines for Management of Habitat for Late-Successional and Old-Growth Forest Related Species Within the Range of the Northern Spotted Owl (USDA and USDI 1994b). The Revised Recovery Plan for the Northern Spotted Owl (USDI 2011) and Endangered and Threatened Wildlife and Plants: Designation of Revised Critical Habitat for the Northern Spotted Owl: Final Rule (USDI 2012) also provide further guidance. Federal lands in the Pacific Northwest are, or soon will be, developing new resource management plans. There is a need to identify knowledge gaps and evaluate the best available science related to key planning and management decisions to support those efforts**. One critical area of ongoing uncertainty relates to developmental outcomes associated with the application of a range of silvicultural practices in "older" stands (generically >80 years of age).** In June 2015, natural resource managers and scientists from several agencies and universities gathered to review our current understanding of management objectives, standards and guidelines, and science relevant to the management and ecology of these stands (http://ecoshare.info/projects/central-cascade-adaptive-management-partnership/workshops/ecological-economic-and-social-objectives-for-managing-stands-over-80/). This annotated bibliography was prepared to build on that workshop by providing a summary of the best available science directly related to management in older stands. We focus on summarizing papers that describe 1) disturbance ecology and stand development patterns in "natural" or unmanaged Douglas-fir forests, 2) structural development following a variety of silvicultural treatments in both younger and older Douglas-fir stands, and 3) the current state of knowledge related to multi-aged management approaches in the Douglas-fir region. The literature listed here is primarily relevant to Douglas-fir dominated stands on sites that fall into the western hemlock and grand fir series, but some conclusions also may be relevant to other systems in the Pacific Northwest.

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# Literature Summaries for Key Questions Related to the Management of "Older" Stands:

### What do we know about natural stand development patterns in "mature" forests?

Although a variety of stand development pathways appear to occur in Douglas-fir forests (Poage et al. 2009, Tepley et al. 2013, Tepley et al. 2014), we have focused here on summarizing a generalized pathway described by Franklin et al. (2002) and illustrating variability around this pathway associated with different disturbance histories and site conditions.

Early stand development in Douglas-fir forests regenerating after severe, stand-replacing fires can be described by typical, process-based stages that include an initial cohort establishment stage followed by a period in which trees overtop and exert dominance on the site as crown expansion leads to canopy closure (Franklin et al. 2002). This period of initial cohort establishment can last as little as 20-40 years for some developmental pathways (Winter et al. 2002a, Poage et al. 2009, Tepley et al. 2013), although establishment periods of 40-60 years appear to have been common (Tepley et al. 2014, Fruend et al. 2014). Even extended periods (80 years or more) of pioneer cohort establishment appear to have been relatively common in the early development of some contemporary old-growth stands (Tappeiner et al. 1997, Poage and Tappeiner 2002, Poage et al. 2009, Tepley et al. 2013). These long establishment periods appear to have been driven by varying combinations of low initial stand densities and repeated, non-stand-replacing disturbances that maintained low densities and delayed crown closure. Growth rates of pioneer Douglas-fir during these long establishment periods were typically high, and appear to contribute to rapid development of large overstory trees (Tappeiner et al. 1997, Poage and Tappeiner 2002).

Canopy closure initiates a period of rapid biomass accumulation and competitive exclusion that frequently lasts until age 80-100 years in Douglas-fir stands (Franklin et al. 2002). This is followed by a maturation stage in which tree mortality shifts from density-dependent processes to disturbance-driven processes. This maturation stage may last 100-150 years, and coincides with low levels of CWD in natural stands (Spies and Franklin 1988, Spies et al. 1988). The rate of biomass accumulation begins to taper off during the maturation phase (Acker et al. 1998a, Franklin et al. 2002), but declines in stand productivity over time are generally quite gradual in naturally-regenerated stands in this age range (Curtis 1994, 1995, Acker et al. 1998a). Vascular plant species diversity rollercoasters through the early stages of stand development. Species diversity increases rapidly after severe disturbances, peaks prior to canopy closure, then declines to its lowest levels under the dense canopies and intense levels of competition that occur during the competitive exclusion phase (Halpern et al. 1995). Some taxa characteristic of older forest conditions appear to be quite sensitive to disturbance, but most forest species persist, at least at low levels, throughout these early stages of structural development.

Following the maturation stage, natural Douglas-fir stands go through a stage of vertical diversification that contributes to significant development of old-growth structural characteristics such as increased vertical canopy continuity, development of a wide range of tree diameters, increasing numbers of large-diameter trees, increasing deadwood inputs, continuing development of large, complex branch systems, and an associated expansion of lichen and bryophyte communities (Franklin et al. 2002, Freund et al. 2015). This stage typically occurs in stands aged 200-350 years, and is characterized by significant amounts of gap-phase mortality and structural development. Shade tolerant species in stands during this "early old-growth" stage, however, are typically in somewhat lower canopy positions than in older stands (Freund et al. 2015).

Continued gap creation and expansion leads to a stage of horizontal diversification in which the stand transitions into a shifting mosaic of conditions (Franklin et al. 2002). This stage often begins when trees in the initial, pioneer cohort reach ages of 300 years or more and is characterized by high levels of vertical complexity, variability in tree size, deadwood, and horizontal patchiness, including areas of dense shade tolerant trees. The spatially heterogeneous environments found during this phase are also linked to high levels of vascular plant species diversity (Halpern et al. 1995). Douglas-fir stands may eventually enter a pioneer cohort loss stage if they remain free of disturbances with sufficient severity to regenerate a new cohort of shade intolerant species for several more centuries. Franklin et al. (2002) estimate this may take 800-1300 years in coastal Douglas-fir forests, depending on site quality.

Franklin et al's (2002) description of stand development in Douglas-fir focuses on patterns of structural development following a single, stand-replacing fire event with other minor disturbances (e.g., wind, insects, and diseases) fostering structural development thereafter. This pattern appears to have been less common than developmental pathways that include one or more non-stand-replacing fires (Weisburg 2004, Poage et al. 2009, Tepley et al. 2013). However, Franklin et al's (2002) estimates of the range of stand ages that represent the maturation stage (approximately 80-250 years) overlaps nicely with the stand ages at which understory cohorts began developing in several of the developmental pathways described in other work (Winter et al. 2002b, Poage et al. 2009, Tepley et al. 2013, Tepley et al. 2014). Thus, it seems that a large proportion of existing mature and old-growth stands that were initiated by a stand-replacing fire began experiencing non-stand-replacing disturbances (including fire, wind, pathogens, and insects) that led to episodes of understory tree establishment and associated structural development somewhere between ages 80 and 250 years. When these disturbances were more frequent or severe, multiple Douglas-fir cohorts were often present in old-growth stands, and shade tolerant species were primarily located in understory and mid-story canopy positions. When partial canopy disturbances were less frequent or lower in severity, Douglas-fir was found primarily in the pioneer cohort, and shade tolerant species were better represented across all vertical layers of older forests.

Although less common than the pathways described above, there are also examples of developmental trajectories in Douglas-fir forests in which frequent, non-stand-replacing fires resulted in repeated periods of extended cohort establishment throughout stand development (Poage et al. 2009, Tepley et al. 2013). These developmental pathways appear to occur when frequent fires maintain relatively low overstory densities that allow for nearly continuous establishment and recruitment of relatively shade intolerant species (e.g., Douglas-fir, western white pine, or sugar pine) and simultaneously limit the establishment of more shade tolerant, but fire sensitive species (e.g., true firs or western hemlock). Such pathways have most commonly been described for stands on drier sites such as southwest Oregon and the fringes of the Willamette Valley.

**Do current practices of mechanical thinning of young stands accelerate the development of late seral and old-growth characteristics?**

Several lines of evidence suggest that thinning young stands could promote the development of late seral and old-growth characteristics:

Reconstructions of early developmental patterns in existing old-growth stands suggest that many of the oldest trees in these stands grew at low densities for at least the first several decades of their lives (Tappeiner et al. 1997, Poage and Tappeiner 2002, Poage and Tappeiner 2009). Retrospective analyses suggest that these low initial stand densities fostered high growth rates at young ages that were key to the development of the largest overstory trees in old-growth stands (Tappeiner et al. 1997, Poage and Tappeiner 2002). Further, non-stand-replacing fires were a common feature in many older Douglas-fir stands throughout their development (Weisburg 2004, Tepley et al. 2013). This suggests that silvicultural treatments designed to emulate at least some impacts of non-stand-replacing fire could foster "natural" patterns of structural development and promote more rapid development of large overstory trees. It should be noted, however, that the oldest cohort in a smaller proportion of existing old-growth stands appears to have established over shorter periods (as little as 20 years) and at fairly high initial densities (Winter et al. 2002a, Poage et al. 2009, Tepley et al. 2013). Development of old-growth structure in these dense, young stands appears to be considerably slower than in lower density stands, and these two initial stand conditions appear to remain on different developmental trajectories up to at least 150 years of age (Acker et al. 1998a). This suggests that structural development in dense young-mature stands is likely to be slow in the absence of silvicultural intervention or non-stand-replacing, natural disturbances.

Comparisons of understory tree and shrub development in stands that were thinned between about age 40 and age 80 to unthinned stands suggest that thinning young stands accelerates the development of an understory shrub layer and promotes the regeneration and growth of shade tolerant conifers (Bailey and Tappeiner 1998, Wilson and Puettmann 2007, Dodson et al. 2012). Treatments that incorporate spatially heterogeneous overstory environments (e.g., gaps, leave patches, and variable overstory densities) further contribute to the development of structural complexity and understory species diversity (Wilson and Puettmann 2007, Cole and Newton 2009, Roberts and Harrington 2008, Comfort et al. 2010, Halpern et al. 2012, Dodson et al. 2012), although density management treatments may not accelerate the development of features such as large-diameter deadwood or complex crown structures (Dodson et al. 2012, Newton and Cole 2015).

Simulation studies suggest that, in the absence of natural disturbance events that reduce overstory densities, active management including heavy thinning in young stands is required to promote old-growth features such as the development of large trees and shade tolerant associates that contribute to vertical layering by age 150-160 years (Latta and Montgomery 2004, Andrews et al. 2005). Further, a conservation strategy that favors a greater proportion of the landscape under active management rather than a higher percentage of reserves may accelerate landscape-scale development of late seral forest characteristics and reduce fragmentation between late seral patches (Carey et al. 1999).

In the absence of partial canopy disturbances, significant vertical diversification often does not begin until stands reach ages of 150 years or more (Franklin et al. 2002, Tepley 2013), Structural development proceeds particularly slowly in high density stands (Acker et al. 1998a, Winter et al. 2002b), suggesting that overstory density reductions could accelerate developmental processes, at least in high density stands.

**Is there a case for managing older stands (> 80 years) to either accelerate the development of late seral and old-growth characteristics in late seral reserves or to produce wood products coupled with meeting some biodiversity interests in matrix lands?**

There are several lines of evidence that suggest active management in older stands may be beneficial in some cases to foster continued structural development along a trajectory that promotes the rapid formation of old-growth characteristics:

Reconstructions of disturbance history and age structures in old-growth stands suggest that the majority of existing old-growth forests experienced repeated non-stand-replacing fires or other partial canopy disturbances (Weisburg 2004, Poage et al. 2009, Tepley et al. 2013). Repeated non-stand-replacing disturbances during the lives of contemporary old-growth stands contributed to multiple, prolonged periods of tree establishment and promoted the development of large trees, varied tree sizes and species compositions that included both shade tolerant and shade intolerant trees in multiple cohorts. In the absence of such disturbances (e.g., the continued suppression of fires burning under weather and fuel conditions that would limit their severity), silvicultural treatments could be used to emulate some of their impacts (e.g., varying levels and spatial patterns of canopy density reductions).

Repeated thinning appears to benefit the growth and vertical recruitment of both shade tolerant and shade intolerant tree species that establish following an initial thinning treatment in young stands, contributing to the formation of a multi-aged/multi-layered stand structure (Miller and Emmingham 2001, Shatford et al. 2009). Repeatedly-thinned, 120-140 year-old stands have been shown to develop structural features that exceed minimum stands for old-growth (Newton and Cole 1987), although deadwood abundance in these stands was low relative to old-growth stands. Simulation studies and some empirical data also suggest that repeated density management treatments up to ages of 150 years that include some fairly heavy removals are required to promote rapid development of late seral forest structure and maintain development of understory cohorts (Latta and Montgomery 2004, Andrews et al. 2005, Cole and Newton 2009). It should be noted, however, that residual overstory densities or stocking levels needed to promote Douglas-fir regeneration are low relative to existing even-aged management guidelines for full stocking (Bailey and Tappeiner 1998, Miller and Emmingham 2001).

