AN ABSTRACT OF THE THESIS OF

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Ages, diameter growth, density, tree size, and species were studied in old-growth, plantation, and young natural Douglas-fir stands in three areas in western Oregon: the western and eastern Coast Range and the western Cascades. The purpose was to compare the development of these three stand types and to determine whether plantations and young natural stands would develop old-growth structures and characteristics.

The Douglas-fir age ranges in plantations (8 to 15 yr) were much narrower and than the ranges of tree ages found in the young natural (21 to 102 yr) and in the old-growth stands (300 to 354 yr). This wide range of tree ages, along with diameter growth rates and tree and stand structural characteristics, supported the hypothesis that old-growth developed at low initial stand densities. These low initial stand densities, probably the result of prolonged stand establishment, likely enabled height and crown size advantages among old and younger trees. Dominant and large codominant trees maintained live crown ratios and sustained

diameter growth resulting in large stable trees indicated by low height-to-diameter ratios. The mean diameters of the dominant trees in the old-growth and the dominant trees in the young natural stands were not significantly different at age 40 and 100, indicating the young natural stands appear to be growing at the same rates as the old-growth in its first 100 years. The mean dominant diameters in the plantations and old-growth at age 40 and 100 were significantly different, indicating the plantations are growing and developing differently than young natural and old-growth forests. Plantations had grown rapidly for the first 20 to 30 years, and computer simulation indicated that a significant rapid decline in radial growth would occur between ages 30 and 55. Simulations also indicate that during this period, the mean diameters of the dominant plantation trees would fall below those of the old-growth in two of the three stands by age 85. Pre-commercial thinning 20 to 25 years ago in the plantations has helped sustain high early growth rates for a longer period of time than would have occurred if thinning had not been performed. Additional thinning in the future is likely needed to maintain rapid current rates. When simulated to age 250 both the young natural stands and the plantations maintained higher densities of smaller diameter trees than the old-growth stands. This simulation result indicates the possible inability of these stands to self-thin to the densities found in old-growth stands without some sort of density-reducing disturbance. The broad range of tree ages in the old-growth stands suggests that stand disturbances are a normal part of old-growth development on these sites.

Five different plantation thinning options were also simulated to age 250, including additional options with thinning of understory trees and ingrowth. The projections indicate that when the plantations are left unthinned they would generally develop trees with small live crowns and mean diameters but still produce stable dominant overstory trees (low H:D ratios).

Shade tolerant understory trees and ingrowth, such as western hemlock, are a key part of old-growth development. These trees may reduce the rate of growth and alter crown structure of the overstory trees over extended periods of time (200+ years). Additional thinning, possibly in multiple entries, in both the overstory and understory may be necessary for dense plantations to develop the tree size heterogeneity found in local old-growth forests.

I also demonstrated a methodology to determine site-specific management targets or goals for creating old-growth structure from plantations. This was performed using past and current forest structure and composition information within a local landscape scale of 500 to 1000 acres, typical of the public land checkerboard ownership pattern. Stand types making up the historical landscape are identified and described retrospectively using historical and current aerial photographs and digital orthophotos, cruise records, previous studies, and sample plots of standing and harvested forests. The degree of detail provided through this methodology will likely help forest managers to define complex late-successional characteristics of stands and landscapes. My results indicate that stand and project area-specific definitions of old-growth and clearly defined goals for young stand management will facilitate development of old forest characteristics.

Comparing Structure and Development of Douglas-fir Old-growth, Plantations, and Young Natural Forests in Western Oregon

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

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CHAPTER ONE: INTRODUCTION

The Northwest Forest Plan set aside approximately 7.4 million acres (3 million hectares), in the range of the northern spotted owl, as late-successional reserves (LSR's) to provide functioning old-growth ecosystems (Barbour et al. 1997). This shifted federal forestland management from primarily wood production to biodiversity and species protection. Approximately one third of the lands devoted to accomplishing these goals had been regenerated into densely stocked timber production plantations and managed forest stands prior to the Northwest Forest Plan. Much is still unknown about how these Douglas-fir plantations develop and grow in comparison to natural forests. The management of many plantations on federal lands for future late-successional forest structures and functions can be aided by understanding how plantations develop compared to natural forest stands.

Plantations and managed forest stands have been established for timber production and have traditionally been managed for homogeneity in structure (Hansen et al. 1991; Coates and Burton 1997; Bailey and Tappeiner 1998) with the purpose of wood production. This type of management was implemented primarily to optimize and predict tree growth (Coates and Burton 1997). Even light to moderate thinnings from below tend to homogenize overstory spatial variability within a stand by reducing the range of diameter size classes (Bailey and Tappeiner 1998). To maintain and develop unique structural features found in old-growth forests across the landscape, there is a need to not only preserve old-growth in reserves, but also to create or enhance old-growth features in managed forests through active silvicultural management (McComb et al. 1993; Coates and Burton 1997; Coates 1997; Hale et al. 1999; Carey and Harrington 2001; Thysell and Carey 2001; Mitchell et al. 2002). In contrast, many people hope that important old-growth structure and habitat elements across the landscape will be maintained simply by lengthening the rotation ages of managed forests on public lands (Hale et al. 1999). This "hands off approach" is one possible strategy that should at least be considered given the level of uncertainty regarding the dynamics of forest development; but an approach that diversifies management strategies across the landscape is likely the most appropriate in case any one strategy proves to be wrong.

Pacific Northwest conifer plantations traditionally have not been managed to encourage biodiversity and ecological function. On both public and private lands they are managed on relatively short rotations (typically 40 to 80 years) and their interval between disturbances is shorter than in natural forests. Plantations alter landscape age-class distributions, may simplify the diversity of forest structure (ecosystem structure) and vegetative community composition at stand and landscape scales (Carey and Curtis 1996), and they have resulted in forest fragmentation (Hansen et al. 1991; Spies and Turner 1999; Carey and

Harrington 2001). Plantations typically have rather uniform tree spacing, species, size distributions, and generally fewer large snags and remnant large old trees compared to some young natural stands (Hansen et al. 1991) and old-growth stands. Among stands, plantation management and harvesting has resulted in more frequent and intense disturbances that are less variable in size, type, and distribution than occurred through natural disturbance events (Hansen et al. 1991).

The structural and compositional characteristics such as ages, densities, diameter growth, tree size, and species of second growth Douglas-fir forests in western Oregon managed on long rotations also have not been quantified, and their similarity to those found in local old-growth forests have not been fully assessed. In addition, these characteristics have not been compared to those produced in thinning management strategies such as variable density thinning.

Various silvicultural approaches, including thinning, are probably needed to manage for old-forest characteristics on the landscape due to the uncertainty inherent in management and in the dynamic nature of these forest systems. Conserving biodiversity and ecological function may only be achieved by maintaining structurally diverse forests that provide habitat niches for maintaining native species (McComb et al. 1993; Drever and Lertzman 2002; Pommerening 2002; Nyland 2003). Silvicultural approaches can sustain biodiversity and reduce the structural differences between managed forests and old-growth (McComb et al. 1993; Barbour et al. 1997; Busing and Garman 2002;

Palik et al. 2002), because many linkages exist between forest structure, forest biota, and ecosystem processes (Palik et al. 2002). In addition, some scientists believe that function will follow form, implying that the structural outcome may be more important than how a forest achieves the structure (Palik et al. 2002). The active restoration of ecosystems through the management of structure may be needed before natural disturbances can operate in forests in ways that will maintain native biodiversity (Mitchell et al. 2002). Adoption of any strategy to sustain biodiversity through management of processes, such as disturbance processes, will require the approaches to be adaptable to site-specific situations and management objectives (Palik et al. 2002).

Within the Northwest Forest Plan thinning is allowed in federal reserve areas to promote late-successional forest structure in plantations younger than 80 years (Bailey 1996), but there is insufficient knowledge of the densities and arrangements of trees surviving natural disturbances to determine exactly how to implement these thinnings. Recent findings by Tappeiner et al. (1997), Poage (2001), and Poage and Tappeiner (2002) suggest that parts of old-growth stands regenerated at low initial densities and over extended recruitment periods. This hypothesis is supported by their evidence that the large old-growth trees had rapid early growth and a wide range of ages. Various conditions could have produced rapid early growth rates and it has been well demonstrated that low stand density enables young trees to grow at rates like those of large old-growth trees. The limited age ranges found in plantations have resulted in narrower ranges of tree sizes than in young natural stands (Hansen et al. 1991) and old-growth forests. Both Poage and Tappeiner (2002) and Tappeiner et al. (1997) found that trees in young stands were growing at a slower rate than old-growth trees in their first 50 years. These differences in growth rates may suggest that these two types of forests are on different developmental trajectories. This was also indicated by the diameter growth and age results found in old-growth forests by Poage (2001), which showed that the potential sizes of trees in old-growth stands were correlated with sizes at early ages. The "diameters of the old-growth trees at older ages is strongly, positively, and linearly related to their diameters and basal area growth rates at age 50" (Poage 2001). Tappeiner et al. (1997) suggested that if the management objective is to produce old-growth from plantations then silvicultural thinning is necessary in order to change their developmental trajectory, otherwise the plantations would require a much longer time to develop typical old-growth structural characteristics. It may be that without some sort of structure-influencing disturbance, many plantations may never achieve old-growth structure.

The overall objectives of this study are to provide forest managers and policy makers with information and methods to help make management decisions regarding plantations in late-successional reserves and other areas where old forest characteristics are a major management objective. This information includes: a) knowledge of what forest structure types were present prior to harvest activity; b) how young natural and plantation stands are developing compared to old-growth and to each other; and, c) consequently, whether management or some sort of density-reducing disturbance is necessary for plantations to develop old-growth structure.

Another objective is to summarize the literature on stand- and landscape-level disturbance, stand development (including forest regeneration, crown structure, structural stability, and advance regeneration), and management of young stands to attain structure and composition of old-growth forests.

CHAPTER TWO: LITERATURE REVIEW

This literature review summarizes information describing: 1) the influences of disturbance processes on forest development at both the stand- and landscape- scales; 2) studies of forest characterization using retrospective methods in old-growth Douglas-fir; 3) variables important to forest regeneration and development; 4) stand and tree stability; 5) crown structure and development; and 6) advance regeneration persistence and potential for response. These six topics are important for understanding the structure and composition of developing forests, identifying how old-growth and young stands developed, and to help identify what management approaches may be used on specific sites to achieve desired forest characteristics.

Landscape and Stand Level Disturbances

Disturbance processes have played an enormous role in shaping the forests of western Oregon at both stand and landscape scales (e.g. Morrison and Swanson 1990; Wetzel and Fonda 2000). Fire, wind, pathogens, insects, slope failures, drought, and ice storms all have had significant influences on stand development. The frequency, intensity, and extent of fires and other natural disturbances across a range of environmental conditions (Rasmussen 1997) have contributed to the diverse structures and wide range of age classes (Agee 1997) shaping the composition and distribution of the flora and fauna present in old-growth forests (Long et al. 1998). These disturbances have occured at various scales and have affected the establishment, development and eventually the replacement of unmanaged forests (McComb et al. 1993). Forest structures can be highly variable from location to location due to site influences, and disturbance and development histories. Old-growth stands are also considerably variable in processes and functions (Carey and Curtis 1996). Therefore, a management prescription for one location may not be appropriate or feasible for another.

Fires

The fire regime is not static. For some areas in the Oregon Coast Range the current fire regime has been present for no more than 1000 years and has been shifting continuously with climate change (Long et al. 1998). A 1000-year time period is a relatively small in the lifespan of the trees in western Oregon Douglas-fir forests. Fire in the Coast Range has occasionally burned extremely large areas of forest (Long et al. 1998) some with large reburns (i.e. the Tillamook in 1933, 1939, 1945, and 1951, Coos fire in 1868, Nestucca in 1853, Yaquina in 1849, and Millicoma in 1775 (Zybach 2003). As climate continually changes, the influences of fires as vegetation-influencing disturbances also change (Long et al. 1998). Morris (1934) described a relatively frequent occurrence of landscape-altering fires, most less than 2,000 acres in size, in western Oregon in the mid-1800's and early 1900's. He described the resulting forest structure in that period as "a maze of young age classes which have been established after fires, and the effect of countless repeated burns makes it impossible to determine the extent of early fires." Part of this resulting pattern on the landscape was also due to the uneven intensity and variable frequencies and sizes of most natural fires (Hansen et al. 1991).

Pathogens, Insects, and Wind

Pathogens and insects also can be influenced by stand density and play a significant role as disturbance agents affecting forest development, composition, structure, and influencing which stands develop into old-growth. For example, the fungal pathogen, *Phellinus weirii,* which causes the root disease laminated root rot in Douglas-fir forests and other tree species, is present in more than 5% of the forests of the Northwest (Edmonds et al. 2000). High stand densities, monoculture species composition, and even-age structures are believed to contribute to the inoculum build-up of this pathogen (Thies and Sturrock 1995). Laminated root rot is significant in ecological processes by indirectly increasing species diversity through gap creation (Thies and Sturrock 1995) allowing the persistence of some species such as red alder and western hemlock and not others such as Douglas-fir and western red cedar (Latten 1998). The resulting structural diversity includes wide age ranges and the development of snags and large down wood. Laminated root rot is considered by some to be the most important root disease in terms of influencing forest stand structure and succession (Filip 2002, personal communication). In old-growth Douglas-fir forests the disease is kept at low levels of tree-killing infection through natural processes that result in low stand densities and mixtures of less susceptible species (Thies and Sturrock 1995) (Or, perhaps some forests were able to develop into old-growth without heavy mortality because of their low initial densities).

Pathogens like *Phellinus weirii* can either speed up succession by releasing an understory of a more tolerant climax species, such as western hemlock, or set back succession because early successional species such as red alder and shrubs can establish and dominate an infection center (Latten 1998). This results in patchy and lower density distributions of susceptible species. The fungus is transmitted when the roots of live trees come into contact with the roots of live infected trees or dead, previously infected trees. Rate of spread can be approximately 1 foot (0.3 meters) per year radially (Edmonds et al 2000; Thies and Sturrock 1995). In young stands contact between infected trees and uninfected trees is dependent on their density and root spread. Trees established at or thinned to a distance greater than a 13-foot (4 meters) spacing can reduce the occurrence of root connections for the first 60 years of age (Thies and Sturrock 1995). Pathogens as well as insects and wind can interact with fire by causing tree death that contributes to heavy fuel loads (Thies and Sturrock 1995).

These fuel loads can result in high fire intensity, possibly decreasing the likelihood of the stand developing into old-growth or in some conditions possibly increasing it.

Wind disturbance usually occurs at a small scale from individual tree mortality to windthrow of small patches generally <25 acres (<10 ha) (McComb et al. 1993). However, the small patches can be widespread across the landscape or, infrequently can create stand or landscape-scale alterations during high intensity events (Coates and Burton 1997) such as the 1962 Columbus Day Storm in western Oregon. Coates (1997) described the primary characteristics that influence wind damage in cedar-hemlock forests of interior British Columbia: (1) "internal stand characteristics (age, species composition, height and diameter distributions, presence of root rot)"; (2) "internal stand treatment history (time since last cutting, percent of stand removed during cutting)"; (3) "adjacent stand history (e.g., clear-cutting)"; (4) "site conditions (soil moisture, depth, and local topography)"; and (5) " storm characteristics (season, wind direction, average and maximum gust wind speed)." A species ability to survive intermediate-scale wind disturbance events, which are a dominant component of the natural disturbance regime for a region determines on part their abundance in old-growth forests (Canham et al. 2001).