For two-aged or multi-aged management, studies suggest that residual overstory basal areas > 80 $ft^2$/ac limit the establishment and persistence of Douglas-fir regeneration (Lam and Maguire 2011), while the growth of both Douglas-fir and western hemlock under a residual overstory increases rapidly at residual overstory basal areas below about 43 $ft^2$/ac (Acker et al. 1998b). Dense understory tree cohorts further reduce understory growth rates, suggesting the need to consider management of both overstory and understory densities to limit reductions in volume growth and promote rapid structural development (Acker et al. 1998b, Zenner et al. 1998). In spite of the growth losses, large, residual hemlock and western red-cedar appear to promote the development of a shade tolerant component in younger cohorts (Keeton and Franklin 2005). Retention of an older overstory cohort has also been shown to promote understory vegetation recovery after harvesting (Halpern et al. 2012) and to enhance within-stand variability in structural characteristics (Maguire et al. 2007). Additionally, residual midstory and overstory trees in Douglas-fir/western hemlock stands have been shown to demonstrate rapid releases following overstory density reductions and gap creation that vary across different environments (Roberts et al. 2008, Comfort et al. 2010), even in mature stands (Gray et al. 2012). For multi-aged management approaches to capitalize on their potential to foster structural complexity, however, they will likely need to incorporate removals and retention across a range of tree sizes rather than using traditional approaches that focus on thinning from below (Miller and Emmingham 2001, Comfort et al. 2010, Kuehne et al. 2015).

**Uneven-aged management experiments in the Douglas-fir region were thought to be a failure by some; why are we considering uneven-aged management alternatives now?**

There was a great deal of enthusiasm for selective cutting and partial cutting in the moist Douglas-fir/hemlock and Sitka spruce/hemlock forests of the PNW during the early 20th century. Foresters at the time were searching for alternative management practices that could be applied to old stands with large, old Douglas-fir containing a high degree of defect and understories of shade tolerant true firs, hemlock, and cedars, which had little economic value (Munger 1950, Curtis 1998). Clearcutting such stands often involved high costs to remove many low value trees. Growth and yield in these stands was considered fairly low, and the recent development of crawler tractors for skidding logs had made individual-tree removals much more economically feasible. There was also concern at the time that large clearcuts with limited regeneration represented both an eyesore and potential threat to forest health and sustainability.

To accommodate these challenges, Kirkland and Brandstrom (1936) suggested that a series of light initial cuttings focused on the removal of large overstory trees followed by the creation of large openings (1-10 acres in size) could lead to the development of a multi-aged, mixed species forest. The large openings would favor regeneration of relatively even-aged patches of Douglas-fir and the thinned matrix would favor regeneration of shade tolerant conifers in a multi-aged structure. Selective cutting trials were installed throughout the PNW across a range of stand conditions and site characteristics, but these trials typically included much heavier initial removals than Kirkland and Brandstrom called for, focused largely on the harvesting of high-value Douglas-fir, and never progressed to the point at which larger openings were created to promote Douglas-fir regeneration (Curtis 1998). These selective cutting trials resulted in high levels of residual tree mortality and logging-related injury, released shade tolerant understory trees to recruit upwards, promoted little Douglas-fir regeneration, and reduced the Douglas-fir component of treated stands (Munger 1950, Isaac 1956).

Kirkland and Brandstrom's ideas about "selective timber management" were not reflected by the partial cutting practices of that period, and were not even intended to represent a form of the selection system for uneven-aged management (Curtis 1998). Even the primary critics of their proposed practices recognized that *selective cutting*, as implemented at that time, was basically high-grading and clearly not representative of a carefully planned *selection system* for uneven-aged management (Munger 1950, Isaac 1956). Nonetheless, this period of experimentation led critics to conclude that uneven-aged management was inappropriate for Douglas-fir and Sitka spruce/hemlock forests (Isaac 1956) and led to a shift back towards clearcutting as the only widely-accepted practice for regeneration harvests in the Douglas-fir region (Munger 1950, Curtis 1998). The backlash against these early partial cutting practices was so strong that little research into alternative silvicultural systems for Douglas-fir management was conducted from the 1950s through the 1990s (Curtis 1998).

Although historical events have limited uneven-aged management research in the Douglas-fir region, there are still some general conclusions that can be drawn to focus future research and management trails:

- Even Isaac (1956), who used the results of early partial cutting trails to pan uneven-aged management in Douglas-fir recognized that the selection system (i.e., a formal silvicultural system for uneven-aged management that involves repeated removals of trees either individually or in groups to promote an uneven-aged stand structure) might be a viable approach on dry sites in southwest Oregon, around the fringe of the Willamette Valley, and on some gravelly soils in the Puget Sound region.
- There has been virtually no research examining stocking control concepts for uneven-aged management (i.e., methods for allocating total density or growing stock among size or age classes) in any part of the Douglas-fir region. There are many methods of stocking control for uneven-aged silviculture (O'Hara and Gersonde 2004), and different patterns of growing stock allocation can provide opportunities to create a wide range of stand structures to meet varied management objectives (Long 1998, O'Hara 1998, O'Hara and Gersonde 2004). Stocking control methods that take advantage of existing even-aged density management concepts such as stand density index (e.g., Long 1998) might offer baselines for research and adaptive management trials to evaluate uneven-aged management options in the PNW. These SDI-based approaches also offer considerably flexibility for creating a wide range of target stand structures to meet varied management objectives (Long 1998, O'Hara 1998).
- Preliminary information about regeneration establishment and growth responses to different overstory densities and stocking levels can be garnered from existing studies of regeneration dynamics following variable density thinning, partial cutting treatments, and assorted regeneration cutting methods (e.g., Acker et al. 1998, Bailey and Tappeiner 1998, Miller and Emmingham 2001, Deal and Tappeiner 2002, Deal et al. 2002, Shatford et al. 2009, Lam and Maguire 2011, Dodson et al. 2012).
- Research in Sitka spruce/hemlock forests suggests that even partial cutting practices that were driven entirely by short-term economic returns without any regard for subsequent stand development, promoted regeneration, growth, and recruitment of both spruce and hemlock (Deal and Tappeiner 2002). Size distributions and species mixtures in partial cut stands were similar to those of old-growth spruce/hemlock forests and both structural and compositional diversity in partial cut stands was greater than that of clearcut stands (Deal and Tappeiner 2002, Deal et al. 2002). The capacity of these exploitive partial cutting practices to generate or maintain old-growth characteristics suggests a strong potential for a more carefully designed uneven-aged management approaches to foster these characteristics in Sitka spruce forests (Deal et al. 2002).
- Comparisons of group selection methods, two-storied systems, and untreated controls in mature Douglas-fir suggest that uneven-aged management may offer greater yields and reduce mortality of residual overstory trees compared to two-storied systems (Garber et al. 2011), while also maintaining opportunities for Douglas-fir regeneration in moderate-sized group selection openings (Lam and Maguire 2011).

- Uneven-aged management systems may offer opportunities to emulate some elements of repeated, non-stand replacing fires, which were critical to the structural development of a large proportion of existing old-growth stands (Weisburg 2004, Tepley et al. 2013), but are uncommon on today's landscape.

## Disturbance Ecology and Stand Development in "Natural" Douglas-fir Forests: An Annotated Bibliography

Acker, S.A., Sabin, T.E., Ganio, L.M., and McKee, W.A. 1998a. Development of old-growth structure and timber volume growth trends in maturing Douglas-fir stands. Forest Ecology and Management 104:265-280.

This study evaluated structural development using long-term, repeated measurements from permanent plots in 20 Douglas-fir stands that are approaching 150+ years of age. Their findings suggest that structural development was most rapid up to about 80 years of age, with half of the transition to old-growth structure occurring by age 100 years and slower structural development thereafter. Dense stands with relatively small trees and uniform sizes were least similar to old-growth throughout the study period, while stands with conditions that promoted development of larger trees (> 100 cm DBH) were most similar to old-growth at the end of the evaluation period. Declines in MAI were gradual, suggested limited impacts of extended rotations on growth. Half of the stands did not develop any shade-tolerant understory conifers during the study, suggesting management activities (planting and overstory release) may be necessary to promote this characteristic in some cases. The authors suggest that early density control may be an important tool in accelerating structural development, while management activities that promote the development of large trees and heterogeneous size distributions may be most beneficial in mature stands. Note: the study plots were not thinned at any point during the evaluation period.

Franklin, J.F., Spies, T.A., Van Pelt, R., Carey, A.B., Thornburgh, D.A., Berg, D.R., Lindenmayer, D.B., Harmon, M.E., Keeton, W.S., Shaw, D.C., Bible, K., and Chen, J. 2002. Disturbances and structural development of natural forest ecosystems with silvicultural implications, using Douglas-fir forests as an example. Forest Ecology and Management 155:399-423.

This paper reviews models of structural development in Douglas-fir dominated forests within the western hemlock and lower Pacific silver fir zones of the Pacific Northwest. They also discuss silvicultural implications for natural disturbance-based management. The authors argue that traditional models of stand dynamics that focus on structural development following high-severity disturbances do not effectively consider the importance of disturbance severity, legacies such as coarse woody debris, spatial heterogeneity, and structural change during later stages of succession. The authors illustrate eight, process-based stages of structural development in PSME-TSHE forests:

1. A disturbance/legacy creation stage in which disturbances create conditions that promote establishment of a new dominant cohort. In natural disturbances, legacies and heterogeneity in disturbance magnitude, frequency, and extent promote environmental heterogeneity at stand-landscape scales during this event.
2. During the cohort establishment stage, a new cohort of trees establishes. The authors note that the duration and density of regeneration establishment are highly variable as a result of variability in disturbance impacts on propagule availability, post-disturbance environmental conditions, competing vegetation, and repeated disturbance events.
3. In the canopy closure stage, trees become the dominant vegetation as they overtop competing vegetation and crown expansion leads to canopy closure. Canopy closure creates large changes in understory light levels and microclimate that lead to significant shifts in the composition and structure of plant and bryophyte communities. The length of this stage is variable, depending upon both stand density and site productivity.
4. Following crown closure, stands enter a biomass accumulation/competitive exclusion stage in which dense canopies and high levels of competition for resources drive rapid biomass accretion, competitive exclusion of many organisms, density-dependent mortality, self-pruning, and crown-class differentiation. This stage frequently lasts until age 80-100 years in Douglas-fir stands.

5. In the maturation stage, tree mortality shifts from density-dependent to disturbance-driven, density-independent processes. The initial, post-disturbance cohort reaches its maximum height and crown spread during this stage. The development of larger, longer lasting canopy gaps promotes re-establishment of shade tolerant trees and other understory vegetation, biomass accumulation tapers off, and damage to overstory trees begins to promote the development of complex crowns and stem decay. This stage can last 100-150 years in natural Douglas-fir stands.
6. During the vertical diversification stage, vertical recruitment of shade tolerant understory species combined with crown expansion on overstory trees resulting from epicormic branching contributes to vertical layering. Small-scale disturbances and senescence contribute to the development of large-diameter snags and logs, and the presence of larger branch systems in overstory trees promotes the expansion and diversification of canopy bryophytes. This stage frequently occurs when the initial, post-disturbance cohort attains ages of 200-350 years.
7. In the horizontal diversification phase, gap creation and expansion becomes the dominant process driving structural dynamics. These processes promote spatial heterogeneity in horizontal structures and microclimate conditions within the stand. This stage often begins after the pioneer cohort has reached ages of 300 years or more.
8. If the interval between successive, high severity disturbances lasts long enough (estimated at 800+ years), stands may lose their cohort of dominant Douglas-fir pioneers. Large gaps created by moderate severity disturbances may allow relatively shade intolerant species to persist in the stand, and the death of large, old Douglas-fir contributes extremely large-diameter, long-lived deadwood to the stand.

Silvicultural approaches that the authors recommend to capture the variability in structural development of natural Douglas-fir forests include structural retention during harvests, extended rotations, and active creation of spatial heterogeneity and legacies in managed stands.

Fruend, J.A., Franklin, J.F., Larson, A.J., and Lutz, J.A. 2014. Multi-decadal establishment for single-cohort Douglas-fir forests. Canadian Journal of Forest Research 44:1068-1078.

This study used dendrochronological analyses to reconstruct patterns of cohort establishment following stand-replacing fires in contemporary mature and early old-growth Douglas-fir stands. The study sites were located in western Washington and northwestern Oregon, and the authors specifically selected sites with little evidence of disturbance following an initial stand-replacing fire. Pioneer Douglas-fir cohort establishment occurred continuously after stand replacing fire in all stands for an average of 60 years with a range of 32-99 years. Across all sites, the majority of pioneer Douglas-fir established within 75 years of stand-replacing fire, and all pioneer trees were established within 100 years of fire. The duration of pioneer cohort establishment was found to have no relationship with environmental variables or current stand structure, suggesting a fairly consistent pattern of pioneer cohort development in the absence of non-stand-replacing disturbance. The authors note that this pattern of prolonged cohort establishment contrasts sharply with intensively-managed plantation forests, and suggest that management agencies interested in restoration of natural stand development trajectories or in generating longer-lasting early seral habitat may want to consider natural regeneration rather than planting after regeneration harvests to emulate the longer periods of cohort establishment documented here.

Freund, J.A., Franklin, J.F., and Lutz, J.A. 2015. Structure of early old-growth Douglas-fir forests in the Pacific Northwest. Forest Ecology and Management 335:11-25.