Timber Harvesting

Since Euro-American settlement and the implementation of fire suppression, timber harvesting has replaced fire as the dominant landscape disturbance in Oregon forests. Young forests created by this new disturbance regime appear to be developing differently than the old-growth forests preceding them (Tappeiner et al. 1997, Poage 2001). In many cases, these new forests are believed to have regenerated at much higher densities and over much shorter recruitment periods than the old-growth forests (Tappeiner et al.1997, Poage 2001; Poage and Tappeiner 2002). These initial densities and recruitment trends will likely determine the growth and structural development of these young forests well into the future (Tappeiner et al. 1997, Poage 2001). In cases where late-successional forest structure, rather than wood and fiber production, is a desired goal, knowledge of site-specific historical stand structural conditions could prove to be a valuable reference for structure management.

Site-Specific Information

The kinds of high variability and dynamic disturbance history found on the landscape necessitate a site-by-site determination of structure to describe past mosaics of stands. Sufficient knowledge of what forest structures were present on specific sites prior to timber harvest could provide valuable site-specific reference conditions to manage the forest landscape and plantations to achieve these historical forest structural conditions that resulted from disturbance processes. The stand structure, composition, and development of these old forests can serve as goals for managed stands (McComb 1993). In other words, they can provide models or desired outcomes for management, for a known point in time, within the specific site's historic range of variability. Currently, no practical and effective retrospective method has been developed for the implementation by land managers to determine the site-specific structure of these past forests for restorative management. This study will utilize various information sources already available for each site and some onsite data collection to develop a methodology for characterizing past forests on a spatial scale of about 500 to 1000 acres (200 to 400 ha). This is a scale typical of management projects on federal lands. This methodology could be used in other applications, such as riparian restoration, for determining historical structure.

Knowledge of post disturbance forest regeneration conditions is important to understanding forest development and structure. The detailed knowledge of disturbances is lacking for most forest landscapes (Spies and Turner 1999). Understanding how disturbances influence, promote, and shape tree characteristics in our forests is valuable for meeting restorative management objectives. Many old forests we see today may be the result of low and moderate intensity fires, wind, ice storms, insects, and disease that selectively killed trees, as well as promoted the establishment of new ones. Other complex interactions of forest dynamics also are involved including, climate, soil, landform, and biotic development (Spies and Turner 1999). For example, fires spared old-growth growing behind natural barriers such as ridges or streams, creating residual patches of old-growth and facilitating the development of feathered boundaries containing a mixture of scattered old trees in young forests (Franklin et al. 1981). This study provides land managers with a methodology to describe specific details about the stand structures resulting from stand development and natural disturbance processes in their forests. Thus, they can design site-specific treatments that mimic disturbance patterns, creating the structural conditions that likely occurred in old forests in the same location.

Forest Characterization Through the Use of Retrospective Methods

Many studies using retrospective methods have been implemented to describe past forest stand structural elements and forest dynamics in order to establish reference conditions for management (Deal 2001; Deal and Tappeiner 2002; Groven et al. 2002; Pommerening 2002). The use of retrospective methods can provide information in a much shorter time-period than experiments and complement and strengthen findings of long-term experiments (Acker et al. 1998). Management that more closely resembles historic conditions is believed to pose a lower risk to native species and ecological processes (Cissel et al. 1999). For example, management that mimics the structural heterogeneity resulting from stochastic disturbances by leaving an appropriate numbers and sizes of trees, snags, and logs that can move stands more toward natural conditions (Mitchell et al. 2002; Palik et al. 2002). The knowledge regarding the historical structure and function of landscapes provides reference conditions to compare managed landscapes (Wimberly 1999). These reference conditions of forest structure can serve as guides to supplement for the incomplete knowledge of ecological functions. Retrospective methods can provide indications of how vegetation will respond to manipulation, leading to determination of appropriate prescriptions needed to meet specific management objectives. Acker et al. (1998) stated that in order to quantify the rate of old-growth structural development a clear definition of old-growth should be identified. Site-specific definitions of old-growth can be determined for management goals by observing tree and stand characteristics in nearby stands of old-growth and by using retrospective methods to describe local old-growth forest structures from stumps, historical aerial photographs, and harvest cruise records, rather than trying to apply a much more general "regional definition" of old-growth. This avoids many of the problems of trying to restore structural components that may have never been present on a particular site. Old-growth forest structures and composition are variable among locations and require site-specific identification.

Few studies have described forest patterns and structures at the 500 to 1,000 acre (200 to 400 ha) scales (local scales) that are typical of the checkerboard ownership patterns of the Bureau of Land Management and portions of other federal and state lands. In addition, using a local scale is important because stand management projects are often planned and implemented at this scale. Most retrospective studies of pre-harvest forest structure in western Oregon have been at a regional or large landscape scale (i.e. western Oregon or multiple physiographic province scale). Booth (1991) and Ripple (1994) performed retrospective studies of forest patterns across western Oregon and described the forest as large (>20 inches or 51cm dbh) or small tree size classes, and by dominant conifer species utilizing the 1933 USDA Forest Service's first survey data and estimates of harvested area and human-caused fires. Booth (1991) estimated approximately 62% and Ripple (1994) 71% of the conifer forests were historically old-growth prior to logging. These studies were primarily trying to derive accurate estimates of original amounts of old-growth at a very broad scale, rather than defining the specific structures for particular site.

Rasmussen (1997) conducted a retrospective landscape study to compare pre-harvested forest patterns with current cover and to discuss the disturbance ecology. This was performed at a broad landscape scale of three of the five physiographic provinces of western Oregon by creating maps from 1933 survey data, historical maps, historical aerial photographs, and GIS. Only features larger than 8 hectares were identified. She found greater size and variability of fire patches, shorter average distances between patches, and smaller perimeter-to-area ratios in the Oregon Cascades compared to the Oregon Coast Range. From this she suggested that pre-harvest landscapes contained a high degree of spatial heterogeneity and structural diversity, which since then has declined significantly. She also suggested that the structure of the Oregon Cascade forests were much more strongly influenced by more frequent fire disturbance than the Oregon Coast Range forests.

Morrison and Swanson (1990) reconstructed the fire disturbance history to describe the historical forest structure and disturbance history of two 4792 acre (1940 hectare) areas in the central-western Oregon Cascade Range, by utilizing tree ring records observed on stumps in clearcuts and road right-of-ways. They also used aerial photographs, predating harvests, to interpret the geographic patterns of the forest age classes, verified different degrees of fire-induced mortality from field samples, and sampled tree origin dates. They found that the central-western Oregon Cascade Range contained a highly variable fire regime creating complex forest structural mosaics with more frequent occurrence but lower severity occurring on the steep dissected lower elevation slopes studied.

Cissel et al. (1999) used historic landscape patterns and historic disturbance regimes as a template for management to mimic vegetation in the 59,033 acre (23,900 hectare) Blue River watershed in western Oregon. They expanded on the work performed by Morrison and Swanson (1990) using existing landscape features and retrospective methods including dating fire scars and photo interpretation to map fire severity, frequency, and the distribution of patch sizes. They integrated the historic information with a reserve network and designed three types of timber harvests to approximate the frequency, intensity, and spatial extent of past fire disturbances. They used growth models to project forest structure resulting from treatments and management, which resulted in much higher amounts of future late-successional owl habitat, overstory structure in young stands, and large patches, and less edge between young and old forests compared to the Northwest Forest Plan's standard prescription.

At the stand level, a smaller scale than the other studies, Tappeiner et al. (1997), Winter (2000), Poage (2001), Poage and Tappeiner (2002), and Sensenig (2002) used retrospective methods for describing forest development density, ages, and growth rates in young forests that regenerated after harvesting and from stumps in harvested old-growth forests in the Oregon Coast Range, Washington Cascades, Oregon Cascades, and Southwestern Oregon. Tappeiner et al. (1997), and Poage and Tappeiner (2002) found old-growth stands had a wide range of tree ages. Tappeiner et al. (1997) found tree ages ranging from 77-223 years and Poage and Tappeiner (2002) found tree ages ranging from 134-214 years. Although Winter (2000) found old-growth to establish within a 21-year age range within a 3.3 hectare area, large old-growth trees generally sustained high growth rates early in age and established over a long period.

Forest Regeneration and Development

The regeneration and development of forests are influenced by many variables. Seed source and dispersal, herbivory, competing vegetation (Oliver and Larson 1993), intensity and type of disturbance, species composition, soil type, and moisture availability all influence how a forest regenerates, its density, and its rate of development. The regeneration of plantations is usually much more controlled, with trees planted or thinned to prescribed densities for wood and fiber production. For plantations, seed source availability and the microsite conditions for germination play a much smaller role in the initial stand densities. Most of the planting stock in plantations is at least two years old when planted. The effects of herbicides can also be quite influential (Oliver and Larsen 1996) by increasing tree density, tree growth, and survival. Young plantations are typically planted at densities of over 250 trees per acre (600 trees per hectare). Stocking can range much higher when natural regeneration is established among planted seedlings. "Plantations usually have a narrow age range, both because planted seedlings grow vigorously" (Oliver and Larsen 1996), and site preparation and vegetation control also may shorten the recruitment period. "The uniform age and spacing of forest plantations may be creating stands that approach stagnation (or self thinning) more commonly than do naturally grown forests" (Oliver and Larsen 1996), or possibly degenerate rather than continuing to develop (Carey and Curtis 1996).

Many studies have observed how stands naturally regenerated after harvesting, but little information can be found on how young natural forests regenerate after a stand-replacing disturbance like fire. Is their development similar to plantations? Natural stands can regenerate from 0 to thousands of trees per acre/hectare, but many parts of old-growth forests are believed to have regenerated at low densities because big trees were growing at similar rates as young stands growing from 40 to 50 trees per acre (100 to 120 trees per hectare) (Franklin et al. 1981; Tappeiner et al. 1997; Poage and Tappeiner 2002). There is little information about the differences between these young naturally regenerated stands and young plantations that now exist in their place, adjacent to and/or on the same site. Few studies have made comparisons of ages and growth rates of young natural stands and plantations, though Hansen et al. (1991) compared structures. Understanding how plantations differ in growth, structure, and development from natural stands may help resource managers understand how to alter plantations to initiate natural development toward late-successional forest conditions.

It is important to not simply assume young natural forests are regenerated and developing on a similar trajectory as late-successional forests. If these young natural stands are developing similarly to the young plantations, then this may indicate that the conditions and processes for the development of the young natural stands has significantly changed since the old-growth forests developed. In this study I observed the range of ages, density, projected future size and development and structural variability of these two stand types to described their differences both without future management and with plantation future managment. The results can help show silvicultural treatments can be used to manage stand development in these young plantations to achieve old forest characteristics.

This study will test the hypothesis of Tappeiner et al. (1997), Poage (2001), and Sensenig (2002) that stands established after timber harvest are developing at much higher initial densities and with slower diameter growth rates than old-growth Douglas-fir stands that preceded them. For example, Poage and Tappeiner (2002) found that the large trees > 39.4 inches (1.0 meter dbh), typical of old-growth forests had rapid early diameter and basal area growth and sustained growth later on. If inter-tree competition were present, then diameter growth would have been found at consistent and low levels. They also found that the low height to live and dead meristematic branches of many old-growth trees also indicate that these trees grew at low densities.

Reduced inter-tree competition may have been created by many forms of disturbance (Tappeiner et al. 1997; Poage and Tappeiner 2002). Old forest stands regenerating at low densities or over a long recruitment period could have had significant effects on the rate of crown differentiation and the rapid early growth rates of the dominant Douglas-fir trees in old-growth stands. This long recruitment period, spread over several decades, potentially could have increased the range of tree sizes, (growth rates), and species diversity (Acker et al. 1998) and rate of differentiation. In certain stands or in stands of variable density dominance may have been established and maintained by the initial germinants, minimizing the severity and duration of competitive exclusion stage, with little growth reduction incurred by the dominant trees. Soil disturbance after harvesting can be much more amenable to the establishment of Douglas-fir trees from seed than after a natural disturbance that leaves the duff layer in place. This could have increased the tendency for stands, naturally regenerating after harvests like plantations, to have developed at higher densities and to have been fully established before competing vegetation occurring with most natural disturbances. Tappeiner et al. (1997) stated that with the low density conditions even "multiage forests with variable structures might occur without the processes of self-thinning and reinitiating an understory."

Site productivity conditions also can have some influence on the development of heterogeneity in tree size. Sites with high productivity tend to develop wide ranges in tree sizes earlier than low productivity sites (Franklin et al. 1981). Open initial forest conditions also could have been created and maintained in a number of other ways, such as competing vegetation, which can cause long delays in forest regeneration and in some cases exclude forest regeneration (Walstad 1992). One of the ways old-growth forests may be characterized is by their understory patchiness (Franklin et al. 1981). The established understory vegetation in these patches can resprout through rhizomes, seed banks, etc. after a stand-replacing disturbance, influencing the regeneration conditions in those patches, thus increasing the heterogeneity of tree seedling recruitment occurrence. Open stand conditions also may have been maintained by disturbances such as repeated low or moderate intensity fire disturbance or reopened by wind disturbance after a period of crown closure. Low intensity surface fires can kill thin-barked species such as red alder and western hemlock, while allowing more fire resistant species, such as large diameter Douglas-fir, to grow (Agee 1993, Oliver and Larsen 1996; Wetzel and Fonda 2000). Moderate and severe fires can leave varying amounts of residual trees (Morrison and Swanson 1990; Wetzel and Fonda 2000). These variances in fire intensity can result in the potential for tree regeneration and growth as well as the creation of a patchy mosaic of forest structure (Morrison and Swanson 1990; Wetzel and Fonda 2000). Other disturbances, such as wind, have been found to selectively kill specific strata (Oliver and Larsen 1996). The resulting uneven distribution of growing space can lead to a higher degree of structural differentiation between trees (Poage 2001).

Using data from the Hoskin's density management study area Poage (2001) compared the development of tree growth in young stands with old-growth trees. He found the largest diameter trees occurred in the lowest density treatment area 52 tpa (127.7 tph) and had growth rates similar to old-growth at age 50, which when projected to 100 years of age, most closely resembled the growth rates of the large trees in old-growth stands. The trees that grew in the high density treatment area 207 tpa (510.7 tph) developed mean tree diameters of 16.5 in (41.9 cm) and 23.1 in (58.7 cm) at age 50 and 100 years respectively, compared to the low density treatment 52 tpa (127.7 tph) that produced mean tree diameters of 23.5 in (59.7 cm) and 35.1 in (89.2 cm) at age 50 and 100 years respectively. Also, on average, the trees in the low stand density treatment developed larger diameters, and contained longer crowns, higher live crown ratios, and lower height-to-diameter ratios than the trees developing in the high density treatment.