This study compared the structure and composition of "early" old-growth stands (ages 200-350 years) to that of older stands (ages 400-600 years) to examine structural transitions from late-seral forests to a full old-growth condition. Diameter distributions were found to be similar between early and full old-growth stands, although the authors did not attempt to fit different diameter distribution models (e.g., negative exponential vs increasing q vs. rotated sigmoid vs multimodal or polynomial) for this analysis. Early old-growth stands scored high on multivariate old-growth indices, but their scores were lower than full old-growth stands. Vertical structure in early old-growth was characterized by shade tolerant species in lower canopy positions than in full old-growth. Structural variability was largely explained by basal area and stem density of shade tolerant trees, density of large-diameter trees, and log volumes. The authors note that their results indicate a continuous process of structural development towards a high quality old-growth condition that lasts well over 300 years in natural stands, suggesting that strictly age-based approaches to management may not meet goals related to providing wildlife habitat with old-growth characteristics.

Halpern, C.B., and Spies, T.A. 1995. Plant species diversity in natural and managed forests of the Pacific Northwest. Ecological Applications 5(4):913-934.

This study analyzed data from repeated measurements on permanent plots and retrospective, chronosequence studies to examine patterns of vascular plant diversity in natural and managed stands dominated by Douglas-fir. In natural stands, vascular plant species diversity generally increases with time following canopy closure. In natural stands, most understory species were present, at least in low levels, through all stages of stand development. There were, however, large changes in the abundance of different species as stands age. These differences appear to be due to individual species tolerances for disturbance and stress (e.g., fire or shade), differences in establishment and growth rates following disturbance, and changes in environmental heterogeneity during stand development. High levels of diversity in old-growth stands appear to be linked to high levels of structural complexity that foster spatial heterogeneous environments and resource availability to promote a species with a wide range of life history traits.

Species diversity declined briefly following disturbance (logging and burning), but exceeded old-growth levels within two years of clearcut logging and broadcast burning as a result of an increase in native, ruderal plants. Diversity then generally rose over time to a peak prior to canopy closure, declined to its lowest point during the period in which canopy densities are highest, and then increased over time as canopies begin to open up and reorganize during mid-later stages of succession. At finer temporal scales, diversity actually showed several different peaks prior to canopy closure, representing short-term shifts in the composition and abundance of annual and perennial plants. The authors note that rapid recovery of residual species diversity following clearcutting and burning suggests that old-growth understory species have a large degree of tolerance (or at least resilience) to these disturbances. At a finer scale, however, residual species recovery was slower in areas where disturbance intensity was higher and some taxa showed as much sensitivity to canopy removal as to fire. These observations of species diversity in managed stands, however, only extend up to the point of canopy closure, and the authors note that our understanding of long-term management impacts on species diversity is limited by a lack of studies in older managed stands. The authors also suggest that silvicultural approaches incorporating a high degree of spatial variability including gaps, retention patches, and areas of dispersed retention should contribute to maintaining taxa that are either disturbance-sensitive, environmentally sensitive, or that display long recovery times after disturbance. Similarly, variable planting densities (and species) and legacy retention should contribute to the maintenance of species diversity in managed forests.

Keeton, W.S., and Franklin, J.F. 2005. Do remnant old-growth trees accelerate rates of succession in mature Douglas-fir forests? Ecological Monographs 75(1):103-118.

The authors examined the influence of residual old-growth hemlock and red-cedar trees on the development of a shade tolerant conifer component in fire-origin, mid-successional Douglas-fir stands in the Washington Cascades. The presence of old, remnant hemlock and red-cedar was found to be the strongest predictor of seedling densities for these species in mature stands, although other factors (basal area of mature hemlock and red-cedar, relative density, stand age, and microsite characteristics) were also important predictors of shade tolerant seedling densities.

Shade tolerant seedling densities were also negatively correlated with distance from residual old-growth trees, suggesting the importance of residual trees as seed sources. These results suggest that residual shade tolerant overstory trees may accelerate succession by promoting the establishment of shade tolerant understory layers during post-fire stand development. The authors note, however, that partial canopy disturbances may be necessary to promote continued growth and vertical diversification of these stands following initial establishment of shade tolerant conifers in the understory.

Nonaka, E., Spies, T.A., Wimberly, M.C., and Ohmann, J.L. 2007. Historical range of variability in live and dead wood biomass: a regional-scale simulation study. Canadian Journal of Forest Research 37:2349-2364.

This study modeled the historic range of variability in deadwood biomass for the Oregon Coast Range based on pre-Euro-American settlement fire regimes. As expected the results suggest that deadwood biomass was generally high in mature to old-growth stands, low in young, closed-canopy stands, and highly spatially variable across the landscape. The amount of the landscape characterized by very high deadwood biomass (e.g., immediately after a severe fire), was estimated to be fairly small at any given time.

Poage, N.J. and Tappeiner, J.C. 2002. Long-term patterns of diameter and basal area growth of old-growth Douglas-fir trees in western Oregon. Canadian Journal of Forest Research 32:1232-1243.

The authors reconstructed patterns of diameter growth and age from stumps of recently cut old-growth Douglas-fir at 28 sites in western Oregon. The results suggest that fast growth rates at young ages were characteristic of large-diameter, old trees in the harvested stands. Period basal area increments increased for the first 30-40 years of all the sampled trees, then plateaued and remained relatively constant (and high) up to age 300 years. The largest old-growth trees had significantly higher growth rates when they were young than smaller old-growth trees. A wide range of Douglas-fir tree ages within the old-growth stands prior to harvest also suggests low initial densities (or periodic disturbances) that would allow for prolonged establishment periods and the survival of this relatively shade intolerant species in understory conditions. The combination of rapid early growth, sustained levels of high growth over time, weak relationships between site quality and individual tree growth, and wide ranges of Douglas-fir ages support the hypothesis that the large-diameter Douglas-fir in old-growth stands developed at low stand densities with limited competition. The results also suggest that silvicultural approaches to generate large-diameter trees should focus on creating low density conditions at young stand ages or using repeated thinning to maintain limited competition since rapid growth prior to age 50 appears to be a key factor associated with attaining large diameters by ages 100-300.

Poage, N.J., Weisberg, P.J., Impara, P.C., Tappeiner, J.C., and Sensenig, T.S. 2009. Influences of climate, fire, and topography on contemporary age structure patterns of Douglas-fir at 205 old forest sites in western Oregon. Canadian Journal of Forest Research 39:1518-1530.

This study used estimated establishment dates of Douglas-fir at 205 old forest sites in western Oregon to examine current patterns of Douglas-fir age structure and historical patterns of Douglas-fir establishment in natural stands. Preliminary analyses were used to cluster age structures into four groups, and sites falling into these groups were compared based on climate, topography, and fire history. They found considerable variability in age structure and establishment patterns, but multiple Douglas-fir age classes and prolonged establishment periods were common.

- The first group of sites included an initial cohort of trees establishing over an 80 year period and limited establishment thereafter. This would be consistent with a pattern of prolonged establishment after a single, severe disturbance event or with a series of disturbances over this initial 80 year period followed by a period of limited disturbance for the next 300 years or so.

- The second group of sites also included a prolonged period of initial establishment, but with a much later peak (circa 100 years) followed by a second peak in Douglas-fir establishment after 200-300 years. This could be indicative of an initial, high-severity disturbance followed by several moderate-high severity disturbances that might have delayed the initial establishment peak. A later, moderate severity disturbance would have been necessary to promote the second peak of Douglas-fir establishment while retaining many of the large, old Douglas-fir from the initial cohort.
- The third group of sites displayed a more classical pattern of two-aged structure and establishment. The two establishment peaks on these sites were more distinct and abrupt, but still spanned several decades. This could be indicative of an initial, severe disturbance followed by relatively rapid period of initial cohort establishment, and a second, moderate severity disturbance that left a fairly low density of residual trees and led to the fairly rapid establishment of a second cohort.
- The fourth group of sites was characterized by extended periods of Douglas-fir establishment with long, broad peaks and long periods of survival for older cohorts. The age structure and establishment patterns on these sites is typical of forests where fairly frequent and relatively low intensity fires contribute to repeated canopy disturbances and maintain lower overstory densities. This seems appropriate as these sites were mostly found in the driest, most fire-prone portions of the study area (SW Oregon) where historical fire frequencies were relatively high.

Spies, T.A., and Franklin, J.F. 1988. Old growth and forest dynamics in the Douglas-fir region of western Oregon and Washington. Natural Areas Journal 8(3):190-201.

This paper reviewed existing literature to evaluate changes in the composition, structure, and functioning of Douglas-fir/western hemlock forests over a developmental trajectory from young stands to old-growth. They argue that many of the structural and functional changes that occur during succession in Douglas-fir forests are due to shifts in the density, spatial distribution, and crown structures of the dominant Douglas-firs, their shade tolerant associates, and the deadwood legacies that they ultimately produce. The authors identify two general patterns that capture the temporal trends of many important structural features in old-growth:

- Features such as total deadwood volumes and the numbers of large snags and logs, understory species diversity, mammal diversity, and spatial heterogeneity of the understory follow a U-shaped curve over the course of succession in natural Douglas-fir/western hemlock forests. These features have high values during the early stages of succession following a severe disturbance event, decline to low levels through the middle phases of succession, and then increase to moderately high levels in late seral and old-growth forests.
- The second pattern describes the development of features such as total biomass, average tree size, the diversity of tree sizes, limb sizes, and forest floor depth. This pattern follows an S-shaped trend through time with low levels and relatively small temporal changes occurring during earliest stages of succession followed by rapid increases over time during the middle stages of succession, and then approaches an asymptote representative of high levels, but limited change in old-growth stands. If the interval between severe disturbances is long enough, these characteristics may decline to somewhat lower levels in very old stands.

The authors also suggest that a structural diversity index to rate "old-growthiness" would offer a more nuanced metric of structural development and successional status than systems that categorize stands into discrete categories of structural development. They suggest that such an index should include a set of characteristics that show significant change over the course of succession and are directly tied to ecosystem functioning. Densities of large trees and CWD abundance are provided as examples of such characteristics, but they do not suggest a specific set of metrics and weights for calculating such an index.

The authors also note that natural disturbances are both spatially and temporally variable in their frequency, extent, and magnitude in these systems. In addition to the patchy impacts of mixed-severity fire regimes, finer scale and lower severity disturbances associated with winter storms, insects, and pathogens contributed to the formation of a range of gaps sizes as well as creating areas of dispersed residual trees at varying densities. These low-moderate severity disturbances accelerate structural development from young to mature to old-growth stages by creating woody debris, promoting the establishment of shade tolerant species, contributing to vertical layering, and creating spatial heterogeneity.

Spies, T.A., Franklin, J.F., and Thomas, T.B. 1988. Coarse woody debris in Douglas-fir forests of western Oregon and Washington. Ecology 69(6):1689-1702.

This paper examined changes in the structure and abundance of CWD across a chronosequence of Douglas-fir stands in western Oregon and Washington. They included stands aged 40 to 900 years, and also examined the effect of moisture availability on CWD dynamics. CWD abundance followed a characteristic U-shaped pattern with moderate levels in young stands, low levels in stands aged 80-120 years, and high levels in stands aged 400-500 years. In older stands (>500 years), CWD levels declined to moderate levels. Models of CWD dynamics also suggested low levels of CWD in stands aged 80-200 years, with the longest periods of low CWD levels occurring when repeated fires events occurred in early successional stages. The authors note that CWD levels in managed stands are significantly lower as CWD inputs are reduced by density management practices and the harvesting of live trees.

Spies, T.A., and Franklin, J.F. 1991. The structure of natural young, mature, and old-growth Douglas-fir forests in Oregon and Washington. P91-109 in Wildlife and vegetation of unmanaged Douglas-fir forests. Ruggiero, L.F., Aubrey, K.B., Carey, A.B., and Huff, M.H. (tech. cords.). USDA Forest Service General Technical Report. PNW-GTR-285.

The authors sampled a chronosequence of Douglas-fir stands aged 40-900 years in western Washington and Oregon representing sites with moderate moisture conditions along with a series of old-growth stands (ages > 200 years) across a moisture gradient. They evaluated structural differences among young (40-80 years), mature (80-195 years), and old-growth (>195 years) stands as well as structural differences among old-growth stands on sites with varying moisture conditions (classified as dry, moderate, or moist). Their results underscore the fact that structural conditions are highly variable across the landscape, particular among old-growth stands. This variability is likely driven by differences in site conditions and disturbance history.

- Overstory variables related to stand density, the density of large trees, mean tree size, and variation in tree diameter had the most power for differentiating between age classes. Attributes related to CWD abundance and sizes provided less discriminatory power among age classes, and understory characteristics were generally poor indicators or age-related differences.
- Disturbance history and the basal area of shade tolerant trees were among the main drivers of structural differences among old-growth stands. Drier regions (e.g., SW Oregon and the eastern Coast Range) have likely experienced more frequent fire and tended to have lower abundances of shade tolerant trees. Old-growth stands on drier sites with more frequent fire also tended to have higher evergreen shrub and graminoid cover in the understory, while high levels of herbaceous cover was more typical of old-growth understories on moist sites. These differences are likely due to the lower canopy densities, lower abundance of shade tolerant overstory trees, and higher fire frequencies on dry sites relative to moist sites.

Tappeiner, J.C., Huffman, D., Marshall, D., Spies, T.A., and Bailey, J.D. 1997. Density, ages, and growth rates in old-growth and young-growth forests in coastal Oregon. Canadian Journal of Forest 27:638-348.

The authors used analyses of cut stumps or tree cores in 10 pairs of old-growth (tree ages > 150 years) and young (age 50-70 years) Douglas-fir stands in the Oregon Coast Range to examine differences in age structure and growth rates between these two age classes. The early growth rates of trees in old-growth stands were significantly higher than those of trees in young stands during the same portion of their lives. Early growth rates of trees in old-growth stands were consistent with growth of trees at stand densities of about 100-120 trees/ha (about 40-50 trees/acre). The ages of overstory trees in old-growth stands varied by over 300 years, while ages of overstory trees in young stands varied by just 5-10 years. These results suggest that prolonged or multiple establishment periods of trees in old-growth stands were common, and that these trees grew at low densities with limited competition when young. Growth simulations for trees in young stands suggest that densities lower than 250 trees/ha (about 100 trees/acre) would be needed to promote growth trajectories similar to those that characterized early growth of overstory trees in old-growth stands. The authors suggest that repeated thinning in young stands would likely be necessary to achieve developmental trajectories similar to those of present-day old-growth trees when they were young.

Tepley, A.J., Swanson, F.J., and Spies, T.A. 2013. Fire-mediated pathways of stand development in Douglas-fir/western hemlock forests of the Pacific Northwest, USA. Ecology 94(8):1729-1743.

The authors evaluated stand structure and used tree ring data to estimate age structures and establishment dates. This data was used to draw conclusions about patterns of stand development in response to fire. Differences in fire frequency and severity were linked to several different developmental pathways and age structures.

- Stands subjected to a single, stand-replacing fire event were characterized by a single overstory age class of shade intolerant trees and made up 27% of the sample. These stands were characterized by increasing structural complexity in late seral and old-growth stages associated with gap-phase regeneration of shade tolerant species.
- In contrast, a majority (63%) of stands were characterized by a disturbance regime that included at least one non-stand-replacing fire event between stand replacing events. In these stands, the oldest cohort was composed of shade intolerant species, while younger cohorts were dominated by shade tolerant species with limited recruitment of shade intolerant species in the younger cohorts that established in short, distinct pulses after fire events. Shade tolerant species were abundant in the lower canopy and understory, but uncommon in the upper canopy.
- A small percentage of stands (10%) experienced repeated non-stand-replacing fires between stand-replacing events. Short fire-free intervals in these stands limited regeneration of fire-sensitive, shade tolerant species, but contributed to the presence of multiple cohorts of shade intolerant species. Shade intolerant species were found in all canopy layers in these stands, but shade tolerant species were low in density and limited to understory positions.

In general, nearly ¾ of stands included multiple age classes that established following a combination of stand replacing and non-stand replacing fire events. When repeated, non-stand-replacing fires left live tree densities ≤ 45 trees/ha (18 trees/acre), stands contained up to four age classes of shade intolerant species. When residual tree densities were 60-65 trees/ha or greater after non-stand-replacing fire, post-fire regeneration was dominated by shade tolerant species. Successional pathways that lacked non-stand-replacing fire were less common, but led to complex vertical structures and tree size distributions.

Tepley, A.J., Swanson, F.J, and Spies, T.A. 2014. Post-fire tree establishment and early cohort development in conifer forests of the western Cascades of Oregon, USA. Ecosphere 5(7):1-23.

This study evaluated patterns of Douglas-fir cohort establishment following fire events spanning several centuries across two watersheds in the west-central Cascades of Oregon using dendrochronological techniques. They evaluated cohort development after both high severity (i.e., stand replacing) and moderate-severity (i.e., non-stand replacing) fire events. The results suggest that post-fire Douglas-fir establishment occurred primarily over a period of approximately four decades regardless of stand development pathway and fire severity. Topography and fire severity had little impact on this pattern, although slower patterns of cohort establishment appeared to be more likely in topographic positions that were close to Douglas-fir's upper elevation limit. Eighty percent of Douglas-fir cohort establishment occurred during two broad periods (1470-1610 and 1780-1940) in which fires have been identified as being widespread across the west-central Cascades.

In stands that appeared to follow a relay-floristic pattern of succession after high severity fire (i.e., Douglas-fir establishment primarily preceded the establishment of shade tolerant species), current Douglas-fir densities were much higher than the densities of shade tolerant trees. In contrast, stands that followed an initial floristics pattern of development (i.e., Douglas-fir and shade tolerant cohorts established simultaneously after a high severity fire) had higher densities of shade tolerant trees and lower densities of Douglas-fir as mature stands. Stands in which cohorts developed after moderate severity fire had an average of 43 Douglas-fir/ha that appear to have survived a given fire, and the lowest ratio of Douglas-fir to shade tolerant trees in the post-fire cohort. In contrast with Douglas-fir, shade tolerant species showed considerable differences in establishment patterns following disturbance. In stands that followed relay floristics, very few (about 4% on average) shade tolerant stems established prior to the completion of Douglas-fir cohort establishment, while the majority (73-80%) of shade tolerant trees established during the same period as the Douglas-fir cohort in stands that either experienced moderate severity disturbance or established following an initial floristics pathway after severe disturbance.

Douglas-fir growth patterns were heavily influenced by the different cohort development pathways. When stands followed a relay floristics pattern after fire, basal area increment of the new Douglas-fir cohort increased rapidly to a peak near the end of Douglas-fir cohort establishment around age 40 and then gradually declined to an equilibrium level around age 80-90. A similar, but much less distinct peak in Douglas-fir growth occurred in stands that followed the initial floristics pattern of development after severe fire. Growth of the new Douglas-fir cohort following moderate severity was generally slow for the first 20-30 years, and gradually increased over a period of about 100 years following the disturbance before showing a graduate decline similar to the other pathways. The authors report that the range of Douglas-fir ages in many of their stands was quite broad (an average of 173 years), and suggest that this reflects multiple periods of cohort establishment that include at least one moderate severity fire during the course of stand development. They did not find evidence of prolonged periods with low initial tree densities in most stands, as has been reported in studies in the Oregon Coast Range (e.g., Tappeiner et al. 1997).

Weisburg, P.J. 2004. Importance of non-stand-replacing fire for development of forest structure in the Pacific Northwest, USA. Forest Science 50(2):245-258.

This study examined relationships between the occurrence of non-stand-replacing fire and structural development across 90 sites in the central western Cascades of Oregon. The occurrence of non-stand-replacing fire appears to have promoted development of a wide range of diameter classes, large overstory trees, and a greater component of shade tolerant species in existing stands aged 108-517 years. Results suggest that direct fire effects (e.g., gap-phase succession) and an increasing likelihood of experiencing repeated fires as stands age contribute to structural development in Douglas-fir forests. These results suggest that repeated, non-stand-replacing fires played a critical role in the structural development of existing mature and old-growth Douglas-fir stands in the western Cascades.

Winter, L.E., Brubaker, L.B., Franklin, J.F., Miller, E.A., and DeWitt, D.Q. 2002a. Initiation of an old-growth Douglas-fir stand in the Pacific Northwest: a reconstruction from tree-ring records. Canadian Journal of Forest Research 32:1039-1056.

This study used pre-harvest inventory data and tree rings from cut stumps at a single site to reconstruct establishment dates and growth rates of Douglas-fir and western hemlock in an old-growth stand that was harvested on the Gifford Pinchot. Sampling was limited to Douglas-fir and western hemlock ≥ 40 cm dbh. Their results suggest a short wave of Douglas-fir establishment (21 years) following stand-replacing fire. A smaller number of pioneer western hemlock established over a 40-year period after the fire. Initial stand densities were high (around 800 trees/ha), and the stand appears to have gone through a prolonged period of intense competition and density-dependent mortality with no evidence of non-stand replacing disturbances that generated gaps in the canopy. There was no Douglas-fir establishment after the initial pioneer cohort, but western hemlock established gradually in the understory, apparently in response to small gaps created by a prolonged period of self-thinning. The authors indicate that the Douglas-fir overstory developed long, deep crowns characteristic of old-growth canopies despite high initial stand densities and a lack of signifant non-stand-replacing disturbance or epicormic branching, but this conclusion is based on visual observation and detailed analysis of a single tree.

Winter, L.E., Brubaker, L.B., Franklin, J.F., Miller, E.A., and DeWitt, D.Q. 2002b. Canopy disturbances over the five-century lifetime of an old-growth Douglas-fir stand in the Pacific Northwest. Canadian Journal of Forest Research 32:1057-1070.

This study used tree ring records from a large stem-mapped plot to reconstruct canopy disturbance history in an old-growth stand in the Washington Cascades. They sampled all live Douglas-fir, all live western hemlock ≥ 40 cm dbh, and many snags within a 3.3 ha plot. Their results indicate that the stand experienced repeated moderate-large extent canopy disturbances during succession. that each reduced overstory densities, but did not completely removed the canopy to create large, open gap environments. None of these disturbances resulted in Douglas-fir regeneration, and their largest effect was to increase growth rates of western hemlock. The authors note that 80% of western hemlock growth increases were individual tree events, suggesting that repeated, small-scale disturbances also occurred during the life of this stand and contributed to structural development and vertical diversification.

# Management Impacts on Growth and Structural Development in Douglas-fir Forests: An Annotated Bibliography

Acker, S.A., Zenner, E.K. and Emmingham, W.H. 1998b. Structure and yield of two-aged stands on the Willamette National Forest, Oregon: implications for green tree retention. Canadian Journal of Forest Research 28:749-758.

This was a retrospective study of two-aged stands on the WNF to evaluate the effects of overstory retention on structural characteristics and yield. Basal area, volume, and MAI of the understory cohort declined as residual overstory basal area increased. Understory growth increased most rapidly with reductions in overstory basal area below about 10 $m^2$/ha (43 $ft^2$/ac). Note that the stands in this study had high densities of understory trees relative to typical managed stands (total relative densities between 0.68 and 1.05), so the effects of overstory retention level may have been exacerbated by high levels of competition within the understory cohorts. Understory recruitment periods after partial overstory removals were long, often lasting several decades within individual plots.

Andrews, L.S., Perkins, J.P., Thrailkill, J.A., Poage, N.J., and Tappeiner, J.C. 2005. Silvicultural approaches to develop northern spotted owl nesting sites, central Coast Ranges, Oregon. Western Journal of Applied Forestry 20(1):12-27.

This study used modeling approaches to evaluate the effects of various silvicultural treatment regimes at promoting the development of structural characteristics associated with habitat requirements for northern spotted owls. The results suggest that young stands (beginning at age 50) will not develop structural features associated with NSO nest sites by age 160 years in the absence of silvicultural intervention or natural disturbance. Silvicultural treatments that included heavy thinning in young stands (ages 50-80 years) followed by planting and repeated thinning in older stands were effective at creating NSO habitat characteristics by age 160.

Bailey, J.D., and Tappeiner, J.C. 1998. Effects of thinning on structural development in 40- to 100-year-old Douglas-fir stands in western Oregon. Forest Ecology and Management 108:99-113.

This study evaluated understory tree and shrub communities in Douglas-fir stands that had been thinned or unthinned and compared them to understory communities in adjacent old-growth stands. Study sites were spread throughout the Oregon Coast Range and western Cascades. Thinned stands had much higher understory conifer densities than unthinned stands and similar understory tree densities to old-growth stands. Thinned stands also had greater tall and low shrub cover than unthinned stands, and similar tall shrub cover to old-growth stands. LAI was similar across stand types, but more of the total LAI was found in the shrub layer in thinned stands than in other stand types. RDI's above the self-thinning threshold were associated with reduced understory tree densities in younger stands, but not in old-growth. The authors note that these responses suggest that even conventional commercial thinning treatments can promote tree regeneration establishment, shrub growth, and the initial development of multi-storied stands.

Burton, J.I., Ganio, L.M., and Puettmann, K.J. 2014. Multi-scale spatial controls of understory vegetation in Douglas-fir-western hemlock forests of western Oregon, USA. Ecosphere 5(12):1-34.

This study examined relationships between overstory environment, climate, incident radiation, and understory plant cover across a range of spatial scales in 40-60 year-old Douglas-fir stands across seven sites included in the BLM's Density Management Study. Thinning treatments included varying levels of overstory retention coupled with unharvested leave patches and gaps ranging from 0.1-0.4 ha in size. Overstory retention levels included high density (300 trees/ha distributed uniformly), moderate density (200 trees/ha distributed uniformly), and variable density (varying retention levels between 100-300 trees/ha across each treatment unit). At neighborhood scales, overstory density was associated with decreases in total understory cover, and the effect of overstory density became greater as the relative importance of western hemlock increased in all treatments except for the high density treatment. Total understory cover was higher in areas with higher potential radiation (e.g., southern exposures) in thinned treatments, but lower in areas with higher potential radiation in untreated controls. Increases in the cover of early seral understory species associated with reductions in neighborhood-scale overstory density were greater in treatments with higher disturbance severity (i.e., variable density or moderate density) than treatments with lower disturbance severity (i.e., high density or untreated control treatments), increased with increasing moisture deficits in areas with high potential radiation, and decreased with the cover of late seral understory species. Cover of late seral species decreased with increasing climatic moisture deficit when overstory density was high and the relative important of hemlock was high, and also decreased with increasing cover of early seral species.