Old-growth forests are much more heterogeneous in stand structure than young stands (Franklin et al. 1981). Management activities in forest stands that enhance the development of large diameters, reduce tree densities, and increase the heterogeneity of tree sizes may be important for speeding the development of old-growth structural characteristics (Miller 1997; Tappeiner et al. 1997; Acker et al. 1998; Bailey and Tappeiner 1998; Busing and Garman 2002; Poage and Tappeiner 2002). Acker et al. (1998) found the presence of shade tolerant tree species significantly affects the rate of development of the variability in tree sizes. In addition, tree species diversity (particularly hardwoods) and understory tree crowns are also significant contributors to the complexity of canopy architecture (Dubrasich et al. 1997; Schutz 2002). In many young plantations, the number of shade tolerant conifers and hardwoods may be low due to practices favoring rapid growth of Douglas-fir. However, shade tolerant species also can be reduced in natural stands by the fire frequency and intensity that can favor shade intolerant Douglas-fir over shade tolerant species such as western hemlock and western redcedar (Wetzel and Fonda 2000). The use of vigorous single species planting stock (Douglas-fir), site preparation methods, and pre-commercial thinnings (juvenile thinning) generally can reduce, eliminate, or postpone the occurrence of these species in managed stands.

Stand and Tree Stability

Structural stability, including resistance to wind and snow breakage, is an important element influencing stand development and should be considered in the timing (O'Hara 2001) and the intensity of treatments in young stands to promote structural heterogeneity. The higher the initial stand density after regeneration, the sooner height-to-diameter ratios begin to rise, shrinking the effective thinning window (Wilson and Oliver 2000; Wilson and Baker 2001). Plantations with uniform spacing, tree size (Hansen et al. 1991; Wonn and O'Hara 2001), age, species composition, genetic growth potential, and vertical structure (O'Hara 2001) may be dependent on management intervention to prevent growth reductions, maintain structural tree form to resist wind, snow, and storm breakage, and sometimes to avoid stagnation (Wilson and Oliver 2000; Wilson and Baker 2001; Schutz 2002). Douglas-fir plantations are generally dense and develop high height-to-diameter ratios (H:D both in the same measurement units*) fairly early making them unstable and prone to windthrow and stem breakage (Gardiner et al. 1997; Wilson and Oliver 2000; Wilson and Baker 2001; Wonn and O'Hara 2001; Moore 2002, unpublished; Schutz 2002). This is because crown differentiation is slower and not as pronounced due to the uniformity of plantations (Curtis and Reukema 1970). Height-to-diameter ratios indicate the general amount of taper (slenderness) in a tree bole. The smaller a tree's diameter in relation to it's total height, the higher the H:D, and thus, the more structurally unstable it may be. Stand density generally does not influence height growth in productive Douglas-fir forests, but it strongly influences diameter growth. Thus, as the density increases in relation to the height, the more unstable the trees become. The structural stability threshold of high susceptibility to wind damage has been generalized as somewhere near H:D 80 (Wonn and O'Hara 2001) for inland Douglas-fir but may be somewhat lower for coastal Douglas-fir (H:D 60-70). Height-to-diameter ratio is also a useful indicator for young trees. Trees with H:D > 60 (Emmingham et al. 2000) or H:D ≥ 70 (Cole and Newton 1987; Hughes et al. 1990) are suggested to indicate poor vigor and growth potential for very young (2-10 yrs) coastal Douglas-fir. These trees can suffer reductions in long-term diameter, height, and volume increment (Newton and Comeau 1990). As plantations develop their H:D ratios begin to rapidly increase after crown closure. The following may create early or rapid increases in H:D ratios by promoting uniformity in tree size in plantations: 1) greater the initial planting densities (Wilson and Baker 2001; Wonn and O'Hara 2001); 2) uniform tree spacing (Wilson and Oliver 2000); 3) short seedling recruitment period; 4) increased uniformity of the microsites from site preparation practices; 5) control of vegetative competition; and 6) low species diversity. Lack of inclusion of trees with poor genetic growth potential may also be influential. In addition, H:D ratios will increase sooner on productive sites (Wilson and Oliver 2000; Wilson and Baker 2001). Carey and Curtis (1996) suggest that without early and timely thinning to reduce stem density many of these stands cannot be expected to survive long rotations or to thinnings at a later age, particularly on windy sites (Wilson and Baker 2001). In this regard, Wilson and Oliver (2000) believe that many plantations will require management to maintain options for early stand development or management. Early control by reducing planting densities, planting mixed species, planting at variable spacings, and more site-specific management in plantations would maintain developmental options (Wilson and Oliver 2000; Wilson and Baker 2001). Most plantations on federal lands are already established, thus thinning is the only density management option. In dense stands thinning will not always lower H:D ratios, and may only reduce the rate of H:D ratio increase (Wilson and Oliver 2000). Once a stand develops high H:D ratios thinning will not make them much more stable and vigorous immediately. Timely entries for density reduction before the stand reaches 27 feet (10 m) in height has the greatest effect on maintaining structural stability because H:D ratios increase rapidly between 27 and 82.0 ft (10 and 30 m) in height (Wilson and Oliver 2000). In Douglas-fir forests on federal lands in western Oregon, the plantations that have not yet reached commercial size (generally under 20 years old), can benefit the most from thinning. Plantation stands of commercial size (approx. 35 to 50 years old), with age (as a surrogate for height), will decrease in the stability benefits from thinning over time.

Forests that developed at wider spacing and established wind-firm and snow-break resistant trees, are not limited to a single trajectory or endpoint (Wilson and Baker 2001). Stands with wide initial recruitment periods could facilitate crown differentiation, so even if the stand average H:D ratios are high, the dominant and co-dominant trees can maintain adequate H:D ratios. Forests developing in locations of low wind and snow loading exposure also tend to have lower H:D ratios (Wilson and Baker 2001). Trees developing at wider spacing have been found to be more resistant to stem breakage (Gardiner et al. 1997; Wilson and Oliver 2000; Wilson and Baker 2001; Wonn and O'Hara 2001; Moore 2002, unpublished). Well spaced trees or trees thinned early in development, also increase resistance to uprooting (Curtis and Marshall 1993), but usually not as rapidly as the rate of wind loading with increased spacing from thinning (Moore 2002, unpublished). However, even some stand structures that are considered windfirm stands can lose their advantage when located in areas of heavy wind exposure (Mason 2002) or root disease, reducing their likelihood of developing into old forest structures.

When a young stand is developing, both environmental and competitive factors potentially can influence the height-to-diameter relationships (Ishii et al. 2000). Factors such as herbivory, crown abrasion, snow break, desiccation from wind, and shading from above can delay height growth, altering the relationship

(Ishii et al. 2000). Species vary in their susceptibility to damage, which can create a competitive advantage between species, depending on the dominant damaging agent present. Crown damage is an important part of crown differentiation and can increase structural heterogeneity in height-to-diameter relationships. Crown differentiation results when larger trees, with higher growth rates, develop a competitive advantage and eventually out-compete their smaller neighbors through height growth and overtopping. In even-age forests, live crown ratio, leaf biomass, stem diameter, radial growth increment, and tree vigor decrease both from dominant trees down to suppressed trees (Nyland 2003) and with increasing relative density after crown closure. Wind disturbance can be beneficial in other ways. It is an important disturbance for forming canopy gaps that increase the horizontal (Coates and Burton 1997) and vertical structure of a forest. Wind continues to be influential even in old-growth forests. Franklin and DeBell (1988) found in a 36-year study of mortality of a 500 year-old old-growth stand that wind mortality generally was low, near 0.75% stems per hectare per year and accounted for 45.5% of the annual mortality. They attributed 39.4% of the annual mortality to suppression and unknown causes. Nearly 22% of the original stems died within the 36-year period, with Douglas-fir declining in stand basal area composition by 1.8%.

The relationships between stand density, structural stability, and disturbance may be one of the reasons why trees from old-growth forests that developed from low initial densities with rapid early growth rates over extended recruitment periods have been found in western Oregon. Forests developing at higher densities with too narrow a recruitment period and slow early growth rates or located in heavily exposed areas may have been too structurally unstable to survive disturbances to old age.

After thinning the level of susceptibility to windthrow and stem breakage is increased for a short time, especially if H:D ratios are high (Wonn and O'Hara 2001), until H:D ratios decrease. When stand density is reduced by thinning: 1) trees lose the damping effect created by the trees swinging against each other; 2) turbulent eddies between tree crowns are increased; and 3) the increased exposure allows wind to penetrate deeper into the canopy (Green et al. 1995; Wilson and Oliver 2000; Moore 2002, unpublished). In some cases, a certain level of wind damage can be ecologically desirable for enhancing structure and increasing spatial heterogeneity, but when too high it can compromise the management objectives (Coates 1997). Windthrow was the lowest in partially cut stands with a cutting pattern that was dispersed and consisted of small openings < 1.2 acres (0.5 ha) (Coates 1997). Minimizing high-contrast edges can help reduce turbulence that cause windthrow (Chen et al. 1995). Careful attention to the direction of prevailing winds and to topographic features are also important in reducing the probability of high windthrow and breakage (Coates 1997). The frequency of wind disturbance along a gradient of storm severity can be difficult to quantify and predict based on retrospective evidence because climate change may be an influential factor (Canham et al. 2001).

Crown Structure and Development

Horizontal and vertical heterogeneity of the forest canopy is an important characteristic of old forest stand structure (Dubrasich et al.1997; Schutz 2002). Timing of tree establishment, tree density, and species height growth potential and rate of height growth influence the vertical structure of a stand. The resulting structure from tree growth and survival is also influenced by the relative shade tolerance of a species. The species differences in shade tolerance and successional status influence the range in tree sizes of each species and their abundance (Ishii et al. 2000).

Old-growth Douglas-fir stands have live crowns that are long, deep, and irregular (Franklin et al. 1981), with flat or broken tops, abundant dead and epicormic branches, low live-branch density, high branch size variability, cylindrical profile, and large gaps within the crown (Ishii and Wilson 2001; Ishii and McDowell 2002). These crown characteristics are the results of site productivity, degree of competition, genetic influences, and disturbances (Franklin et al. 1981). Epicormic branches increase crown length, fill inner regions of the crown, and increase the tree's branch-size variability (Ishii and Wilson 2001). Branch size variability is created by presence of epicormic branches because the epicormic branches are smaller in diameter and shorter than the original meristematic branches (Ishii and Wilson 2001). This development of large-diameter original meristematic branches and the production of epicormic branches increase the crown structural complexity of old Douglas-fir trees (Ishii and McDowell 2002). These branching patterns result in complex stands having taller vertical distributions of canopy (Dubrasich et al. 1997).

Wind exposure may influence the rates at which individual trees develop irregular crowns. Complex crown structure develops from the interaction between tree growth and damage and dieback and low-severity crown damage (Ishii and Wilson 2001). Increased wind exposure from thinning increases the movement of turbulent air (Moore 2002, unpublished), and the variability produced in thinning treatment densities could increase the variability in the wind exposure to individual trees. Density management of young stands through commercial thinnings may increase branch growth and influence the level of crown exposure to breakage, thereby speeding up the formation of with-in crown gaps (higher within crown porosity), dead branches, and the development of epicormic branches. Thinning, if intense enough, could allow the trees, when older, to support large meristematic branches farther down the bole. The increased light could promote sprouting of epicormic branches. Epicormic buds are released with damage and dieback within the crown (Ishii and Wilson 2001). Ishii and Wilson (2001) defined the structural complexity of a tree crown as "the variability found in branch size age, biomass, type (live or dead, original or epicormic), and spatial distribution within the crown." Old-growth Douglas-fir trees have similar numbers of live-branches as young trees, but the majority of the biomass in old-growth trees occur in the middle to upper half of the crown rather than the lower half (Ishii and Wilson 2001; Ishii and McDowell 2002), producing a more top heavy distribution. Dubrasich et al. (1997) found crown area distributions of old forests to be distributed over the middle to lower half of the crown. This distribution is believed to shift with age in some trees resulting from the combined effects of branch death and growth (Ishii and McDowell 2002) as trees approach their maximum height. It is unclear whether thinning will accelerate the development of this top-heavy distribution of crown biomass. Though these characteristics occur along the entire length of Douglas-fir old-growth crowns, the lower crown usually contains a greater proportion of the epicormic branches and dead branches with a lower density of live meristematic branches (Ishii and Wilson 2001; Ishii and McDowell 2002). Tree species diversity (particularly hardwoods) and understory tree crowns are significant contributors to the complexity of canopy architecture (Dubrasich et al. 1997; Schutz 2002). A mixture of hardwood and conifer species provides structural heterogeneity of leaf area for a given tree size and variances in tree heights and crown areas add vertical heterogeneity to forest canopies (Dubrasich et al. 1997). High tree height variances, within a tree diameter size, (trees with equivalent DBH's), and between tree diameter sizes, can be used to measure canopy structural complexity.

Advance Regeneration Persistence and Potential for Response

Predicting establishment and response of advance regeneration is important in understanding the development of late-successional forests and for prescribing management to enhance old forest characteristics. Generally, if not heavily suppressed for too long a duration, when advance regeneration is released through disturbance or overstory removal, the trees often respond with morphological characteristics that facilitate rapid growth, irrespective of their age (Oliver and Larson 1996). When advance regeneration is heavily suppressed for a long duration, they undergo physiological and morphological changes to their shoots and needles, and may or may not respond to release (Oliver 1985; Helms and Standiford 1985; Tesch and Helms 1992; Tesch and Korpela 1993; Kneeshaw et al. 2002), depending on the species plasticity.

Several indicators can be used to help determine how well advance regeneration will respond when the overstory is reduced. The seedling pretreatment height growth and percent live crown are considered the most effective for predicting responses (Oliver 1985; Helms and Standiford 1985; Tesch and Helms 1992; Tesch and Korpela 1993; Kneeshaw et al. 2002). The other possible indicators available for predicting response are the species shade tolerance, condition of the overstory crown, species of advance regeneration, and size (height). These can give some indication of what trees can persist in the understory, but the ability of seedlings to survive and respond in height growth after release is really dependent upon their capacity to make rapid adjustments to the changes in the microclimate (Tucker and Emmingham 1977; Helm and Standiford 1985). These changes include increasing air and soil temperature extremes, air movement, and shortwave radiation that challenge the regeneration's ability to control water loss from transpiration, adjust to the exposure to shortwave radiation, and to quickly increase the net production of photosynthate (Tucker and Emmingham 1977; Helm and Standiford 1985).

In general, the trees growing well before release tend to grow faster after release (Tesch and Helms 1992; Tesch and Korpela 1993) primarily because they have a greater photosynthetic area than respiring surface (Oliver and Larson 1996). Trees growing slowly before release tend to have a variable growth response after release (Tesch and Helms 1992; Tesch and Korpela 1993). Western hemlock and Douglas-fir advance regeneration usually have an immediate increase in radial growth, but a delayed height growth response (Klinka et al 2000). Douglas-fir is typically considered shade intolerant, which gives it the strategic ability to grow rapidly in high light environments, but limits its ability to persist at low light levels (Chen 1997). Thus, if an objective of a thinning is to develop a new cohort of Douglas-fir then a much greater amount of overstory would need to be removed than if managing for a shade tolerant cohort such as western hemlock. In addition, the ability of understory trees to survive for a long duration under suppressed growing conditions also varies depending on their shade tolerance (Oliver and Larson 1996).

At least 20% full sunlight is needed for coastal Douglas-fir to persist in the understory, and approximately 40% full sunlight is needed for efficient crown height growth (Mailly and Kimmins 1997; Drever and Lertzman 2002). Understory trees need to be in a condition to respond in growth, and not deteriorating in tree form (e.g. developing poor height-to-diameter ratios), so they can be able to eventually replace the older cohorts (O'Hara 2001; Schutz 2002) or to contribute to the wide range of age and size classes characteristic of old-growth. Therefore, low overstory stocking may be required and maintained, possibly through repeated thinning, to sustain adequate understory tree growth (Miller and Emmingham 2001) depending on the understory species shade tolerance (Schutz 2002). As trees mature they begin to slow in their lateral branch growth, which can delay the rate of canopy closure after a disturbance, thus sustaining the development of sub-canopy layers and the understory for a longer duration (Nyland 2003). Therefore, thinning intervals can be longer or remove a smaller portion of the canopy as stands mature. This can make it difficult to treat the density of young stands with only a single entry, and may indicate the importance of having management flexibility that allows for multiple entries. This decline in growth for lateral branches may have influenced the age distributions of the Douglas-fir trees that grew into the overstory in old-growth stands.

Literature Review Conclusions

This literature review identifies three important needs: a) to describe past forest stand structure, at a scale of typical management projects, to serve as a reference or as a model for management; b) to describe how plantations and young natural stands are developing compared to each other and to late-successional stands; c) to project and compare several scenarios of management with target old-growth structures.

Few studies have developed methods of determining important information on past forest structure on project size areas of 500 to 1000 acres (200 to 400 ha) typical of the public land checkerboard ownership pattern. The literature indicates the large role disturbance plays in creating late-successional forest structure and describes the coarse scale stand replacing disturbances and some of the effects of low intensity disturbances, such as low intensity fire and wind, on individual physical stand structure and development. A greater degree of detail of historical structure is necessary for managers to adequately manage for late-successional characteristics within the natural range of variability for a specific location than can be given by using a general regional definition of old-growth structure. This study will develop and utilize the methods needed for determining these historical physical structures of reference stands.

With regard to b), it is unclear whether young natural upland Douglas-fir stands regenerated at densities similar to upland Douglas-fir plantations. But if present, structural legacies that survived catastrophic events can add structural complexity to young stands (Hansen et al. 1991). In addition, the similarity between these stand types age ranges and growth rates have not been compared to late-successional old-growth stands. This is important to predict whether the plantations in the federal Late Successional Reserve lands will grow and develop in the same way as old forests and fulfill the purposes the reserves were created for, or whether management, or some other type of density reducing disturbance, is necessary to achieve this. The association of structural instability with the development of poor height-to-diameter ratios seems to indicate limitations to the ability of young uniform stands to develop at high densities and to survive to old age. Knowledge about young natural stand structure and development is also not just important for understanding how old-growth forests developed but also important for managing for young natural stand structures across the landscape to achieve objectives of the Northwest Forest Plan or late-successional reserves.

Finally for c) there is a need to test the following null hypotheses to determine if upland Douglas-fir plantations are likely to develop the same as young natural forests and toward the structure of late-successional forests:

- The range of ages, growth rates, densities, and height-to-diameter ratios are not significantly different between young natural stands and young plantations;

- Growth model projections of live crown ratios, diameters, densities, and height-to-diameter ratios will predict that the plantations will grow and develop the same as young natural stands and old-growth;
- It is an appropriate management strategy to develop old-growth structure by only walking away from young natural stands and plantation stands without any form of density management;
- Plantations will develop into old-growth in 250 years with or without management.

CHAPTER THREE: MATERIALS AND METHODS

Objectives

This study was conducted, in three study areas, to: a) provide a methodology for land managers to identify site-specific historical stand structure and conditions for management reference, b) identify how old-growth developed compared to young natural and plantation forests, and c) determine how stand management, if necessary, might be used to help restore old-growth structure.

The historical types of stands and the developmental differences in the overstory and understory trees among young natural forests, late-successional forests, and plantations in each of the study areas were quantified and described. The size of each study area ranged from 500 to 1000 acres (200 to 400 ha). This study area size was chosen because it is a management size typical of the BLM landscape ownership pattern. Each study area includes 15 to 25 young natural stands (70 to 125 years old), old-growth (> 250 years old), and plantations (10 to 48 years old). Young natural stands were defined for this study as a forest naturally regenerated after a natural disturbance such as fire and < 250 years of age. Old-growth was defined as a forest containing many large old trees, large dead and down trees, well developed understory vegetation (Franklin et al. 1981), and layered canopy structure (Curtis et al. 1998). Plantations were defined as any planted forest regenerated after timber harvest and containing no remnant trees from the previous stand. Only plantations at least 40 years (35 years breast height age) or older were selected for sampling. One representative stand for each of the three upland forest types was selected. The stands in each stand type were treated as separate sampling units within each study area. The late-successional stands and young natural stands were selected to contain no known evidence of harvesting. Each study location contained some harvested units, which have detailed cruise records and aerial photos dating back to pre-timber harvest periods as well as current aerial photos and digital orthophotos. Old-growth tree age and growth data from the previous study (Poage 2001; Poage and Tappeiner 2002) were available for the old-growth stands in the three study areas.

To assist in determining the young stand growth of each stand type and each plantation management option, the growth and yield simulation program, ORGANON (Hann et al. 1997), was used.

Study Areas

Three study areas on upland Douglas-fir sites were selected for this study. No riparian forests were sampled. All three are located in the *Tsuga heterophylla* Zone (Franklin and Dyrness 1973). Three of the locations selected for this study are found in two of the five physiographic provinces found in western Oregon

(Franklin and Dyrness 1973). One of the provinces is the Oregon Coast Range and the other is the Central Cascades. The study areas are located in: (1) Alsea River basin, Coast Ranges; (2) Five Rivers Basin, Coast Ranges; and (3) Quartzville, Western Cascades. (See table 3.1)

Table 3.1. Study site and plot characteristics

Physiographic Province	Coast Ranges				Western Cascades			Coast Ranges			
Location	Alsea, Oregon				Quartzville, Oregon			Five Rivers Basin, Oregon			
Study Area	North Prairie				One-eyed Fish			Five Rivers			
Stand Type	OG	PLT	YN	YN Thin	OG	PLT	YN	OG (Lobster Creek)	PLT	YN	Two-Story
Age (Years)	46-434	29-44	70-125	70-125	175-475	36-43	61-83	180-534	29-41	47-149	45-80
‡ Current Densities (TPA)	45-88	230-380	120-160	184-252	42-87	190-260	320-888	39-43	100-260	48-108	172-208
General Aspect (Azimuth)	20	80	300	270	190	300	190	140	33	210	220
Ω General Elevation (Feet)	2700	2000	2000	2000	2000	1600	2100	1300	1000	1000	1000
Site Index (Feet at age 50) Ω	*	117	100	117	*	134	100	*	123	121	122
Δ Number of 0.25 or 0.10 Acre Plots in Clearcuts	† 9	0	6	0	† 7	0	0	† 11	0	3	0
Δ Number of 0.25 or 0.10 Acre Plots in Existing Forest	0	5	3	3	0	5	3	0	5	3	3
Δ Acres of BLM 100% Cruise Records	57	0	0	0	86	0	0	64	0	0	0

† Sampled by Poage (2001)
* No data available
‡ 1.0 tph = 2.54 tpa.
Δ 1.0 ha = 2.54 ac.
Ω 1.0 m = 3.28 ft.

The landscape surrounding each of the study areas contains a mixture of private and public lands with unmanaged forests and young managed forests. Western Oregon's history of intensive land conversion from old natural forests to rapidly growing plantations on the majority of private lands and public lands has resulted in this mixture of forest types managed at varying intensities and in different stages of forest development. Two study areas, North Prairie (Coast Ranges) and One-Eyed Fish (Western Cascades) had 100% pre-harvest Bureau of Land Management cruise records of Douglas-fir old-growth stands harvested in the late 1980's, located adjacent to or in proximity of currently existing old-growth forests, and containing tree growth increment data from the study by Poage (2001) and Poage and Tappeiner (2002). Each of these study areas also contained young naturally regenerated Douglas-fir forests of fire origin absent of evidence of timber harvest activity and young Douglas-fir plantations over 40 years of age within a ½ mile radius. I selected stands located with similar aspect, elevation, geomorphology, and with no obvious site productivity differences within each study site (Hale et al. 1999). The third study area, Five Rivers (Coast Ranges), was located on U.S. Forest Service land within the Five Rivers watershed basin. Five Rivers met the same criteria as the other two study areas, with the exception of the criteria of having old-growth stands with 100% cruise records within close proximity. The old-growth reference stand for this study area adjoined the east boundary of the Five Rivers watershed, on Bureau of Land Management lands near Lobster Creek. Also an additional natural origin

Douglas-fir stand, characterized by a two-story structure in Five Rivers, was sampled and included in some of the analysis and projections. The stand types within each study area were identified based on canopy uniformity in recent color aerial photographs, digital orthophotos and when possible aerial photographs dating back to stand origin, and verification through field reconnaissance. Only old-growth and young natural stands, with no visible evidence of past harvest or management activity, were selected. Adjacent clearcuts that had contained any of the three stand types were sampled for age and tree diameter growth on stumps. The plantations had been established by planting, shrub control, pre-commercial thinning, and in one case, commercial thinning. Douglas-fir (*Psedotsuga menziesii* (Mirb.)) was the primary tree species in the three study areas, generally composing over 75% of each stand's basal area. Other minor tree species included western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), bigleaf maple (*Acer Macrophyllum* Pursh), red alder (*Alnus rubra* Bong.) in all three study areas. The One-Eyed Fish area in the central Oregon Cascades also included golden chinkapin (*Castanopsis chrysophylla* (Dougl.) A.DC.), and Pacific madrone (*Arbutus menziesii* Pursh). The understory shrub component at all sites included salal (*Gaultheria shallon* Pursh), vine maple (*Acer circinatum* Pursh), California hazel (*Corylus cornuta* var. *californica* (DC.) Sharp), and salmonberry (*Rubus spectabilis* Pursh). The site-indices of the three study areas were in the moderate site productivity range: 100-117 feet (30-36m) at North Prairie, 100-134 feet (30-41m) at One-Eyed Fish, and 121-123 feet (37-38m) in height at Five Rivers (base age 50 years King (1966)). The plantations generally had higher site-indices than adjacent young natural stands. This could have been attributed to the site preparation and vegetative management use for plantation establishment. Early site treatments can reduce conditions that interfere with height growth of dominant and co-dominant trees and affect site productivity estimates.

Retrospective Methods for Describing the Historic Forest Structure

The forest stand types were initially classified based on visible differences in the texture of the overstory composition viewed from the earliest aerial-photos taken for the study areas, from 1940 and 1960. These historical stand boundaries were identified and traced out onto the photos. Polygons of each of the current stand types were also traced out onto recent digital orthophotos (1996 to 2000) using GIS, and the unharvested remnant patches of each stand type, still present, were ground verified. The harvested stands were also ground verified. The structure and composition in remnant patches were described by on-site data collection and the use of BLM cruise records. The sampling was based on similar species composition, tree size, density, age ranges, elevation, aspect, and slope. I determined the past stand structure of harvested stands from available BLM and Forest Service cruise records, similarity of canopy texture on historical air photos to current adjacent unharvested stands, and data from the retrospective study by Poage (2001). I used the residual patches of old forest scattered across the landscape to provide density, species composition, age, crown, and tree size information of the harvested matrix forestland in between residual patches.

Age and growth increments from a total of 557 trees and stumps were sampled from the three study areas. Including 166 from young natural stands, 27 from a two-story stand, 119 from the plantation stands, and 245 from the old-growth stands (sampled by Poage 2001).

Stand composition, density, and tree size data for the late-successional old-growth stands within these study areas were obtained by Poage (2001) by using BLM 100% cruise records. Poage (2001) measured radial growth in 10-year increments of recently cut old-growth Douglas-fir trees, across a range of observed diameters, in 0.25-acre (0.1ha) plots, and opportunistically within each of the three study areas. Poage's data also includes old-growth Douglas-fir tree stem and crown measurements from remnant old-growth patches adjacent to the harvested areas where the growth increments were obtained.

I measured growth rates, ages, density, tree size, and species on 0.1-hectare 0.25-acre (0.1ha) and 0.10-acre (0.025ha) circular fixed plots in young natural stands and plantations. Five to fifteen well-distributed plots were installed in each stand type within each study location. I used aerial photographs to establish pre-assigned locations for the initial plot in each stand. Plots were located in the interior of each forest type to avoid influences from clearcuts, roads, riparian areas, and changes in forest types. In each plot, the diameters of live trees over 6 inches (15cm) dbh were measured (± 0.1 inch) using a diameter tape. Diameter at breast height of trees under 6 inches (15cm) dbh were estimated. Snags were tallied as either young snags > 10 inches (25cm) dbh, young snags < 10 inches (25cm) dbh from self-thinning of the current stand, or as old snags from the previous stand. Evidence of fire was noted from fire scars and charcoal on live trees. I recorded the plot elevation and aspect, and measured the total tree heights and height to live crown based on the five largest, the smallest, and a medium-size tree on each plot, and used a Vortex digital hypsometer, recalibrated for horizontal distance each day, for height measurements.

Tree growth rates and ages were measured by counting annual growth rings on stumps and increment cores, using a hand lens as needed. I measured by 10-year increments (± 0.1 inch), starting from the pith (year of origin) to the bark (Tappeiner et al. 1997). On stumps, an average radius was measured and on standing trees the increment core was taken from the upslope side of the tree at breast height. Stump surfaces were prepared for measurement with a wire brush. I assumed that all stand cohorts reach stump height or breast height (4.5ft or 1.37m) in about the same number of years, while assuming spatial and temporal heterogeneity in growth rates. Ideally, to estimate the ages of trees using a nondestructive method, I would have obtained samples of the root-shoot boundary of every tree using an increment borer (Wong and Lirtzman 2001).

Due to time and resource constraints, and level of accuracy needed for this study, I sampled at breast height and used the breast height age. The growth and yield simulation model used added 5 years as the number of years for each tree sampled to attain breast height, but all other ages described in this study are the breast height age. When a tree core clearly missed the pith a second was taken. For cores that just barely missed the pith, concentric circles were used to determine the number of years required for an accurate age at breast height (Abrams et al. 1999; Groven et al. 2002). This was performed ocularly. I expect some degree of error in ages and growth by using increment cores. However, following Poage and Tappeiner (2002), cross-dating was not deemed necessary. Weisberg (1998) quantified the error associated with not cross-dating tree ring counts in western Oregon to be ± 1.5 years, and found that cross-dating can require more than 22 times the amount of time as careful field counting.