Carey, A.B., Lippke, B.R., and Sessions, J. 1999. Intentional systems management: managing forests for biodiversity. Journal of Sustainable Forestry 9(3/4):83-119.

This study used forest-scale models of three management strategies for forests in the western hemlock series including a reserve approach (no management); maximum NPV approach focused on timber and fiber production, and an active management for conservation approach. The examined outcomes related to economics and the provisioning of a broad array of ecosystem services. The reserve-based approach resulted in long periods of competitive exclusion associated with an abundance of young forest types on the landscape, which would likely promote declines in some species. The maximum NPV approach produced late-seral forest only if wide riparian buffers were used, and even then over 200 years were required for 30% of the landscape to reach a late-seral condition. An active conservation/ecosystem management approach required only 80 years to get 30% of the landscape in late seral forest, and maintained over half of the landscape in late seral conditions in the long term. Net present values for the active conservation approach were 82% of those for the maximum NPV approach with small stream buffers, and greater than those of the maximum NPV approach with wide buffers. Their results suggest that active management may be necessary to promote rapid development of late seral habitat across a large portion of the landscape. Further, the incorporation of large riparian buffers delayed the time needed to attain a landscape condition of 30% late seral forest relative to an active-management conservation strategy.

Chambers, C.L., McComb, W.C., Tappeiner, J.C., Kellogg, L.D., Johnson, R.L., and Spycher, G. 1999. CFIRP: what we learned in the first ten years. The Forestry Chronicle 75(3):431-434.

This paper summarized 10-year results of the CFIRP study in terms of costs, biological responses, and human responses related to several silvicultural alternatives in mature Douglas-fir forests. CFIRP treatments included clearcut-with-reserves, shelterwood-with-reserves, and group selection cutting methods along with an untreated control. Stands were 80-120 years old at the time of harvest. Two-story and group selection treatments increased harvesting costs by 2.5-32% relative to clearcutting. Treatments had limited impacts on understory plant composition, apart from an increase in early seral species after harvesting. Seedling growth was similar among the clearcut and shelterwood treatments, but lower on average and more variable within the group selection treatment. Bird and small mammal communities in the group selection treatment were similar to unharvested control stands. Bird and small mammal communities in the shelterwood treatment, in contrast, were more similar to those in the clearcut treatment. Recreational forest users generally preferred the group selection and control treatments to the shelterwood and clearcut treatments.

Cole, E., and Newton, M. 2009. Tenth-year survival and size of underplanted seedlings in the Oregon Coast Range. Canadian Journal of Forest Research 39:580-595.

This study evaluated the growth of planted Douglas-fir, western hemlock, grand fir, and western redcedar seedlings following varying levels and patterns of overstory density reductions in 50-55 year-old Douglas-fir stands at two sites in the Oregon Coast Range. Thinning treatments were designed to reduce stocking levels to approximately 33% (low density), 42% (medium density), 50% (medium-high density) and 60% (high density) of full stocking. Post-thinning basal areas ranged from 19-33 $m^2$/ha distributed either uniformly, or by creating 0.06-0.1 ha gaps across 20% of the treatment area and thinning the matrix between gaps as needed to reach target stocking levels. The study also incorporated understory vegetation control treatments, but we have not summarized those results here. First-year mortality was unusually high as one of the two sites due to poor planting stock and dry, windy conditions during planting. At this site, seedling survival was adjusted for first-year mortality by using only those seedlings that survived through their first year to calculate mortality rates.

Seedling survival generally decreased as residual overstory density increased, but the effect was not consistent across sites or species. At the drier interior Coast Range site, adjusted survival of western hemlock did not vary with overstory density, but all other species had lower survival in the high density treatment (initial post-harvest basal areas of 31-33 $m^2$/ha). Seedling survival was lowest for Douglas-fir and hemlock, and highest for redcedar at the interior site. At the wetter, more coastal site, overstory density did not impact seedling survival of any species. Vegetation control treatments increased Douglas-fir seedling survival, but had little impact on the other species that were planted and had a minor effect on survival overall when compared to the effect of overstory density on survival.

Seedling size generally had a negative relationship with overstory density at both sites with greater growth in the low density treatment than the high density treatment for all species and sites. Douglas-fir growth, in particular was impacted by overstory basal area with notable declines in growth relative to open conditions at basal areas of 20 $m^2$/ha and very rapid declines in growth at basal areas of 27 $m^2$/ha or higher. Seedlings of the other, more shade tolerant species had greater heights than Douglas-fir in the medium and medium-high density treatments, although even the growth of shade tolerant species was very limited at basal areas of 30 $m^2$/ha or greater (i.e., in the high density treatment). Seedlings in gaps generally grew better than seedlings in the thinned matrix or in uniformly thinned treatments, regardless of species or site. High levels of herbivory on redcedar and Douglas-fir seedlings also reduced their growth and confounded overstory treatment impacts, particular for western redcedar at the moist coastal site.

The authors suggest that their results indicate repeated thinning would likely be necessary to keep overstory densities low enough to maintain understory cohort development in a two-aged stand. They indicate that even the growth and development of shade tolerant conifers in their low density treatment (thinned to about 33% of full stocking) is likely to decline as the overstory continues to develop, but they suggest that shade tolerant conifers in this treatment will likely be able to form a mid-story layer even without further thinning.

Comfort, E.J., Roberts, S.D., and Harrington, C.A. 2010. Midcanopy growth response following thinning in young-growth conifer forests on the Olympic Peninsula western Washington. Forest Ecology and management 259:1606-1614.

This study examined the growth response of mid-canopy western hemlock and western redcedar trees to variable density thinning treatments in young forests on the Olympic Peninsula. The study sites were part of the Olympic Habitat Development Study, which includes variable density thinning treatments in even-aged stands dominated by Douglas-fir, western hemlock, Sitka spruce, and western redcedar. Thinning treatments included 20-25% basal area reductions in a uniformly-thinned matrix with 10% of stand area in 0.1-0.3 ha leave patches and 15% of the stand area in 0.04-0.05 ha canopy gaps. Both mid-canopy western hemlock and western redcedar showed significant increases in basal area increment within 3-6 years of thinning, but mid-canopy trees in unthinned leave patches did not show a clear growth response following thinning. Live crown ratio displayed a significant, positive relationship with the magnitude of release, suggesting that crown size may be a good predictor of release potential in mid-canopy trees.

Competition with adjacent trees, measured by crown overlap, also appeared to have significant impacts on the growth of mid-canopy hemlock and redcedar. Relative size and age, along with general measures of competition such as the basal area of larger trees (i.e., neighborhood competitive environment), however, only had significant relationships with the growth response of western redcedar to thinning. Relative size and neighborhood-scale competition did not appear to have a significant impact on the growth response of western hemlock. These results suggest that mid-canopy hemlock and redcedar have the potential for rapid growth responses to thinning, and that silvicultural treatments that generate variable overstory environments can foster increased heterogeneity in the sizes of mid-canopy trees over time.

Curtis, R.O. 1994. Some simulation estimates of mean annual increment of Douglas-fir: results limitations, and implications for management. USDA Forest Service Pacific Northwest Research Station Research Paper. PNW-RP-471.

This study used several growth and yield models to evaluate impacts of various thinning regimes and site qualities on volume production in Douglas-fir stands. Culmination of MAI was generally late, and was delayed further by thinning. Additionally, the MAI curve is relatively flat around culmination, suggesting the potential for rotations that extend beyond culmination to maintain high volume production and yields. Short rotations (40-50 years) reduced volume production by 20-50% depending on site quality, with larger reductions occurring when initial stand densities were lower. These results suggest that extended rotations (circa 120-150 years) that include thinning could produce relatively high levels of volume while providing flexibility to meet other, non-commodity management objectives, particularly on low quality sites.

Curtis, R.O. 1995. Extended rotations and culmination age of coast Douglas-fir: old studies speak to current issues. USDA Forest Service Pacific Northwest Research Station Research Paper. PNW-RP-485.

This study evaluated MAI and PAI trends in 17 long-term, Douglas-fir thinning studies in western Oregon, western Washington, and British Columbia. Stand ages at the time of the most recent measurements ranged from 90-117 years, and none of the thinned stands had reached the culmination of MAI. The results suggest that thinning over extended rotations could be used to maintain relatively high levels of timber production while meeting a wide range of non-commodity management objectives. Even heavy thinnings (including a single, heavy initial cut down to circa 50 trees/acre, in one study) provided high-volume yields.

Curtis, R.O. 1998. "Selective cutting" in Douglas-fir. Journal of Forestry 96(7):40-46.

Curtis reviews the history of "selective cutting" experiments applied to old-growth Douglas-fir stands in the 1930s-1950s. He notes that Kirkland and Brandstrom's proposed method of selective (Kirkland and Brandstrom 1936) cutting called for a series of light initial thinnings followed by the creation of large openings in order to establish Douglas-fir regeneration and maintain this species in a multi-aged stand. The matrix between these openings would be treated with individual tree removals at each entry. Although Kirkland and Brandstrom specifically called for a series of light overstory removals followed by the creation of large openings to promote regeneration of a mixture of species, early experiments with selective cutting on federal lands in the PNW were implemented heavy partial cuttings that removed valuable overstory Douglas-fir and effectively released advance regeneration of shade tolerant understory species without promoting the regeneration of Douglas-fir. Residual Douglas-fir (which were primarily large, very old trees) experienced high levels of mortality (primarily associated with windthrow) in most stands and shade tolerant understory trees experienced high levels of damage during harvesting operations. However, trees in younger stands and stands that received only light thinning experienced much less damage. Reductions in the Douglas-fir component of these stands combined with high levels of canopy mortality following selective thinning led to the end of these trials in the 1950s.

Curtis notes, however, that selective cutting as proposed by Kirkland and Brandstrom (1936), would have overcome many of these perceived drawbacks by providing large openings for Douglas-fir regeneration and leaving higher densities of overstory trees to help limit damage and mortality to residual trees. In fact, Kirkland and Brandstrom's "selective cutting" was more similar to a small, patch clearcut system or a gap-based variable retention harvest system than it was to the heavy individual tree removal-based selective cutting trails that were implemented in old-growth Douglas-fir stands in the 1930s-1950s. Curtis also comments that Kirkland and Brandstrom's proposed "selective cutting" system bears striking resemblances to current proposals for repeated thinning in even-aged stands over long rotations followed by variable retention regeneration harvests that incorporate large openings of two or more acres to promote Douglas-fir regeneration establishment. Curtis concludes by observing that the lack of research on any silvicultural systems in the Douglas-fir region other than clearcutting from 1950 to the 1990s "severely handicaps" our current understanding of silvicultural alternatives for meeting

Deal, R.L., and Tappeiner, J.C. 2002. The effects of partial cutting on stand structure and growth of western hemlock-Sitka spruce stands in southeast Alaska. Forest Ecology and Management 159:173-186.

This study evaluates the impacts of partial cutting practices on stand structure, species composition, and tree growth in Sitka spruce/western hemlock forests of southeast Alaska. Stands were selected to represent a range of time-since treatment categories and to ensure that individual sites included varying within-stand harvest intensities. Although these harvests were designed to remove high value wood products and had not specific regeneration objectives, both hemlock and Sitka spruce regenerated effectively after harvesting. Residual hemlock and Sitka spruce showed rapid, positive growth responses to partial cutting across all size classes. Heavier cuttings favored more regeneration and increased Sitka spruce regeneration, while light cuttings primarily contributed to growth and crown expansion of residual trees. Size distributions of trees in partial cut stands were similar to those of the original, pre-harvest old-growth forest. Although these economically-driven partial cutting treatments made little effort to manage stand structure or encourage regeneration of Sitka spruce, they maintained stand structures similar to uncut old-growth stands. This strongly suggests that a more carefully designed silvicultural system based around partial overstory removals should be able to effectively maintain species compositions and stand structures characteristic of old-growth Sitka spruce/western hemlock in managed stands.

Deal, R.L., Tappeiner, J.C., and Hennon, P.E. 2002. Developing silvicultural systems based on partial cutting in western hemlock-Sitka spruce stands of southeast Alaska. Forestry 75(4):425-431.

This study compared stand structure, growth, species composition, and forest health indicators in partial cut Sitka-spruce/western hemlock stands to young, even-aged stands regenerating after clearcutting and uncut old-growth plots. Although partial cut stands were harvesting with an emphasis on extracting specific wood products and lacked specific objectives related to regeneration or stand structure, partial cuttings did not significantly alter species composition, stand-scale growth, or stand vigor and health. Structural diversity and plant species diversity were much greater in partial cut stands than in even-aged stands created by clearcutting. These results suggest that silvicultural systems that incorporate partial overstory removals could be an effective means of maintaining complex stand structures characteristic of old-growth conditions in managed Sitka spruce/hemlock forests.

Devine, W.D., and Harrington, T.B. 2008. Belowground competition influences growth of natural regeneration in thinned Douglas-fir stands. Canadian Journal of Forest Research 38:3085-3097.