Average stand density was estimated using average trees per hectare, relative density (Curtis 1982), and basal area per hectare from the sample plots. The presence or absence of small down wood, early growth rates, and live crown ratios were utilized to indicate whether self-thinning had taken place and to indicate whether there was a high stand density in the past. Live crown ratios were calculated from total tree height and the height to the lowest live meristematic branches. I used BLM cruise records, stand exams, and data from past research study records (Poage 2001) that were available for these old-growth stands.

Tree heights and height to live crown were also sampled for use as indicators of crown structural heterogeneity. Tree height in this study is defined as the vertical distance between the highest foliage on the tree to the ground on the uphill side of the tree.

Historical and current areas of each forest stand type within each study area were compared using recent digital orthophotos and historical aerial photographs. GIS was used to create polygons for each stand type on digital orthophotos to determine the area of each stand type. The dot tally method was used to calculate area on the historical aerial photographs.

Determining Past Harvest Activity in Old-growth Stands and Remnant Patches

Initially, old-growth stands and patches were identified in current color aerial photographs and photos were visually scanned for the presence of what appeared to be red alder. Red alder is an early successional species and can indicate disturbances such as the removal or death of groups or individual old-growth trees. Other indications of harvest activity used included the visual appearance of unusually well spaced old-growth trees indicative of past thinning activity, and the appearance overstory trees forming lines in the photos indicating the possibility of skid trails.

On the ground the old-growth stands and patches were confirmed as having no past harvest activity by the absence of stumps, cut logs, visible skid trails, or lack of snags. (It is important to note that some timber old-growth sales that were never implemented had a few trees "bucked and scaled" as part of their pre-harvest timber cruise).

Assumptions of Retrospective Methods

There are several challenges with characterizing past forest structures such as the density and size range of large trees, species composition, and tree distribution based on retrospective methods. Retrospective methods in this study include measuring remnant existing structures (including stumps and standing trees), cruise records, and historical air photos. Retrospective methods assume a relatively high level of repeatability in the influence of local site characteristics on disturbance intensity and extent, and an understanding of local disturbance regime. In addition, the effects of fire, wind, pathogens, and climate may not be apparent. For example, fire exclusion, particularly the exclusion of low intensity burns, may have played a great part in the maintenance of forest structure and young stand development (Kirkland and Brandstrom 1936). The frequency of such fires may be underestimated (e.g. Morrison and Swanson 1990; Wetzel and Fonda 2000) because low intensity fires scar fewer trees (Morrison and Swanson 1990). Scarring on trees can be created by events other than fire, such as falling trees, bears, falling rocks, and mass movement. However, this is rare on trees over 50 years of age, which is the general minimum age at which western Oregon trees have been found to survive a fire (Morrison and Swanson 1990), although Sensenig (2002) in southwest Oregon found surviving trees that had fire scars when they were as small as 4.0 inches (10cm) dbh. Alternatively, fire intensity overall may have been lower in unharvested landscapes due to the microclimate created by a contiguous forest (Kirkland and Brandstrom 1936). Fire scars produced on moister sites may be more difficult to detect, and are described by Morrison and Swanson (1990) and Wetzel and Fonda (2000) as "buried" fire scars. They believe these scar characteristics on moist sites are caused by higher growth rates, lower intensity of fires, and higher mortality of massively scarred trees from fungal activity. More recent fires and other disturbances, such as wind and pathogens, can also destroy the evidence of past fires (Morrison and Swanson 1990). Dating fires by tree origin dates may also be difficult due to re-burns at close intervals. In addition, not all the tree mortality caused by fires happens immediately, and fire scars do not indicate other agents such as wind, insects, or pathogens. Some injured overstory trees could die slowly over many years from insects, fungi, or other subsequent disturbances thus creating canopy gaps and regeneration of new cohorts. Low intensity fires and other disturbances not recorded in fire scars may have played a greater role than assumed in reducing the stand densities of these forests and facilitating the development of a wide range of cohorts.

Another challenge to using retrospective methods is that existing forest stands and remnants may not be a representative sample of forest on the landscape historically because of timber harvesting priorities. The highest valued timber (densest, slowest growing, knot-free, and fine grained wood) in many cases, may have been harvested first as well as declining forests that contained snags and posed a high fire risk (Kirkland and Brandstrom 1936). However, Poage (2001) compared old-growth data from the early 1900s to early 1990s Bureau of Land Management records from 91 stands and found no significant difference between the old-growth stands left on the central western Oregon landscape today and those present in the early 1900s. Old-growth was likely harvested largely based on accessibility rather than on high volume or value. In either case, the local history may not always be detectable in the texture of historic air photos or available in cruise records.

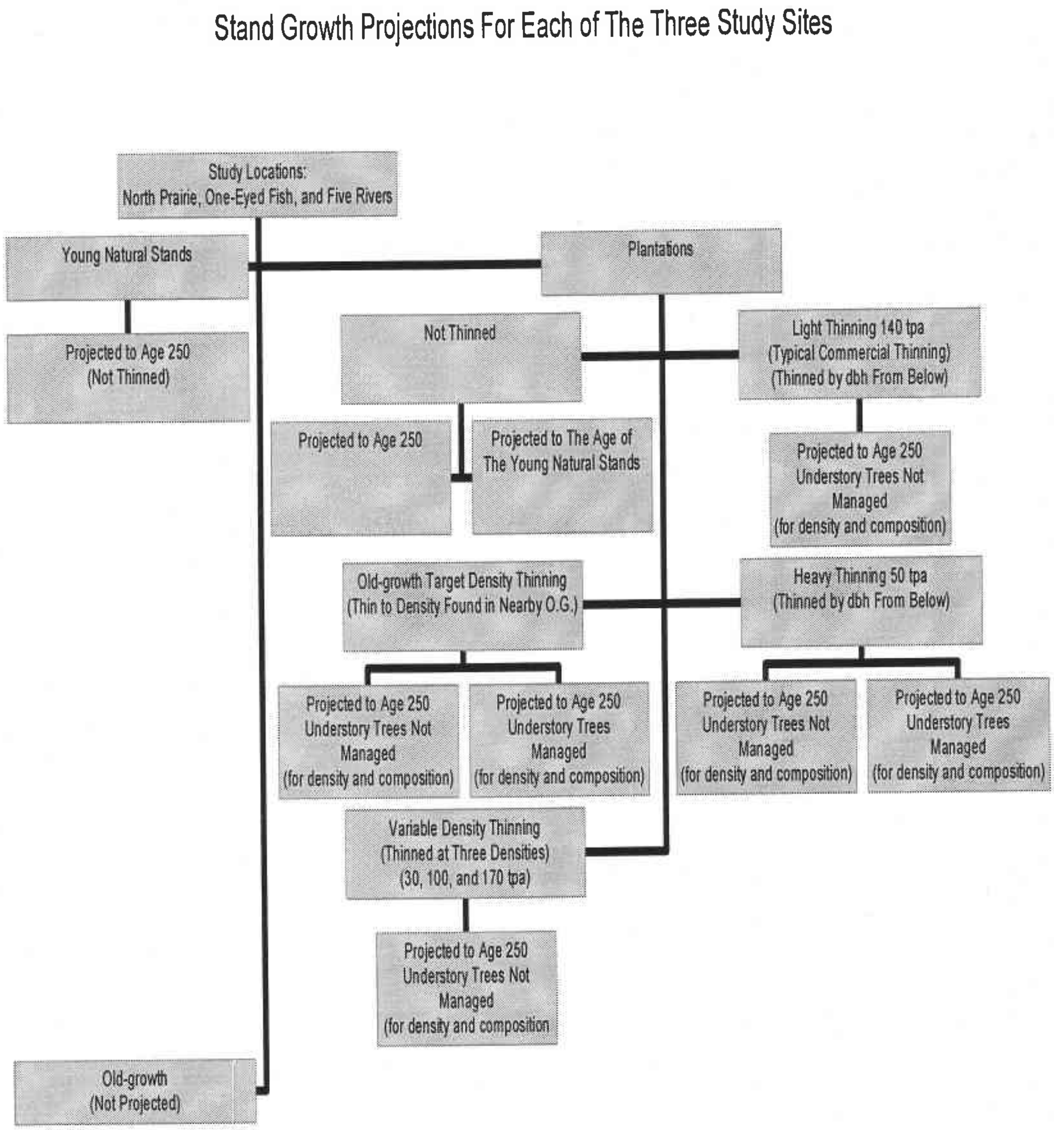
Retrospective methods also assume a level of uniformity among past and present natural forest structures (Pommerening 2002). For example, we assume that patches of forest appearing as a particular texture in historical photographs that have since been harvested were of similar composition and structure as nearby patches of a similar "texture" that have not been harvested. Past Native American practices also played a very influential role in fire disturbance in many locations (Morris 1934, Agee 1993). They could have been influential to regeneration conditions 100-500 years ago or longer (Swanson 2003, personal communication). In general, some of the assumptions regarding a given study site's history may be impossible to test (Acker et al. 1998), and we cannot be completely confident that the natural unmanaged forests found today represent the full range of stand conditions existing before European settlement (Pabst and Spies 1999).

All these variables make it difficult to quantify the accuracy of identifying the historical forest structure present in an area. Thus, it is important not to rely on one method to determine historical forest structure, but to utilize as many as practical. Therefore, I used cruise records, historical and current aerial photographs, and field samples. Even with the assumptions and uncertainty involved, I believe the structure identified at the local scale is more likely to resemble the characteristics of the historic old-growth structures more closely than are characteristics of a regional old-growth definition.

Stand Projection/Simulation Methods

Stand projections were performed using ORGANON (Hann et al. 1997) to project the observed diameters, heights to live crown, live crown ratios, total tree heights of the young natural stands and plantations and to simulate their development at various densities. (Figure 3.1 illustrates the projections performed in this study) To make the projections the following were measured and calculated: site index, stand ages, diameters, total trees heights, live crown ratios, expansion factor (the reciprocal of the area of the plot in acres), and radial growth (last 5 years growth). The site index for each of these projections was determined from the height of dominant trees and the program SICAL (Hann et al. 1997). The live crown ratio was calculated with the following formula (1.0-HTCB/HT Hann et al. (1997)).

Figure 3.1. Flow chart of stand growth projections and plantation thinning treatments.



Assumptions of Using Stand Projections

Stand projections can provide insightful information for possible structural outcomes to help guide the prescription development and decision-making process. They can be used to show the potential relative differences in outcomes of different thinning management regimes. The primary advantage of using stand projections is the ability to make a prediction, in reasonable detail, of tree and stand growth, including stem size distributions (Monserud 2002), heights, crown sizes, and tree form. Projections also incorporate competitive effects at both the stand and tree level (Monserud 2002).

Several assumptions are implicitly part of using growth and yield models like ORGANON: a) The model reasonably projects the overstory trees, even though the extrapolations of tree growth for my stands were beyond the range of data on which this version of ORGANON was based on (e.g. 135 years) (McComb et al. 1993). (Other studies have made projections of stand growth outside the data that ORGANON was developed on (e.g. McComb et al. 1993).) b) The projected difference between stands with uniform spacing and non-uniform spacing is not significant. The model is an individual tree distance independent model so the projections are based on every tree being spaced an equal distance. None of my stands have uniform tree spacing, though the plantations are usually much more uniform in spacing than the natural stands. Thus, any projection of the overstory tree growth is probably slightly overestimated and the range of understory growing conditions is possibly underestimated. c) The model assumes that no disturbance mortality occurs that is greater than the normal annual mortality rate. No mortality caused by a major disturbance agent is projected (such as wind storms, fire, insect outbreak, or pathogens). (For example, the increased risk of blowdown in heavily thinned stands is not included in the projections (Barbour et al. 1997).) d) The model does not project that natural regeneration establishment. Only estimates can be added as ingrowth. e) The projections assume that no significant damage from logging occurred to the overstory or understory trees that could affect the mortality rate. f) The model does not "grow" understory shrubs and woody plants that might compete for resources but also add to the structural complexity (Barbour et al. 1997). Understory vegetation can cause differences in rates of establishment and tree growth. g) The model is not sensitive to environmental change, static environmental conditions are assumed (i.e. no climatic changes) and therefore, they have no connectivity to the underlying mechanisms of productivity (Monserud 2002). There is also an important assumption made when attempting to model variable density thinning with a distance independent model: there are no interactions between each of the densities, when in reality there may be. That is, the smaller the patch sizes, the more interaction can be expected, reducing the projection accuracy.

Care must be taken to keep all the assumptions in mind and to recognize potentially unrealistic portions of projection results. Projections of stand development are the only ways, other than retrospective methods, of ascertaining the possible effects of implementing silvicultural strategies and differences in strategies over extended periods until long-term field experimentation can produce results (Hansen et al 1995).

Projecting Stands without Thinning

I performed simulations to demonstrate how plantations and young natural stands are developing relative to each other and to old-growth at each of the three study areas. The plantations at each study location were projected to the age of the young natural stands and to age 250 years, and the young natural stands were projected to the age of 250 years without any form of thinning or density management. The projected height-to-diameter ratios, diameter distributions, heights, and crown ratios were compared to those for the old-growth stands and to each other.

Projecting Thinning of Plantations

I chose five thinning options to be projected for the plantations to indicate how management may affect plantation development of old-growth characteristics. These five options included: 1) unthinned, 2) light thinning (typical commercial thinning), 3) heavy thinning, 4) variable density thinning, and 5) old-growth target density thinning. With the exception of the unthinned option, all these options could be considered commercial. The plantations prior to thinning at the three study areas contained basal areas between 203 and 309 square feet per acre (47 and 71 square meters per hectare), and Curtis's relative densities between 0.63 and 1.08 (weighted average based on English units) (Curtis 1982).

The unthinned option was projected for the plantation stands to age 250 for each of the study locations without underplanting, thinning, or other forms of management to accelerate, enhance, or redirect the stand development toward old-growth structural objectives.

The thinning option similar to typical wood production thinning (light thinning) was projected for the plantations to the age of the young natural stands and to age 250 for each study location. This consisted of thinning-from-below extracting trees with a diameter of 6 inches and above to a density of 140 trees per acre (346 tph).

The heavy thinning option projected the plantations thinned to 30 trees per acre (74 tph) greater than 6 inches (15cm) dbh. The trees chosen for extraction were removed proportionally from the initial diameter distributions for each study location. All trees ≥ 20 inches (51cm) diameter were not thinned but were counted in the tpa target retention densities.

The variable density thinning option was modeled by projecting three thinning densities as if they were separate stands, and then combining them at the end of the projection. The trees chosen for extraction were removed proportionally from the initial diameter distributions to obtain the desired residual densities. The three thinning densities were 30, 100, and 170 overstory trees per acre (74, 247, and 420 tph). All trees ≥ 20 inches (51cm) diameter were not thinned and were counted in the tpa target retention densities.

The old-growth target density thinning used current existing densities and species composition of overstory trees in nearby old-growth stands as thinning targets. This thinning strategy was a thinning by diameter class from below. The target densities varied between study sites, but were thinned to result in the target density of overstory trees by age 250.

Each of the plantation thinning regimes was modeled with a single silvicultural entry (similar to Barbour et al. 1997) then projected to age 250. The basal areas and Curtis's relative densities directly after the thinnings are shown in Table 3.2. The application of multiple entries could allow for further enhancement of structural habitat characteristics (Barbour et al. 1997) but was not simulated in this study. I chose a projection age of 250 years for this study. Other authors have used, age 240 (Hansen et al. 1995), age 185 (McComb et al. 1993), and age 260 (Busing and Garman 2002). Also Franklin et al. (1981) hypothesized that forests require 175 to 250 years under natural conditions to develop old-growth.

Table 3.2. Residual overstory trees per acre, basal area, and Curtis's relative density directly after thinning.

	North Prairie			One-Eyed Fish			Five Rivers		
	tpa ‡	BA Ψ (sqft/ac)	RD †	tpa ‡	BA Ψ (sqft/ac)	RD †	tpa ‡	BA Ψ (sqft/ac)	RD †
Control	230-380	310.2	1.09	190-260	239.5	0.76	100-260	203.2	0.63
Light Thinning	140	221.7	0.79	140	192	0.59	140	178.3	0.54
Heavy Thinning	30	37.2	0.18	30	33.8	0.12	30	30.7	0.10
Variable Density Thinning	30, 100, 170	37.2-196.7	0.18-0.73	30, 100, 170	33.8-180.4	0.12-0.58	30, 100, 170	30.7-182	0.10-0.57
Old-growth Target Thinning	43	95	0.28	15	28	0.10	16	20	0.07

‡1.0 tph = 2.54 tpa
Ψ 1.0 m^2/ha = .229 ft^2/ac
† The relative density values above are based on English units.

Post-thinning natural regeneration in thinned stands has been found to occur at a much higher frequency than in unthinned stands (Bailey 1996; Bailey and Tappeiner 1998). Therefore, estimates of probable amounts of ingrowth were added to the thinning projections. Bailey (1996) and Bailey and Tappeiner (1998) found, in 32 pairs of thinned and unthinned 40 to 100 year-old Douglas-fir stands in western Oregon, an average seedling density of 580 tpa (1,433 tph) in the thinned stands (>809 tpa or 2,000 tph in the heavy thinnings) and 94 tpa (233 tph) in the unthinned stands 10-24 years after the thinning. Out of the 32 pairs in Bailey and Tappeiner's (1998) study, I chose the average seedling density for the three thinned stands closest to each of my study areas. These were selected as the estimated ingrowth for the light thinning, variable density thinning, heavy thinning, and site-specific old-growth target thinning for our projections 15 to 20 years post treatment (reaching breast height). Only the number of existing seedlings currently present were used in the unthinned projections. For simplicity, the ingrowth seedlings in thinned stands were assumed to be western hemlock. The dominance of shade tolerant species in these projected stands will likely be dependent on seed availability (Bailey and Tappeiner 1998). The seedling distribution pattern within the treated stands can be attributed to soil disturbance from thinning that enhances the seedbed conditions (Bailey and Tappeiner 1998). Therefore, when ingrowth was added to the growth and yield projection program ORGANON, with its assumption of equal spacing, it should have reasonably predicted the regeneration seedling growth.

Data Analysis

I compared the data between stand types at each of the three study sites but not among sites. Diameter data comparisons between stand types were determined to be normally distributed, therefore, I utilized a standard paired t-test with the assumption of unequal variance, $\alpha = 0.05$. I made statistical comparisons of mean diameters derived from growth increments to age 40 and 100 between the young natural, plantation, and old-growth forests. The total mean diameter growth of the dominant trees for the young natural, plantation, and old-growth forest types were all compared at the oldest common age, about age 40 (the age of the plantations), and at age 100 with the plantations projected from age 40 to 100 years of age.

Age ranges, growth increments, height-to-diameter ratios, live crown ratios, and diameter distributions between the three different stand types were compared. Confidence intervals and graphs of diameter growth show whether the largest 24 tpa (60 tph) in plantations and young natural stands fall within the 95% confidence interval of late-successional stands at specified ages. Growth increments, height-to-diameter ratios, and live crown ratios from the unthinned control plots at the Hoskins replication of the Levels of Growing Stock (LOGS) study also were compared to the three stand types. Established in 1963, the LOGS study was implemented to describe the relationship between tree growth and growing stock when controlling thinning type and initial densities (Marshall and Curtis 2002). The Hoskins plots are one of several replications of the LOGS study located in western Oregon and Washington.

I compared my results to those of Poage and Tappeiner (2002) and Tappeiner et al. (1997), who evaluated young and old stand development on similar sites.

Similarity Index

I used an adaptation of the Morisita's community similarity index (Bower and Zar 1977) similar to McComb et al. (1993) to compare tree diameter distributions between stand types. An index value of 1.00 indicates identical diameter distributions between stand types, but if the index value is 0.00, then there is no similarity between stand diameter distributions. This index is based on the probability that each of the individual diameters randomly selected from each of the two stand types will belong to the same diameter size class, relative to the probability of drawing a pair of diameters of the same diameter size class from one of the stands types (Bower and Zar 1977). Old-growth stands from each study area were compared to the selected young natural stands at the projected age of 250. The old-growth stands were also compared to the plantations with and without the projected density management (thinning) treatments. The plantation treatments similarity indices were also compared to each other and to the young natural stands.

Stand Heterogeneity

When determining the heterogeneity of vertical stand structure I used live crown ratios as a surrogate for the level of individual crown development, including crown shape, within crown porosity, and individual branch size and development. I used the diameters and tree heights as measures of tree size and height-to-diameter ratios and live crown ratios as measures of tree stability and structure. In addition to using Morisita's similarity index, I compared the coefficients of variation of tree diameter with the assumption that higher coefficients of variation equated higher stand heterogeneity in tree size.

CHAPTER FOUR: RESULTS AND DISCUSSION

Stand Age Ranges and Their Influence on Growth and Density

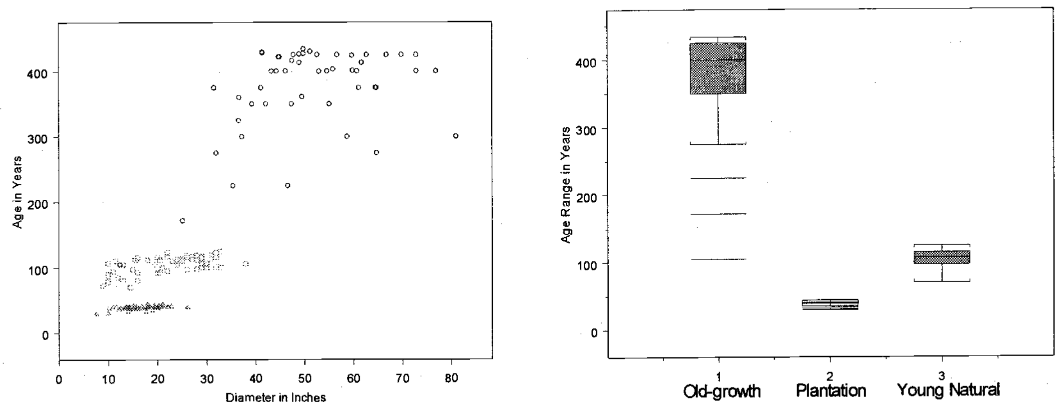
The age range of trees in plantations was much narrower than the ranges of tree ages for the young natural stands and the old-growth. (See figure 4.1) The Douglas-fir recruitment periods for the three young natural stands were (55, 21, and 102 years), though much larger than the plantations (15, 8, and 12 years), was considerably shorter than the age range found in the old-growth (333, 300, and 354 years). A wide age range likely indicates low initial stand densities that create growing conditions that may be important for the development of old-growth structure and composition. The age distribution of a stand may in turn provide a mechanism for the development of a range of tree sizes. Both low initial densities and the influence of density-reducing disturbances throughout the life of a stand may be important for the establishment and growth of the large tree component of old-growth, and the development of large live crowns, low height-to-diameter ratios, heterogeneity in tree sizes, and well-developed understories found in nearby old-growth forests.

The old-growth in this study likely had initial recruitment periods and densities similar to young natural stands. This is supported by early radial growth rates of large trees in both the old-growth and young natural stands (presented later in this paper, see page 75 and figure 4.2). Given this evidence, the old-growth would have required multiple density-reducing disturbances to develop its present age range from the initial recruitment period.

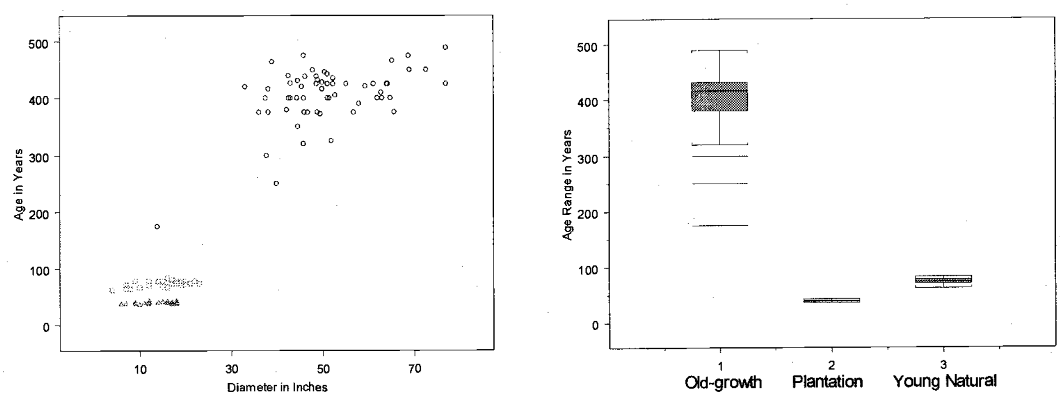
Wide age ranges of tree recruitment may indicate low densities and competition for initial trees. Shade tolerant trees can also affect the recruitment period of Douglas-fir. For example, the presence of western hemlock can shorten the recruitment period of Douglas-fir trees particularly because western hemlock can more readily establish than Douglas-fir in partially shaded environments. I believe this happened in the young natural stand at the One-Eyed Fish study site resulting in a shorter Douglas-fir recruitment period (21 years). The western hemlock at this site made up 110 to 160 overstory tpa (272 to 395 tph) > 8 inches (20cm) dbh in contrast to 20 to 40 tpa (49 to 99 tph) at North Prairie and none at Five Rivers. Also, growth rates and little evidence of past self-thinning indicate a low initial stand density.

Figure 4.1 Diameter age distributions: (O) Old-Growth, (□) Young Natural, and (Δ) Plantation. A very wide range of overstory tree ages exhibited by the old-growth followed by the young natural stands and then the plantations in all three study sites.

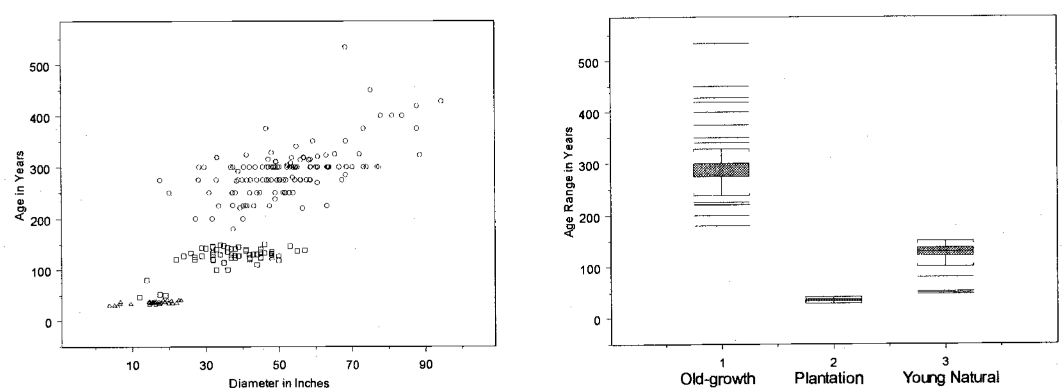
North Prairie



One-Eyed Fish



Five Rivers / Lobster Creek



The current densities in each of the young natural stands is relatively high. This resulted because the stands accumulated trees to reach full stocking over the entire recruitment period, but the wide range of ages created differences in crown sizes that allow the larger trees to more readily express dominance over the smaller, oftentimes younger, neighboring trees. In contrast, crown differentiation was less pronounced and took place at a slower rate in uniform plantations compared to naturally established stands (Curtis and Reukema 1970). Longer recruitment periods found in natural stands would have allowed the older individuals or species, with rapid early growth rates, to overtop younger or slower-growing neighbors.

In the three plantations, most of the Douglas-fir trees sampled (≥85%) are within 3 to 6 years of age. The reasons for these narrow age ranges are the high survival rate of planted seedlings, probably due to site preparation and vegetation management, and pre-commercial thinning that may have removed many of the smaller trees that naturally seeded in after planting, thus effectively narrowing the age range.

In the young natural stands, the Douglas-fir trees are somewhat evenly distributed across their recruitment periods (55, 21, and 102 years) rather than concentrated at the beginning presumably due to low initial stand densities (See Figure 4.1). The old-growth contained Douglas-fir recruitment in groups, but distributed over a much greater period of 300 to 350 years, possibly because of low initial densities and periodic density-reducing natural disturbances that extended recruitment.

Old-growth forests, as with uneven-age stands (O'Hara 2001), are usually not all-aged stands, because natural disturbance events and conditions that coincide with tree regeneration are much more likely to be more episodic rather than occur every year, unless the intermediate ages are made up of shade tolerant species (Isaac 1940). This age structure is not always visible in the form of aggregates of Douglas-fir regeneration through time nor is it an even distribution (See figure 4.1). Cohorts of similar ages of recruitment within relatively narrow age ranges can form two or more distinct age classes and may have become established under a residual stand, possibly following events like a moderately severe fire, windthrow (Isaac 1940; Morrison and Swanson 1990; McComb et al. 1993), or periods without fire (disturbance). If the overstory trees are nearing their site potential maximum height, their crowns cannot rapidly fill newly created openings from disturbance and significantly reduce seedling tree growth. As height growth slows, so does lateral branch growth. This can delay the rate of canopy closure after a disturbance and the understory can develop for a longer duration (Nyland 2003). This also enables the understory regeneration to sustain growth and eventually replace older cohorts (O'Hara 2001; Schutz 2002), or simply to achieve an overstory crown position, resulting in an increase in the overstory range of ages.

The observed wide age ranges influenced by disturbance and overstory growth response in nearby old-growth may provide indications that repeated disturbances, such as repeated natural disturbances or thinnings, are necessary for plantations to develop similar structure. For example, a thinning schedule could be implemented to create opportunities for tree recruitment of similar composition, density, and tree size observed in adjacent old-growth.