This study used removals of competing understory vegetation and trenching experiments to examine relationships between understory vegetation, belowground competition from overstory trees, and the growth of natural Douglas-fir regeneration in thinned stands of Douglas-fir in western Washington. Sapling height and diameter growth were significantly reduced by the presence of belowground competition from overstory trees, but not by belowground competition from understory vegetation. Belowground competition from overstory trees also appeared to have greater impacts on growing season soil water content than competition from understory vegetation, although the removal of belowground competition from understory vegetation had an additive affect with the removal of belowground competition from overstory trees on soil water content. These results indicate that the growth of Douglas-fir saplings in the low-moderate light environments generated by a thinned overstory was significantly reduced by belowground competition from overstory trees, but was much less heavily impacted by competition from belowground resources from understory vegetation. The authors suggest that treatments designed to generate multi-cohort Douglas-fir stands must consider overstory treatments that generate both sufficient understory light levels and sufficiently large openings to reduce belowground competition from overstory trees. The authors also suggest that repeated entries may be necessary to manage overstory competition in a way that will maintain the development of understory cohorts of Douglas-fir.

Dodson, E.K., Ares, A., and Puettmann, K.J. 2012. Early Responses to thinning treatments designed to accelerate late successional forest structure in young coniferous stands of western Oregon, USA. Canadian Journal of Forest Research 42:345-355.

The study examined variable density thinning treatment impacts on structural development in 40-60 year old Douglas-fir stands across seven sites included in the BLM's Density Management Study. Thinning treatments included varying levels of overstory retention coupled with unharvested leave patches and (in some density management treatments) large gaps. Thinned stands had greater spatial variability in tree density, lower live crowns, and greater densities and growth of tree regeneration. This was especially true in thinned treatments that incorporated lower residual densities (mean densities of around 260-300 trees/ha 11 years after treatment). Treatments that incorporated canopy gaps had greater spatial variability, and increased overstory tree growth around gap edges compared to interior positions within the thinned matrix. Thinning treatments did little, however, to promote the development of large snags or CWD, and had limited impacts on the growth of the largest overstory Douglas-fir. The authors suggest that lower residual overstory densities and the incorporation of gaps appear to accelerate the development of understory trees and add to spatial heterogeneity, but may not contribute to the rapid development of other aspects of old-growth structure such as the presence of large trees and snags.

Dodson, E.K., Burton, J.I., and Puettmann, K.J. 2014. Multiscale controls on natural regeneration dynamics after partial overstory removal in Douglas-fir forests in western Oregon, USA. Forest Science 60(5):953-961.

The study examined variable density thinning treatment impacts on regeneration establishment in 40-60 year old Douglas-fir stands across seven sites included in the BLM's Density Management Study. Thinning treatments included varying levels of overstory retention coupled with unharvested leave patches and (in some density management treatments) large gaps. Multiple factors that operate across varying spatial scales were found to influence regeneration dynamics (e.g., species composition, landscape position, and neighborhood-scale variability in overstory and understory vegetation cover). Both seedling establishment and sapling recruitment were influenced by overstory density, with higher regeneration densities in areas of lower overstory basal area. This was particularly true for the relatively shade intolerant Douglas-fir, although western hemlock seedlings were able to establish in neighborhood environments with high residual basal area. Sapling recruitment, however, was largely limited to areas with lower residual overstory densities (100 trees/ha or less), particularly for Douglas-fir. Seedling establishment was found to be more heavily influenced by competition with understory vegetation than sapling recruitment. Douglas-fir regeneration also appeared to benefit from topographic positions with higher potential incident radiation, while western hemlock regeneration had a negative relationship with potential incident radiation.

Garber, S., Lam, T.Y., and Maguire, D.A. 2011. Growth and mortality of residual Douglas-fir after regeneration harvests under group selection and two-story silvicultural systems. Western Journal of Applied Forestry 26(2):64-70.

This study evaluated residual overstory tree responses 13-15 years after initial harvesting in the CFIRP study. CFIRP treatments included clearcut-with-reserves, shelterwood-with-reserves, and group selection cutting methods along with an untreated control. Stands were 80-120 years old at the time of harvest. Volume growth after harvesting was greatest in untreated controls and lowest in the two-storied treatments, although volume growth per unit of initial growing stock was similar across treatments. Residual tree mortality was highest in the two-storied treatments, although windthrow and logging injury accounted for less than ¼ of mortality. Growth releases took up to ten years or more to manifest, and the largest trees showed no statistically significant growth response to harvesting.

Gray, A.N., and Spies, T.A. 1996. Gap size, within-gap position and canopy structure effects on conifer seedling establishment. Journal of Ecology 84:635-645.

This study examined seedling establishment for Pacific silver fir, Douglas-fir and western hemlock in silvicultural gaps with gap diameter-tree height ratios ranging from 0.2-1.0 in mature and old-growth stands in the western Cascades of Oregon and Washington. On average, seedling establishment was higher in gaps than in closed-canopy areas, but establishment patterns were influenced by species, gap size and gap position. Establishment of silver fir and hemlock seedlings was lower in the northern portions of large gaps, suggesting that areas with direct solar radiation may be detrimental to the establishment of these species. The highest rates of seedling establishment for all species tended to be in the shaded environments of small gaps (diameter-height ratio of 0.2) and the shaded southern portions of larger gaps (diameter-height ratios of 0.4 and 1.0). Seedling size increased with increasing gap size, and was greatest near gap centers. Douglas-fir seedling growth was low in all but the largest gaps, while hemlock size increased with increasing gap size and silver fir size showed a more limited increase with increasing gap size. Natural regeneration of western hemlock in gaps was very limited in mature stands, but abundant in old-growth stands where hemlock seed trees were much more common in the overstory.

These results suggest that gap environments which promote high rates of establishment and survival (i.e., the moderated microclimate of small gaps and the southern portions of larger gaps) may not foster high rates of seedling growth. The high resource levels found in exposed gap environments (i.e., large gaps and central-northern portions of gaps), in contrast, contribute to greater seedling growth, but also promote increased stress that leads to higher seedling mortality. Compared to gap environments, the extremely low resource levels under closed canopy mature and old-growth forests contribute to low seedling establishment, survival, and growth, even for shade tolerant species.

Gray, A.N., and Spies, T.A. 1997. Microsite controls on tree seedling establishment in conifer forest canopy gaps. Ecology 78(8):2458-2473.

This study examined the impact of substrate type and understory vegetation density on the establishment and growth of Douglas-fir, western hemlock, and Pacific silver fir seedlings in experimental gaps with gap diameter-tree height ratios ranging from 0.2-1.0 in mature and old-growth stands in the western Cascades of Oregon and Washington. Seedling establishment was greater on deadwood than on an intact forest floor or mineral soil in untreated, closed-canopy areas, particularly for western hemlock. In general, seedling establishment was less heavily influenced by substrate as gap size increased, although seedling establishment on intact forest floor layers was lower than on mineral soil or deadwood in the northern portions of large gaps. Shade from woody debris or shade cloths in the northern portions of larger gaps promoted greater seedling establishment for all species, but shade from understory vegetation only promoted the establishment of Douglas-fir in these larger gaps. In contrast, shade from understory vegetation and shade cloths reduced seedling establishment in smaller gaps, southern portions of larger gaps, and in closed-canopy areas. Seedling size increased with increasing gap size, decreased with increasing levels of shade, and was typically highest on microsites with intact forest floor layers and lowest on microsites with deadwood.

This study's results suggest that microsite conditions are critical to the establishment and early growth of western hemlock seedlings, but somewhat less important for Douglas-fir and silver fir. Decayed logs appear to be important to hemlock establishment in shaded conditions due presumably to their ability to retain moisture longer into the growing season than intact forest floor environments. In the exposed conditions of large gaps, shade from decayed logs appears to provide an important amelioration of the local microclimate to promote greater rates of hemlock establishment. Both silver fir and Douglas-fir seedlings appear to benefit from the shade generated by woody debris or understory vegetation in the exposed areas of large gaps, but appear much less sensitive to microsite conditions and substrate type than western hemlock across a range of gaps sizes and positions as well as under an intact overstory. This appears to be particularly true for Douglas-fir.

Gray, A.N., Spies, T.A., and Pabst, R.J. 2012. Canopy gaps affect long-term patterns of tree growth and mortality in mature and old-growth forests in the Pacific Northwest. Forest Ecology and Management 281:111-120.

This study examined the impacts of gap size on the growth and mortality of trees surrounding gap edges over a 16-year period following experimental gap creation in mature (90-145 year-old overstory trees) and old-growth (350-525 year-old overstory trees) Douglas-fir stands in the western Cascades of Oregon and Washington. Experimental gaps were created with gap diameter-tree height ratios ranging from 0.2-1.0. Mortality of overstory trees within 8 m of gaps was no different than overstory trees in untreated control areas, regardless of gap size. In contrast, mortality of understory trees directly adjacent to gaps was higher than in untreated controls, but mortality of understory trees several meters away from the gap edge (i.e., further into the closed-canopy forest matrix) was lower than in untreated controls. Gap size had varying impacts on growth of edge trees however, and these impacts varied with stand age, crown class, and direction from gap center.

Growth of overstory edge trees in mature stands was generally greater than in untreated controls for all gap sizes, but growth of overstory edge trees in old-growth stands increased with gap size up to 1.0 gaps, where overstory edge tree growth was similar to that of overstory trees in untreated controls. In general, growth responses of edge trees to gap formation in mature stands were more consistently positive and less heavily influenced by gap size than growth responses of edge trees in old-growth stands. Diameter growth of edge trees decreased with distance from gap for all trees, but the effect varied with gap size, position, and crown group. For understory edge trees, growth appeared to decline more with distance from gap on the north side of smaller gaps and on the south side of larger gaps. In general, these results suggest that gap formation benefits the growth of residual trees around gap edges in both mature and old-growth stands, although growth responses of edge trees in old-growth stands may be limited when gap sizes are large. Gap formation did not appear to impact overstory tree mortality, although understory trees directly adjacent to gap edges appear to experience an increase in mortality after gap formation. The authors suggest that the contrasting growth responses of edge trees in mature and old-growth stands may suggest that trees in mature stands are more limited by belowground resources, while trees in old-growth stands are more limited by aboveground resources.

Halpern, C.B., and Spies, T.A. 1995. Plant species diversity in natural and managed forests of the Pacific Northwest. Ecological Applications 5(4):913-934.

This study analyzed data from repeated measurements on permanent plots and retrospective, chronosequence studies to examine patterns of vascular plant diversity in natural and managed stands dominated by Douglas-fir. In natural stands, vascular plant species diversity generally increases with time following canopy closure. In natural stands, most understory species were present, at least in low levels, through all stages of stand development. There were, however, large changes in the abundance of different species as stands age. These differences appear to be due to individual species tolerances for disturbance and stress (e.g., fire or shade), differences in establishment and growth rates following disturbance, and changes in environmental heterogeneity during stand development. High levels of diversity in old-growth stands appear to be linked to high levels of structural complexity that foster spatial heterogeneous environments and resource availability to promote a species with a wide range of life history traits.

Species diversity declined briefly following disturbance (logging and burning), but exceeded old-growth levels within two years of clearcut logging and broadcast burning as a result of an increase in native, ruderal plants. Diversity then generally rose over time to a peak prior to canopy closure, declined to its lowest point during the period in which canopy densities are highest, and then increased over time as canopies begin to open up and reorganize during mid-later stages of succession. At finer temporal scales, diversity actually showed several different peaks prior to canopy closure, representing short-term shifts in the composition and abundance of annual and perennial plants. The authors note that rapid recovery of residual species diversity following clearcutting and burning suggests that old-growth understory species have a large degree of tolerance (or at least resilience) to these disturbances. At a finer scale, however, residual species recovery was slower in areas where disturbance intensity was higher and some taxa showed as much sensitivity to canopy removal as to fire. These observations of species diversity in managed stands, however, only extend up to the point of canopy closure, and the authors note that our understanding of long-term management impacts on species diversity is limited by a lack of studies in older managed stands. The authors also suggest that silvicultural approaches incorporating a high degree of spatial variability including gaps, retention patches, and areas of dispersed retention, should contribute to maintaining taxa that are either disturbance-sensitive, environmentally sensitive, or that display long recovery times after disturbance. Similarly, variable planting densities (and species) and legacy retention should contribute to the maintenance of species diversity in managed forests.

Halpern, C.B., Halaj, J., Evans, S.A., and Dovciak, M. 2012. Level and pattern of overstory retention interact to shape long-term responses of understories to timber harvest. Ecological Applications 22(8):2049-2064.

This paper evaluated 10-year responses to the varying levels and patterns of overstory retention following variable retention harvests in 70-170 year-old Douglas-fir stands in western Oregon and Washington. Vegetation recovery after harvest was generally rapid. Most functional groups of understory plants returned to or exceeded pre-harvest levels within 6-10 years. Both rapid recruitment and growth of early seral species and recovery of disturbance-tolerant forest herbs contributed to the rapid recovery of herbaceous cover. Shrubs recovered more slowly due to slower growth rates and greater levels of harvest-related damage. Bryophyte cover did not recover from harvest-related declines within the 10 year post-harvest study periods. In general, increased levels of overstory retention moderated harvest impacts on understory communities. Dispersed retention moderated changes in cover of most plant groups relative to aggregated retention.

Early seral species herbs and shrubs contributed significantly to understory recovery in low retention areas regardless of retention pattern, but only increased in the open areas of aggregated retention treatments at higher retention levels. Cover of forest generalist herbs increased in every treatment except for high levels of aggregated retention, while forest generalist shrubs generally declined following harvesting. Although aggregates provided refugia for late seral herbs and bryophytes, large declines in the harvested matrix between aggregates and at low retention levels led to overall declines in late seral herb cover in all treatments except for the high density, dispersed retention treatment and in all treatments for bryophytes. These results suggest that silvicultural treatments may need to create a mosaic of retention patterns and levels across the landscape to target the conservation of a variety of understory functional groups. Areas of moderate-high dispersed retention or large undisturbed patches appear to benefit late seral herbs and bryophytes, large openings benefit early-seral species, and low-moderate levels of dispersed retention appear to benefit forest generalist herbs.

Harrington, T.B. 2006. Five-year growth responses of Douglas-fir, western hemlock, and western redcedar seedlings to manipulated levels of overstory and understory competition. Canadian Journal of Forest Research. 36:2439-2453.

This paper compared growth of Douglas-fir, hemlock, and redcedar seedlings planted in 40-70 year-old Douglas-fir stands that received either a clearcut, shelterwood (with reserves), or commercial thinning treatment. These treatments corresponded to understory light levels ranging from 100% full sun (clearcut), to 62% full sun (shelterwood), and 34% full sun (thinning). Treatments also included varying levels of chemical vegetation control including no vegetation control, a 4.5 $m^2$ area of vegetation control around selected seedlings, and a 9 $m^2$ of vegetation control around selected seedlings. Five years after planting, seedling stem volumes were four-eight times higher in clearcuts than in thinned stands and four-five times higher in shelterwoods than in thinned stands. Vegetation control increased seedling stem volume by two-four times in any given overstory treatment. Five-year seedling survival was high (>90%) regardless of treatment or species. Hemlock and redcedar growth responses to vegetation control were relatively consistent across overstory treatments, but Douglas-fir growth responses to vegetation control appeared to be limited by overstory competition in shelterwoods and thinned stands. Light availability appeared to be the greatest limitation to seedling growth for all species in thinned stands. In shelterwoods and clearcuts, however, there was evidence that belowground competition was the primary limitation to seedling growth.

Isaac, L.A. 1956. Place of partial cutting in old-growth stands of the Douglas-fir region. USDA Forest Service Pacific Northwest Forest and Range Experiment Station. Research Paper No. 16.

Isaac summarizes the results of partial cutting trials in Douglas-fir stands on federal lands of the Pacific Northwest during the 1930s and 1940s. Isaac *specifically states* that these cutting practices, which focused on the removal of individual high value overstory Douglas-fir in stands of varying age structure and composition, should not be confused with thinning (which is performed to benefit residual trees and vegetation in even-aged stands) or selection cutting (which is a regeneration cutting method intended to promote and maintain an uneven-aged stand structure). As implemented, these partial cutting experiments focused on individual tree removals of high value overstory trees (primarily Douglas-fir) across stands with overstory ages of 150-600 years, variable structures, and a range of species compositions in western Oregon and Washington.

On average, these harvests removed 36% of standing volume, with a range of about 20%-50%. Douglas-fir and Sitka spruce trees, primarily the oldest trees in these stands, showed either no change or decreasing growth rates during the 10 years after cutting, while shade tolerant species typically showed positive growth responses to partial cutting. Mortality was high during the first 5-10 years after cutting due to high levels of windthrow, and damage to residual trees during logging operations was also high (about 1/3 of residual trees experienced some logging-related damage). Douglas-fir regeneration was scarce and trends suggest a trajectory that would shift species composition towards shade tolerant hemlock, cedar, and true firs. Although Isaac specifically stated that these partial cutting treatments were not synonymous with the selection system for uneven-aged silviculture, he concludes that the results of partial cutting trails in Douglas-fir forests suggest that uneven-aged management would be inappropriate for this system *in most cases*. He does, however, note that the selection system might be a viable approach on dry sites in southwest Oregon, around the fringe of the Willamette Valley, and on the gravelly soils of the Puget Sound.

Kirkland, B.P., and Brandstrom, A.J.F. 1936. Selective timber management in the Douglas fir region. USDA Forest Service. Washington, DC.

Kirkland and Brandstrom proposed a method of “selective timber management” for Douglas-fir in the Pacific Northwest. The foreword makes it clear that this was intended to be a flexible approach that could be adapted to local conditions rather than a rigid silvicultural system, and that it was intended to provide a distinct alternative to exploitive partial cutting practices of the day (which were also called “selective logging” or “selective cutting”). Kirkland and Brandstrom based their approach on economic objectives with the intention of creating a method that would promote sustained yields and economic returns rather than contemporary partial cutting practices that focused on liquidating the highest value trees without consideration for future value or development. Their selective timber management approach included several key concepts:

- A light initial cut of 15-25% of the standing volume to remove “overmature” timber. This entry would include both individual tree removals and patch cuttings of 1-10 acres and served as a mixture of a salvage cut and thinning.
- Development of a permanent road system during the initial cut for skidding, to facilitate repeated entries, and to facilitate fire suppression efforts.
- Repeated entries on very short cutting cycles (as little as five years) to manage the growth and recruitment of understory trees.
- Management of the growing stock that allowed the majority of volume to come from the harvest of large, 100-200 year-old trees in each entry.

Kirkland and Brandstrom argued that this approach would promote a forest with densely-stocked patches of Douglas-fir (that established in the patch cuttings) as well as multi-aged patches of shade tolerant conifers. Although cutting cycles were intended to be short, overstory trees intended were to reach 100-200 years of age and these large overstory trees were meant to provide the bulk of the volume removed in each individual entry.

Kuehne, C., Weiskittle, A.R., Fraver, S., and Puettmann, K.J. 2015. Effects of thinning-induced changes in structural heterogeneity on growth, ingrowth, and mortality in secondary coastal Douglas-fir forests. Canadian Journal of Forest Research. 45:1448-1461.

The study examined variable density thinning treatment impacts on the development of structural diversity along with relationships between structure and plot-level growth and yield in 40- to 60-year-old Douglas-fir stands across seven sites included in the BLM’s Density Management Study. Thinning treatments included varying levels of overstory retention coupled with unharvested leave patches and (in some density management treatments) large gaps. Compared to unharvested control stands, thinning treatments created only marginal differences in most measures of stand structure including mean tree diameters (larger in some thinned treatments), spatial arrangement of trees (trees were more aggregated/clustered in thinned treatments), and lower canopy roughness in the moderate density and variable density treatments. The authors suggest that limited time-since harvest (11 years) and the use of a thin-from-below approach that removed most trees in overtopped and intermediate crown classes from thinned stands both contributed to the lack of strong differences in structural complexity among between thinned and unharvested stands. The authors did not find evidence of broad-scale differences in structural heterogeneity among the three thinning treatments represented in the Density Management Study, and suggest that this was likely caused by the inclusion of similar elements in many or all of the treatments (e.g., underplanting, leave islands, canopy gaps, riparian buffers, etc.). The variable density treatment, which included leave islands, canopy gaps, and varying residual overstory densities in the thinned matrix did, however, show a more consistent pattern of increasing structural heterogeneity over the 11-year post-treatment period than the uniform density thinning treatments. All thinning treatments promoted sapling ingrowth, but overstory tree mortality rates were higher in the uniform density thinning treatments (overstory densities of either 200 trees/ha or 300 trees/ha in the thinned matrix) than in the variable density thinning treatment (overstory densities ranging from 100-300 trees/ha in the thinned matrix). The authors suggest that thinning methods which retain trees across all crown classes, rather than thinning from below, may offer greater opportunities for increasing structural heterogeneity in young, even-aged Douglas-fir stands.

Lam, T.Y., and Maguire, D.A. 2011. Thirteen-year height and diameter growth of Douglas-fir seedlings under alternative regeneration cuts in the Pacific Northwest. Western Journal of Applied Forestry 26(2):57-63.

This study evaluated planted Douglas-fir seedling responses to varying regeneration cutting methods in the CFIRP study. CFIRP treatments included clearcut-with-reserves, shelterwood-with-reserves, and group selection cutting methods along with an untreated control. Stands were 80-120 years old at the time of harvest. Cumulative height and diameter growth as well as the most recent five years' height growth were all significantly impacted by treatment with seedling growth decreasing as overstory basal area increased. Their results suggest that residual overstory basal areas < 80 $ft^2$/ac allow establishment, growth, and persistence of Douglas-fir regeneration although growth continued to increase at lower residual basal areas.

Latham, P., and Tappeiner, J. 2002. Response of old-growth conifers to reduction in stand density in western Oregon forests. Tree Physiology 22:137-146.

This study examined the influence of overstory density reductions (both light thinning and irregular shelterwood treatments) on the growth of large, old Douglas-fir, ponderosa pine, and sugar pine. Positive growth responses of large, old trees to stand density reductions were common (68% of trees) and long-lived (elevated growth rates lasted at least 20 years). Growth responses were, however delayed by 5-25 years after thinning with the largest growth responses frequently occurring 20-25 years after thinning. There was no strong evidence that density reductions reduced growth of large, old trees. Although some old trees did not show a growth response to thinning, their stable growth following thinning contrast with old trees in nearby unthinned stands that showed growth declines over the same period. Even relatively small density reductions promoted positive growth responses in old-trees, although larger density reductions did not produce significantly greater increases in growth following thinning.

Latta, G., and Montgomery, C.A. 2004. Minimizing the cost of stand level management for older forest structure in western Oregon. Western Journal of Applied Forestry 19(4):221-231.

The authors evaluated the cost-effective methods for obtaining late seral and old-growth structure on private forestlands in western Oregon by applying an optimization approach to simulations individual tree growth models. They modeled several silvicultural alternatives using FIA data representing a wide range of site and stand conditions in western Oregon. Silvicultural alternatives included a no action reserve approach, 0-3 thinning at varying intensities with clearcutting at varying stand ages followed by either natural regeneration or planting and an option for early precommercial thinning. Their results suggest that repeated thinnings with heavier removals than typical commercial thinning operations in Douglas-fir were required to generate old forest attributes in managed stands. Earlier thinning was needed to promote old forest attributes on high quality sites than on low quality sites, and rotation lengths that optimized costs while meeting a minimum set of old forest structure requirements ranged up to 155 years. For newly planted stands, opportunity costs associated with management for old forest attributes are highest on high quality sites, but this relationship between site and cost did not apply to the management of existing stands. Active management approaches produced old forest structure more rapidly and had lower opportunity costs than reserve approaches. In general, these results are consistent with recommendations to thin early and repeatedly derived from empirical studies of structural development in managed Douglas-fir forests.

Long, J.N. 1998. Multiaged systems in the central and southern Rockies. Journal of Forestry 96(7):34-36.

Long argues that discussions about the use of even-aged and uneven-aged silvicultural systems should be driven by structural targets deemed necessary to meet management objectives. He notes that silviculturists require methods for assessing, controlling, and allocating growing stock and argues that stand density index (SDI)-based methods offer the flexibility to create a wide range of stand structures that span a continuum from those typical of classical even-aged management to irregular, uneven-aged stands. Basically, SDI assessments and targets for multi-aged or complex stand structures can be generated by calculating component SDI values for each size class (or species, although Long does not address that in this paper) and summing them to get a total stand-value. Different allocations of total target SDI among size classes can be used to generate different stand structures or encourage different patterns of structural development.

Maguire, D.A., Halpern, C.B., and Phillips, D.L. 2007. Changes in forest structure following variable-retention harvests in Douglas-fir dominated forests. Forest Ecology and Management 242:708-726.

This study examined short-term impacts of varying levels (100%, 75%, 40%, and 15% basal area retention) and patterns (aggregated vs. dispersed) of overstory retention on overstory structural characteristics in the DEMO study. For a given target retention level, dispersed retention resulted in significantly higher mean canopy cover than aggregated retention, which could help minimize environmental stress for shade-dependent forest plants associated with harvesting. Variable retention harvesting tended to reduce (at least in the short-term) vertical complexity, regardless of pattern of retention. However, horizontal variability in structural characteristics (including vertical structure) was increased by aggregated retention and decreased by dispersed retention. Initial conditions also played large roles in determining structural responses to harvesting, particularly with respect to within-stand heterogeneity.

Miller, M., and Emmingham, B. 2001. Can selection thinning convert even-age Douglas-fir stands to uneven-age structures? Western Journal of Applied Forestry 16(1):35-43.

The authors evaluated the impacts of selection thinning (i.e., the removal of trees in the dominant crown class to favor trees in lower crown classes) on tree growth, stand yields, and natural regeneration success to determine whether selection thinning could be a viable method for converting even-aged Douglas-fir stands into an uneven-aged structure. Selection thinning in young (<80 year-old) stands was found to produce yields equal to or greater than estimates for unmanaged stands of similar site quality and stocking, but produced lower yields than those estimated for stands managed using traditional thinning from below. Selection thinning did result in the development of multi-aged stands with a range of tree diameters and heights. Natural Douglas-fir regeneration was common and had modest growth rates under selection thinning, although stocking levels under which Douglas-fir regeneration established were generally much lower than those recommended for maximum yields under even-aged management guidelines. As stocking levels increased, natural regeneration of more shade tolerant grand fir and western hemlock became more common.