Densities

The current overstory stand densities (>8 in or 20 cm dbh) in the old-growth stands were low and variable. They ranged from 45 to 88 tpa (111 to 217 tph) in North Prairie, 41 to 86 tpa (101 to 212 tph) in One-eyed Fish, and 39 to 42 tpa (96 to 104 tph) in Lobster Creek (near Five Rivers) (See Table 4.1). The young natural stand densities (>8 in or 20 cm dbh) densities were much higher but still variable with densities ranging from 120 to 160 tpa (296 to 395 tph) in North Prairie, 320 to 888 tpa (791 to 2194 tph) in One-eyed Fish, and 172 to 208 tpa (425 to 514 tph) in Five Rivers. Although pre-commercially thinned 20-25 years ago, the plantations overstory trees (>5 in or 13 cm dbh) were generally still higher in density, but were more variable than expected. They had densities ranging from 230 to 380 tpa (568 to 939 tph) in North Prairie, 190 to 260 tpa (470 to 642 tph) in One-eyed Fish, and 100 to 260 tpa (247 to 642 tph) in Five Rivers. The current densities in the young natural stand and plantation are not very different, with the exception of the current high densities in One-eyed Fish. But it is the low initial densities that were in the young natural stands that provide the structure for sustained growth beyond age 70 or 80. However, at crown closure the young natural stands may have had higher total stand densities than the plantations, but crown closure likely occurred at a later age. When projected to 250 years, in overstory trees per acre, the young natural stands had produced densities 4% to 38% higher than currently found in the old-growth. The plantations at the age of 250 had projected densities with 2% to 53% more overstory trees than the old-growth. The North Prairie young natural stand and plantation are the closest in density to the old-growth because most of the old-growth overstory is composed of Douglas-fir. In general, the higher densities found in the young natural stands and plantations indicates that neither the young natural stands nor plantations in this study were able to self-thin to densities as low or lower than the densities found in nearby old-growth stands by age 250 without disturbance.

Table 4.1. Site index and current stand density by study area and stand type.

Study Area	Stand Type	‡ Trees per acre	† Relative Density	Ψ Basal Area Per Acre	Ω Site Index	Δ Mean Diameter in Inches
North Prairie	Old-growth	45-88	0.91	568	*	31
	Young Natural	120-160	1.04	315	101	20
	Plantation	230-380	1.08	309	117	13
One-eyed Fish	Old-growth	42-87	0.43	221	*	38
	Young Natural	320-888	0.99	307	100	12
	Plantation	190-260	0.76	237	134	13
Five Rivers	Old-growth	39-43	0.46	268	*	32
	Young Natural	48-108	1.00	473	121	35
	Plantation	100-260	0.83	203	123	13
	Two-Story	172-208	0.63	290	122	16

‡ 1.0 tph = 2.54 tpa
Ψ 1.0 m^2/ha = .229 ft^2/ac
† The relative density values above are based on English units.
Ω 1.0 m = 3.28 ft.
Δ 1.0 cm = .394 in.
* No data available

The Curtis's relative densities (Curtis 1982) were all calculated based on all the species present by using a weighted average of the theoretical density maximum. The relative density in all the old-growth stands were between RD .43 and RD .91 (See table 4.1). The high relative density of .91 was found in the North Prairie old-growth stand, again because of the greater composition of large diameter Douglas-fir trees. At their current ages the young natural stands contain relative densities between RD .99 and RD 1.04 and the plantations contain relative densities between RD .63 and RD 1.08. Projected to age 250, without density management such as thinning, the young natural stands developed relative densities between RD 1.00 and RD 1.01, and the plantations were between RD 1.00 and RD 1.09. The young natural stands and the plantations maintained higher densities of smaller diameter trees than the old-growth stands. Again, this may indicate the inability of these stands to self-thin to the densities found in nearby old-growth stands without disturbance. The considerable variability found in the old-growth densities may suggest the need to manage for site-specific targets to achieve pre-timber harvest forest conditions.

Tree Diameter and Radial Growth

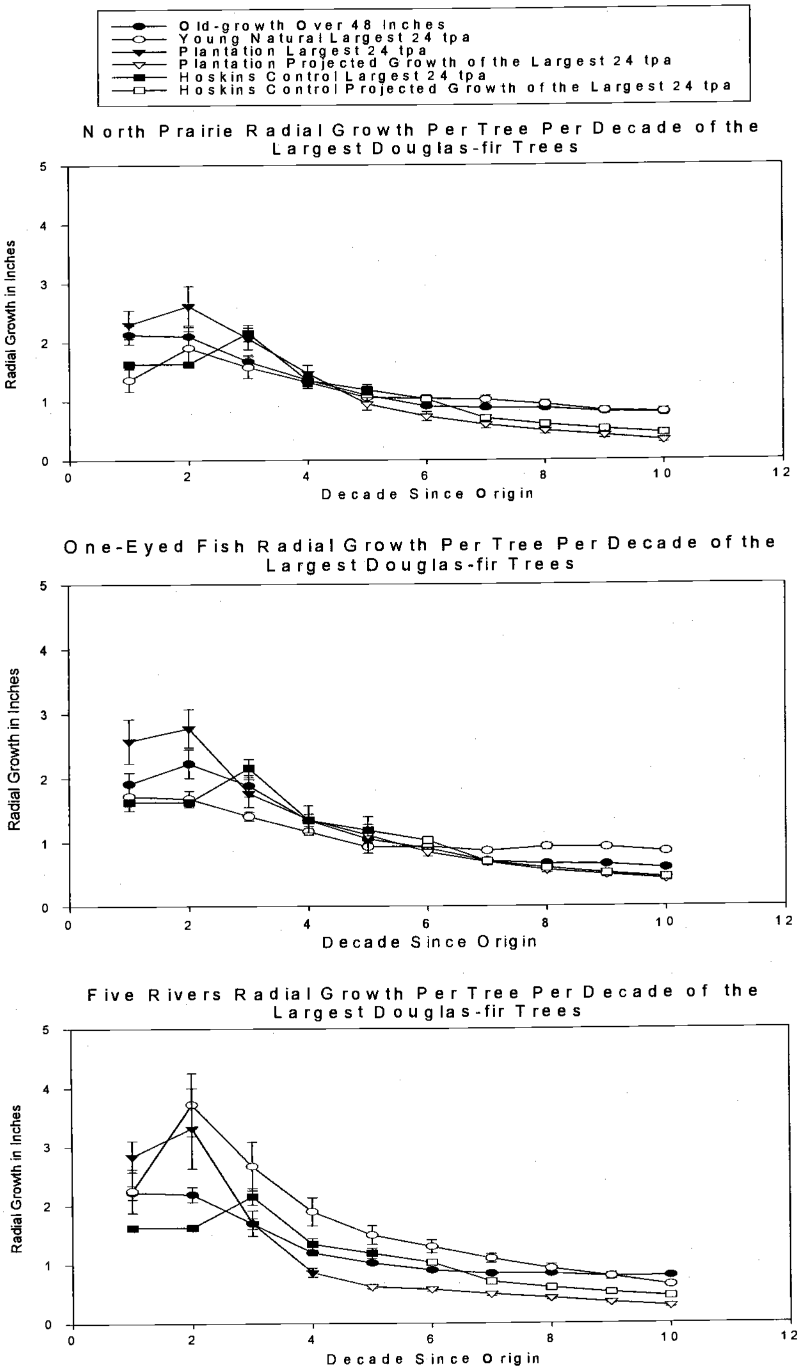
The diameters at age 40 were compared between all the Douglas-fir trees > 30 inches (76cm) in diameter in the old-growth stands (all the large overstory trees), and the largest 24 Douglas-fir trees per acre (60 tph) in the plantations and young natural stands (See table 4.2). The diameters of these same dominant and codominant trees at age 100 were also compared. At all the study sites the mean tree diameters at age 40 of the largest 24 tpa (60 tph) in plantations were significantly larger than the old-growth trees. [North Prairie ($p < 0.0001$), One-Eyed Fish ($p = 0.0325$), and Five Rivers ($p = 0.0005$)] No significant difference in mean tree diameters at age 40 were found in the largest 24 tpa (60 tph) in young natural stands compared to the old-growth trees at North Prairie ($p = 0.3430$) and One-Eyed Fish ($p = 0.2497$), but the young natural stand's mean diameter at Five Rivers was significantly larger ($p < 0.0001$) than the mean diameter old-growth. The young natural stands diameters at age 40 were significantly smaller than the plantations at North Prairie ($p < 0.0001$) and One-Eyed Fish ($p < 0.0001$), and the young natural stand at Five Rivers was significantly larger than the plantations at Five Rivers ($p = 0.0025$). The rapid growth of the Five Rivers young natural stand is most likely due to the density conditions created by its 102-year recruitment period. This long recruitment period was possibly caused by the extremely high quantities of competing vegetation in this study site, reducing available growing space for tree regeneration, but allowing rapid tree growth for trees above the shrub layer. In addition, the old-growth stand it was being compared to- Lobster Creek- is located on the other side of the watershed rather than nearby the young natural stand. No significant difference in mean tree diameters at age 100 was found in the largest 24 tpa (60 tph) in young natural stands compared to the old-growth trees at North Prairie (p-value = 0.2855) and One-Eyed Fish (p-value = 0.3955), but the young natural stand's mean diameter at Five Rivers was significantly larger (p-value <0.0001) than the old-growth.

Table 4.2. P-values comparing diameters of the largest 24 tpa (60 tph) in plantations and young natural stands at age 40 and 100 to old-growth trees greater than 30 inches (76cm) dbh at each study site.

Study Site	Stand Types Compared	p-value for Diameters at age 40	p-value for Diameters at age 100
North Prairie	Old-growth and Young Natural	p = 0.3430	p = 0.2855
	Old-growth and Plantation	p = 0.0003	
One-Eyed Fish	Old-growth and Young Natural	p = 0.2497	p = 0.3955
	Old-growth and Plantation	p = 0.0325	
Five Rivers	Old-growth and Young Natural	p < 0.0001	p < 0.0001
	Old-growth and Plantation	p = 0.0005	

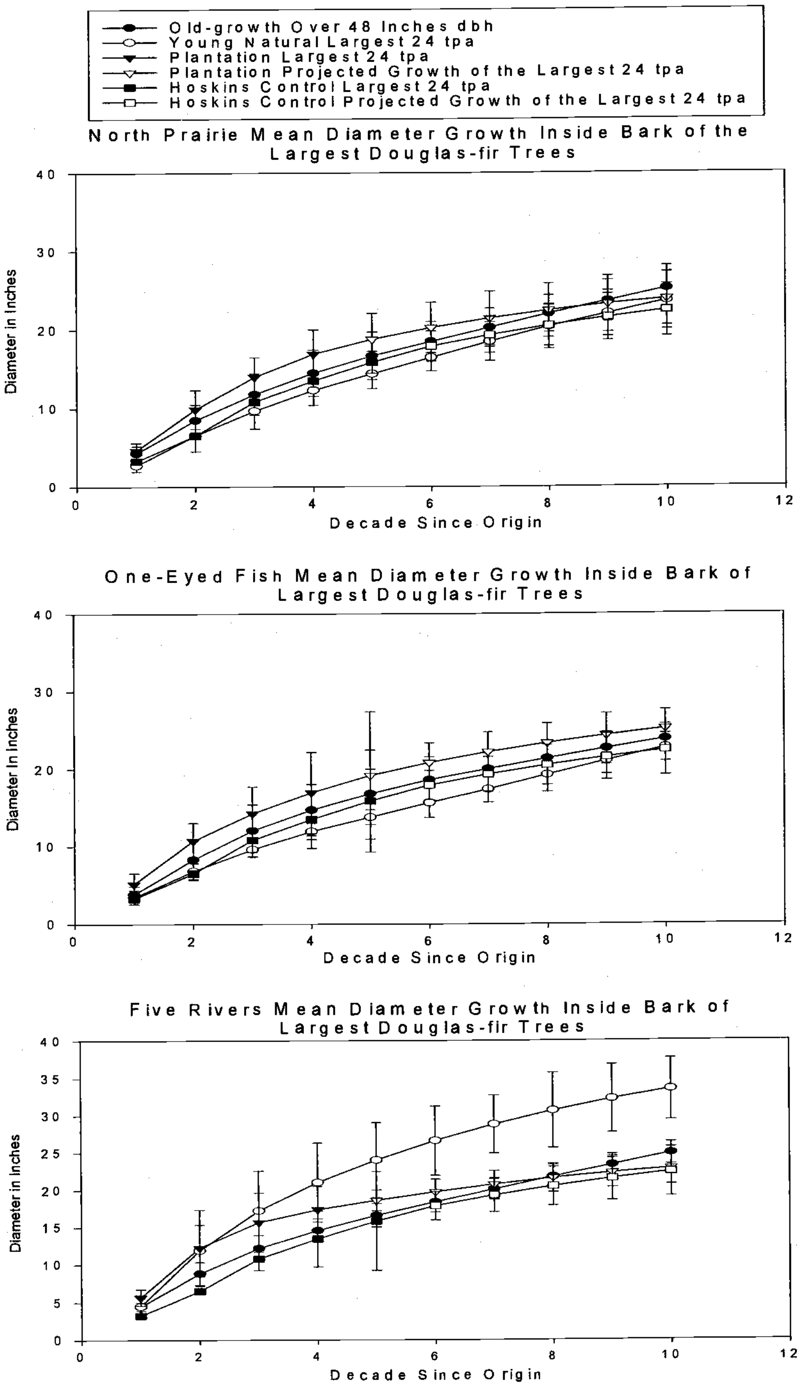
The radial growth in 10-year increments from age 0 to age 40 (the oldest common age between the stand types) and from age 0 to 100 were compared between the old-growth trees greater than 48 inches (122 cm) in diameter and the largest 24 tpa (60 tph) in the plantation and young natural stand types graphically. (See figure 4.2) The plantations grew rapidly for the first 20 to 30 years, followed by a significant rapid decline in radial growth. Though containing greater diameters, they were projected to drop in radial growth below the growth rates of both the young natural and old-growth stands in the three study sites between age 30 and age 55. The plantations in the One-Eyed Fish study site were projected to sustain growth rates above the old-growth the longest to age 55, possibly because of differences in site productivity. The site productivity of the plantation stand at One-Eyed Fish is 134 feet (41 m) at age 50, compared to the young natural stand's site index of 100 feet (30 m) at age 50 (King 1966).

Figure 4.2. Average radial growth per tree in inches of the dominant overstory trees by decade from 10 years old to age 100 with plantation growth projected from age 40 to 100 years. Error bars are the SE (One-eyed Fish young natural stand was projected from age 80 to 100).



Diameter growth in 10-year increments from age 0 to age 40 (the oldest common age between the stand types), and from age 0 to 100, were also compared between the old-growth trees greater than 48 inches (122cm) in diameter and the largest 24 tpa (60 tph) in the plantation and young natural stand types graphically. (See figure 4.3) The plantations sustained rapid growth early, giving them larger diameters than the young natural and old-growth stands, but the growth rates were not sustained and the old-growth had achieved larger diameters than the plantations by age 85 in two of the three study areas. In the third study area- One-Eyed Fish- the plantation was projected to sustain larger diameters than the old-growth past age 100, but this trend is not anticipated to continue much longer. This plantation was able to sustain larger diameters longer possibly because of differences in site productivity and pre-commercial thinning intensity.

Figure 4.3. Average diameter growth per tree in inches of the dominant overstory trees by decade from 10 years old to age 100 with plantation growth projected from age 40 to 100 years. Error bars are the SE (One-eyed Fish young natural stand was projected from age 80 to 100).