Munger, T.T. 1950. A look at selective cutting in Douglas-fir. Journal of Forestry 48(2):97-99.

Munger describes the historical events that led to a temporary shift from clearcutting to partial cutting practices in Douglas-fir forests of the PNW during the early 20th century. He notes that "selective cutting" practices initially developed following the introduction of mechanized tractors for skidding logs in the PNW. These early selective cutting practices were largely a form of high-grading that was focused on harvesting the highest value trees either with or without plans for subsequent entries in the affected stands. Munger suggests that Kirkland and Brandstrom's (1936) ideas about selective cutting drew interest from a logging industry that was losing money clearcutting stands with a high percentage of low value volume. Munger describes Kirkland and Brandstrom's proposed system as synonymous with individual tree selection cutting on short cutting cycles and indicates that an eager forestry community embraced this approach although foresters at the time debated its appropriateness as a silvicultural system for Douglas-fir. Munger describes disagreements about the appropriateness of selective cutting approaches between the silviculturally-oriented and economical-oriented researchers of the day. These early partial cutting experiments, which relied on fairly heavy removals (35-36% of standing volume in a single entry, on average) resulted in high levels of residual tree mortality from windthrow and high levels of tree damage, subsequent decay associated with logging injuries, and a net loss in volume production. Munger indicates that these results led to a shift back towards clearcutting in most of the PNW, and notes that the results of selective cutting trials in older forests should not be used to discredit the validity of thinning as a silvicultural tool in younger "thrifty" stands.

Newton, M., and Cole, E.C. 1987. A sustained-yield scheme for old-growth Douglas-fir. Western Journal of Applied Forestry 2(1):22-25.

This study analyzed growth and yield of repeatedly-thinned Douglas-fir stands aged 120 and 140 years. MAI had not culminated in either stands, and individual tree diameter growth rates were still increasing with time after 120-140 years. Growth responses to removal of understory and midstory bigleaf maple suggest that these understory trees were not having major impacts on overstory Douglas-fir growth. Structural features such as tree size distributions, densities, and damaged tops after repeated thinning were consistent with old-growth definitions, although deadwood abundance was low relative to minimum standards for old-growth

Newton, M., and Cole, L. 2015. Overstory development in Douglas-fir-dominant forests thinned to enhance late-seral features. Forest Science 61(4):809-816.

This study evaluated overstory growth and yield over 15 years after thinning to various residual stocking levels in 50-55 year-old Douglas-fir stands in the Oregon Coast Range. Thinning treatments were designed to reduce stocking levels including approximately 33% (low density), 42% (medium density), 50% (medium-high density) and 60% (high density) of full stocking. Target stocking levels were reached through either uniform thin-from-below treatments or by harvesting 20% of the stand in 0.06-0.1 ha gaps and thinning the matrix between gaps as needed to reach target stocking levels. Volume growth per unit area was greater in the high density treatments (with or without gaps) than in any other treatment, and was higher at medium densities than at low densities for one of the two sites included in the study. Simulation runs suggested that the culmination of mean annual increment would occur after 100 years of age in all treatments. Basal area growth per unit area was greater in the high density treatment than in the low density treatment. Differences in growth between gap-thinned stands and uniformly thinned stands were not statistically significant.

All treatments developed similar densities of trees greater than 30 inches dbh by age 65 and model estimates suggested that all treatments would generate at least 20 trees/acre greater than 30" diameter by age 103. Quadratic mean diameters were lowest in high density treatments, however, due to a higher density of small diameter trees in that treatment. Mortality was generally low across treatments, and the authors note that their thinning treatments would not be likely to create large snags as early as natural stands, unless specific silvicultural interventions were made to generate snags from large live trees.

O'Hara, K.L. 1998. Silviculture for structural diversity: a new look at multiaged systems. Journal of Forestry 96(7):4-10.

O'Hara states that shifting management objectives that encourage the maintenance and development of complex stand structures call for new methods of managing multi-aged stands. He singles out the allocation of growing stock among size or age classes as a significant step in the process of multi-aged management through which silviculturists have the flexibility to generate a wide range of stand structures. He argues that traditional uneven-aged management approaches using the BDq system have little ecological basis in most systems, provide limited flexibility to create irregular stand structures, and promote an overwhelming emphasis on diameter distributions at the cost of consideration for management of other structural attributes. Silviculturists should instead focus on broader elements of stand structure and structural development to meet a wide range of management objectives. He argues that two-aged and multi-aged stands can be appropriate for the management of both pure and mixed stands of shade intolerant species and shade tolerant species by appropriately allocating growing space among different species, canopy layers, and age classes.

O'Hara then compares several elements of even-aged and uneven-aged management. He notes that maintenance of shade intolerant species in multi-aged stands simply calls for lower leaf areas and relative densities in overstory trees. Studies of productivity in even-aged vs. uneven-aged stand structures provide variable results that seem partly to be ecosystem-specific in nature. He argues that costs of uneven-aged management can be moderated by using longer cutting cycles. Uneven-aged systems often offer opportunities for natural regeneration establishment, although a desire for prompt regeneration may necessitate planting. Finally, he argues that growing stock allocation systems based on SDI or leaf area allocation offer greater flexibility to create a range of stand structures than traditional uneven-aged silvicultural systems that use the BDq method of growing stock allocation.

O'Hara, K.L., and Gersonde, R.L. 2004. Stocking control concepts in uneven-aged silviculture. Forestry 77(2):131-143.

This paper reviews several alternative methods of stocking control and growing space allocation in uneven-aged stands. The basic purpose of stocking control is to alter the number and arrangement of trees in stands in order to create varying structures to satisfy different management objectives. By altering the allocation of growing space to different element of stand structure (e.g., different size/age classes, species, or canopy layers), silviculturists can generate or encourage a wide range of stand structures.

- The BDq system uses a target basal area (B), maximum diameter class (D), and q-factor (q), which is the ratio of trees in one diameter class to the next larger diameter class, to allocate growing stock. This method focuses on the manipulation of stem densities within individual diameter classes to create different target diameter distributions. Harvests focus on removing trees form diameter classes that are overstocked relative to targets. The BDq system has been widely researched and its greatest advantage is perhaps the knowledge base and experience available to guide its implementation. However, the approach focuses on generating negative-exponential (a.k.a., "reverse-J") diameter distributions and may lack the flexibility required to create a wide range of stand structures.
- The plenter system is a method of uneven-aged stocking control used in European forests dominated by species that regenerate readily in shaded conditions. The plenter system relies on identifying and carefully maintaining a target diameter distribution in which periodic removals will equal periodic growth. In practice, these target distributions vary with species composition and site conditions and rely on an in-depth understanding of growth patterns in trees of varying sizes.
- In SDI-allocation silviculturists choose a target stand density index for the whole stand, and then allocate this total among size/age classes or crown classes. This method allows for a great deal of flexibility as SDI can be allocated in varying proportions across size classes to create a wide range of stand structures for any given total level of site occupancy. The primary advantages of this method include a great deal of flexibility relative to target stand structures and the ability to use existing density management tools developed for even-aged stands to guide total SDI targets and calculate the contributions of individual size classes to this total.
- Leaf area allocation work similar to SDI-allocation in that a target leaf area index (LAI) is chosen and then allocated among size classes, age classes, or species. This method

relies on predictive models to estimate total LAI and component LAIs using regular inventory data as inputs. The advantages of leaf area allocation are similar to those listed for SDI allocation, as well as creating a linkage between management decisions and the primary physiological integrator of both individual tree and stand productivity (leaf area). The primary disadvantage is that the models required to apply this method have only been developed for a subset of species which do not yet include most species found in Douglas-fir forests of the Pacific Northwest.

Roberts, S.D., and Harrington, C.A. 2008. Individual tree growth response to variable-density thinning in coastal Pacific Northwest forests. Forest Ecology and Management 255:2771-2781.

This study evaluated the impacts that different neighborhood-scale structural environments had on individual overstory tree growth responses following variable density thinning treatments in the Olympic Habitat Development Study. Mean basal area growth rates of trees in the thinned matrix were, on average, 25% higher than trees in unthinned “skips”, and the growth rates of trees on the edges of gaps or skid trails were about 11% higher than those of trees in the thinned matrix interior. Although the thinning treatment was relatively light, removing 20-30% of pre-harvest basal area, these growth responses were apparent just five years after treatment, suggesting the potential for rapid overstory release.

Shatford, J.P.A., Bailey, J.D., and Tappeiner, J.C. 2009. Understory tree development with repeated stand density treatments in coastal Douglas-fir forests of Oregon. Western Journal of Applied Forestry 24(1):11-16.

This study evaluated the impacts of repeated thinning on understory tree growth and development in Douglas-fir/hemlock stands in the Oregon Coast Range. Advance regeneration of Douglas-fir and hemlock established after the first thinning responded to a second thinning with increased growth rates, but responses of understory Douglas-fir to thinning were limited. Repeated thinnings were effective, however at increasing understory tree growth considerably, with the largest 10% of hemlock saplings growing into midstory positions by stand ages of 50-70 years and the largest 10% of Douglas-fir saplings more than doubling their height within a few years of a second thinning. The authors note that heavy and repeated thinning combined with understory thinning of hemlock may be necessary to promote rapid growth in understory Douglas-fir.

Wilson, D.S., and Puettmann, K.J. 2007. Density management and biodiversity in young Douglas-fir forests: challenges of managing across scales. Forest Ecology and Management 246:123-134.

This review synthesized finding from several large-scale silvicultural experiments to examine short-term understory vegetation responses to thinning treatments that incorporated elements such as gap creation, unthinned leave patches, and variable overstory densities. General trends in understory responses to thinning were similar, regardless of thinning intensity. Following thinning, understory vegetation cover briefly declines and rapidly recovers. This period of reduced cover and subsequent recovery is generally longer for shrubs, particularly tall shrubs, than for herbaceous species. Retrospective studies that have examined understory communities one or more decades after thinning, however, indicate that both shrub cover and herbaceous cover are generally higher 10-30 years after thinning than in similar-aged unthinned stands. This recovery is associated with a shift in understory vegetation composition towards early seral species. Thinning promotes increased within-stand variability in herbaceous and shrub cover, particularly when thinning treatments incorporate variable overstory environments (i.e., gaps, leave patches, and variable residual overstory densities). Changes in understory composition across studies were heavily influenced by pre-treatment vegetation and abiotic site characteristics, but general trends following thinning included a short-term (up to 10 year) increase in early seral species followed by a shift towards mature forest communities by 20-40 years after thinning.

Zenner, E.K., Acker, S.A., and Emmingham, W.H. 1998. Growth reduction in harvest-age, coniferous forests with residual trees in the western central Cascade Range of Oregon. Forest Ecology and Management 102:75-88.

This study examined residual overstory tree impacts on the growth of an understory Douglas-fir cohort following fire by comparing trees in stands with residual overstory trees to those in stands without a residual overstory. Understory tree age ranged from about 60-120 years old. Regression models suggested reductions in growth of the understory volume has an exponential relationship with residual overstory density with growth reductions ranging from 23% at five residual trees/ha to 47% at 50 residual trees/ha, although including residual tree volume growth lowered these reductions in stand volume growth to 19% and 41%, respectively. Understory volumes were highest in the stands with the lowest understory densities, suggesting that thinning of the understory cohort in two-aged stands could limit volume production losses associated with competition from residual overstory trees.

## Commentary Pieces and Reviews: A Not-So-Annotated Bibliography

We chose to focus this document on resources that describe 1) patterns of structural development following natural disturbance, 2) developmental responses to a variety of silvicultural approaches in the Douglas-fir region, and 3) the state of knowledge related to uneven-aged management in the PNW. There are, however, many excellent commentary pieces and broad-spectrum reviews of varying management strategies and approaches that are highly relevant to discussions of management in older Douglas-fir stands. Although a thorough listing and summary of this literature base is outside the scope of this document, we have listed several representative commentary and review pieces below for your reference.

Aubry, K.B., Halpern, C.B., and Peterson, C.E. 2009. Variable-retention harvests in the Pacific Northwest: A review of short-term findings from the DEMO study. Forest Ecology and Management 258:398-408.

Bauhus, J., Puettmann, K., and Messier, C. 2009. Silviculture for old-growth attributes. Forest Ecology and Management 258:525-537.

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Shulte, L.A., Mitchell, R.J., Hunter, M.L., Franklin, J.F., McIntyre, R.K., and Palik, B.J. 2006. Evaluating the conceptual tools for forest biodiversity conservation and their implementation in the U.S. Forest Ecology and Management 232:1-11.

Spies, T.A., Hemstrom, M.A., Youngblood, A., and Hummel, S. 2006. Conserving old-growth forest diversity in disturbance-prone landscapes. Conservation Biology 20(2):351-362.

Swanson, F.J., and Franklin, J.F. 1992. New forestry principles from ecosystem analysis of Pacific Northwest Forests. Ecological Applications 2(3):262-274.

Zenner, E.K. 2000. Do residual trees increase structural complexity in Pacific Northwest coniferous forests? Ecological Applications 10(3):800-810.