The North Prairie and Five Rivers plantations' rapid drop in diameter growth rates, and the inability to sustain as high growth rates into the future as either the old-growth or the young natural stands is believed to be a result of the stand uniformity and density found in plantations. Plantation establishment practices create narrow age ranges and low tree species diversity that can lead to uniform tree sizes, which may inhibit the trees ability to differentiate (sort themselves out by expressing dominance over their neighbors) as quickly as naturally regenerated stands. Sustained early rapid growth rates may be necessary for Douglas-fir trees to develop into large old-growth trees. The ability for trees to differentiate is also important for trees to develop low height-to-diameter ratios to maintain structural stability for survival to old ages, and to maintain large live crown ratios for sustained growth. In addition, the growth and yield model projections that were performed from age 40 to 100 on the plantations may possibly be overestimated for the reasons given above because the growth and yield model used to produce the projections was developed from fully stocked naturally regenerated stands, not from uniform plantations.

Overall, the plantations in this study produced higher early growth rates than the young stands in the study by Tappeiner et al. (1997) or the three control plots at the Hoskins Level of Growing Stock (LOGS) study area. I attribute this to the pre-commercial thinning implemented in the plantations in my three study areas, and possibly other vegetation management treatments. None of the young stands in the Tappeiner et al. (1997) study were pre-commercially thinned, they were higher in initial density and naturally regenerated after harvest rather than planted. The pre-commercial thinning in the plantations postponed crown closure, sustained diameter growth rates, and aided or delayed the need for trees to differentiate. Unfortunately, pre-commercial thinning may not prevent the rapid decline in growth rates, they may only postpone it. Also, the pre-commercial thinning does not seem to enhance the plantation's ability to sustain high future growth rates. Pre-commercial thinning generally does increase the early development of large diameter trees, which is an important characteristic of old-growth, but future density management such as thinning, may also be necessary to maintain growth rates and structural characteristics such as low H:D ratios and high live crown ratios in the Douglas-fir (See pages 92-95 and 97-102).

Heterogeneity

Heterogeneity in tree size and stand structure are considered important structural elements of old forests. They can be strongly influenced by current and past stand densities and may be influenced by the stand's age range. I used mean diameters, coefficients of variation (CV) of diameters, and Morisita's similarity index (Bower and Zar 1977) to compare and describe the range of tree sizes and structure developing. In addition, I used height-to-diameter ratios and live crown ratios to compare tree and stand stability, and tree and stand structure, respectively.

Diameters

Projected to age 250, the young natural stands in all three study sites developed mean diameters that were between 4 and 17 inches (10 and 43 cm) greater than the plantations if the plantations were left unthinned (in addition to the pre-commercial thinning) to age 250 (See table 4.3). The mean diameters of the largest 24 trees per acre (60 tph) in the plantation and young natural stands were closer to each other at age 250, and closer to the mean diameter values found in the old-growth stands (with the exception of the young natural stand at Five Rivers that produced a mean diameter much higher than either the plantation or the nearby old-growth stand). The plantation thinning prescription options, in general, increased the mean diameters of the largest 24 tpa (60 tph) by age 250. The largest increases were observed in the heavy thinning and the site-specific target thinning treatments.

The plantations with the understory densities managed for density and composition similar to nearby old-growth forests, in addition to overstory thinning, produced slightly higher mean diameters for the largest 24 tpa (60 tph), and in some cases, substantially higher maximum and mean stand tree diameters (See Table 4.3). In the overstory heavy thinning option and the site-specific target thinning option, managing the understory trees toward a target density resulted in an increase in the mean diameter of the Douglas-fir largest 24 tpa (60 tph) in the overstory by age 250. The largest increase was observed in the Five Rivers site-specific target thinning, increasing it by 16 inches (40 cm). (Note: the understory trees were not included in the calculations of the mean diameters at age 250)

The variability in mean tree size represented by the coefficients of variation (CV) in tree diameter given in table 4.3 were also projected to increase in most of the plantation thinning options by age 250, compared to the unthinned plantations. For example, the heavy thinning generally produced the highest CV of diameter at age 250, producing CV's from 47% to 69%, compared to the unthinned plantations that produced CV's from 27% to 35%. In addition, the mean tree diameters of the largest 24 trees per acre (60 tph) were influenced by these thinning treatment intensities. The heavy thinning and light thinning offered improvements, though often slight, in dominant overstory tree diameters and the stands maximum tree diameters. (See table 4.3)

Table 4.3. Mean diameters and the diameters of the largest 24 trees per acre (60 tph) in inches (2.54 cm/in) by stand type and plantation thinning prescription currently, projected to the age of the young natural stands, and to age 250.

		Mean dbh of Largest 24 tpa	Mean dbh (CV%)	Mean dbh of Largest 24 tpa	Mean dbh (CV%)	Mean dbh of Largest 24 tpa	Mean dbh (CV%)
Study Area	Stand Type	At Current Age		At Age of YN		At Age 250	
North Prairie	Old-growth	*	36 (68)	*	*	*	*
	Young Natural	28	21 (35)	28	21	43	34 (35)
	Plantation (no additional thinning)	19	15 (27)	35	25	48	30 (35)
	Light Thin	19	15 (27)	*	*	49	37 (32)
	Variable Density Thin	19	15 (27)	*	*	45	27 (44)
	Heavy Thin With Understory Managed	19	15 (27)	*	*	51	31 (62)
	Heavy Thin Without Understory Managed	19	15 (27)	*	*	49	26 (69)
	Site Specific Target Thinning with Understory Managed	19	15 (27)	*	*	49	43 (21)
	Site Specific Target Thinning without Understory managed	19	15 (27)	*	*	49	40 (28)
One-Eyed Fish	Old-growth	*	46 (29)	*	*	*	*
	Young Natural	19	13 (29)	19	13	40	33 (34)
	Plantation (no additional thinning)	18	13 (28)	27	19	44	27 (27)
	Light Thin	18	13 (28)	*	*	45	34 (27)
	Variable Density Thin	18	13 (28)	*	*	43	27 (40)
	Heavy Thin With Understory Managed	18	13 (28)	*	*	50	26 (68)
	Heavy Thin Without Understory Managed	18	13 (28)	*	*	50	26 (68)
	Site Specific Target Thinning with Understory Managed	18	13 (28)	*	*	46	29 (50)
	Site Specific Target Thinning without Understory managed	18	13 (28)	*	*	40	25 (41)
Five Rivers	Old-growth	*	45 (31)	*	*	*	*
	Young Natural	38	35 (25)	38	35	54	46 (25)
	Plantation (no additional thinning)	18	13 (33)	33	22	42	29 (32)
	Two-Story	23	16 (35)	*	*	*	*
	Light Thin	18	13 (33)	*	*	42	30 (31)
	Variable Density Thin	18	13 (33)	*	*	28	27 (32)
	Heavy Thin With Understory Managed	18	13 (33)	*	*	49	32 (49)
	Heavy Thin Without Understory Managed	18	13 (33)	*	*	43	23 (47)
	Site Specific Target Thinning with Understory Managed	18	13 (33)	*	*	52	35 (37)
	Site Specific Target Thinning without Understory managed	18	13 (33)	*	*	36	25 (33)
Hoskin	Hoskins Control Plots	21	12	*	*	42	24

Coefficients of variation of diameter in the old-growth stands were generally much higher than those found in the young stands. My results were similar to those of Franklin et al. (1981), who found that coefficients of variation of diameters in young stands ranged from 39-84% and the coefficients of variation of the diameters in old-growth were around 61-131% in the central Oregon Cascades. My CV's are not directly comparable with Franklin et al. (1981) because I had only 4-inch (10 cm) diameter classes available for the old-growth stands and therefore used 4-inch (10 cm) classes in the CV calculations for all of my stands. Much of the variability was lost by using these diameter classes, but the differences in diameter variability between the old-growth and both the young stand types is still quite apparent by the large differences in the CV's. Currently, the unthinned plantations contain CV's from 27-33%, young natural stands are from 25-35%, and the old-growth are from 29-68%. (See table 4.3)

Managing the understory tree density had mixed results on the diameter coefficient of variation. For example, it slightly increased the CV in the heavy thinning from 68% and 47% to 68% and 49% and site-specific target thinning from 41% and 32% to 49% and 36% at One-Eyed Fish and Five Rivers respectively, but it decreased the CV at North Prairie from 68% to 20% in the heavy thinning and from 28% to 20% in the site-specific target thinning. (See table 4.3) This decrease in diameter size variability may be attributed to North Prairie's projected understory tree composition. At this site the advance regeneration combined with the ingrowth (ingrowth added 15 years post thinning) provided a much greater range of hemlock diameter sizes in the unmanaged understory projections than in the managed understory. This is because the North Prairie managed understory projections achieved the understory hemlock density target by only including the advance regeneration alone, so the hemlock ingrowth was not added to the projection.

Morisita's Similarity Index

The diameter distributions of the old-growth stands were compared to the projected diameter distributions of the young natural stands and plantations at age 250, with and without plantation thinning options, using an adapted version of Morisita's community similarity index. With this similarity index 1.00 indicates high similarity and 0.00 indicates no similarity. In general, both the young natural and the plantation diameter distributions without thinning produced a low similarity index value to old-growth (See table 4.4). Due to the site-to-site differences in the old-growth diameter distributions, the young naturally regenerated stands did not consistently produce higher similarity indices than the unthinned plantations. These low values may indicate the need to restore natural disturbance processes in these stands or mimic disturbance processes through management such as thinning. Both North Prairie and One-Eyed Fish produced tree diameter distributions in the unthinned plantations at age 250 more similar to old-growth than those that developed from the young natural stands.

Table 4.4. Morisita's similarity index values for similarity in diameter distributions at age 250 compared to nearby old-growth stands. The index ranges from 0.00 to 1.00 with 1.00 indicating high similarity to nearby old-growth and 0.00 indicating no similarity to nearby old-growth.

		Morisita's Similarity Index
Study Area	Stand Type	At Age 250
North Prairie	Young Natural	0.47
	Plantation (no additional thinning)	0.56
	Light Thin	0.62
	Variable Density Thin	0.03
	Heavy Thin With Understory Managed	0.33
	Heavy Thin Without Understory Managed	0.31
	Site Specific Target Thinning with Understory Managed	0.75
	Site Specific Target Thinning without Understory managed	0.69
One-eyed Fish	Young Natural	0.14
	Plantation (no additional thinning)	0.19
	Light Thin	0.17
	Variable Density Thin	0.05
	Heavy Thin With Understory Managed	0.20
	Heavy Thin Without Understory Managed	0.20
	Site Specific Target Thinning with Understory Managed	0.01
	Site Specific Target Thinning without Understory managed	0.00
Five Rivers	Young Natural	0.57
	Plantation (no additional thinning)	0.30
	Light Thin	0.31
	Variable Density Thin	0.12
	Heavy Thin With Understory Managed	0.07
	Heavy Thin Without Understory Managed	0.03
	Site Specific Target Thinning with Understory Managed	0.04
	Site Specific Target Thinning without Understory managed	0.01

The plantation thinning options that produced the highest Morisita's similarity index value for the diameter distribution at age 250 at each site included: in North Prairie the site-specific density target thinning option producing an index value of .69 (.75 with understory trees thinned) compared to the next best value of .62 produced by the light thinning; in One-Eyed Fish the heavy thinning from below produced an index value slightly higher than the control; and at Five Rivers the light thinning option was slightly higher value than the control. (See Table 4.4). All One-Eyed Fish and Five Rivers management options, including the controls, were relatively low in similarity to the old-growth, possibly indicating that more than a single entry thinning prescription may be necessary at these sites to alter plantation development toward complex local old-growth stand characteristics (further discussion regarding the need for multiple thinning entries is presented later in this paper).

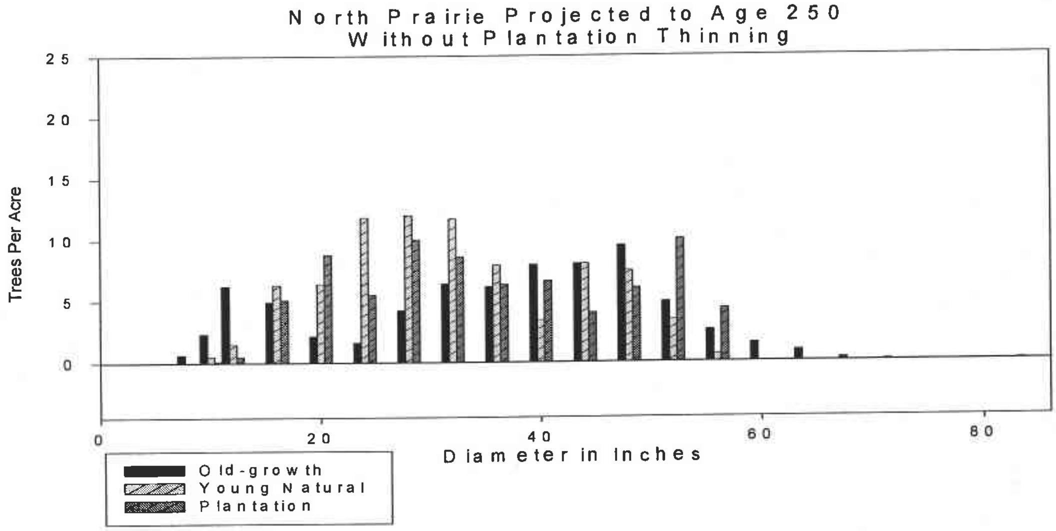
The higher similarities at North Prairie are possibly due to the higher quantities of Douglas-fir in the old-growth overstory, particularly in the larger diameter classes. In addition, the presence of shade tolerant species in the understory and overstory may have had an influence on the diameter distribution similarity between projected stands and the old-growth. Shade tolerant western hemlock was abundant in the North Prairie study area, occurred less frequently in the One-eyed Fish study area, and was nearly absent in the stands at the Five Rivers. Species like western hemlock may be important for providing the trees in the lower diameter classes of the diameter distribution.

Disturbance was likely important for the development of tree size distributions found in the old-growth stands. Density reducing disturbances that reduce overstory stand densities increase the availability of light and other resources for understory tree establishment and release of advance regeneration. Thus advance regeneration can develop into the lower size classes of the tree size distributions. These disturbances can also reduce competition between overstory trees thus furthering the development of the large end of the tree size distribution (See Figures 4.4a, 4.4b, and 4.4c).

In the young natural stands and unthinned plantations projected to age 250 and compared to nearby old-growth both the young natural stands and the plantations are generally lacking the development of both the small and large ends of tree size (diameter) distributions (See Figures 4.4a, 4.4b, and 4.4c). The frequency of disturbance may also be important to the development of distributions similar to the old-growth. In my projections to age 250, with thinning, the ingrowth and understory tree grew beyond the smaller diameter classes and into the middle of the diameter distributions. This suggests that additional disturbances need to occur often enough to maintain new recruitment of trees in the smaller diameter classes. My projections to age 250, with thinning, also resulted in overstory trees developing into much higher diameter classes than the unthinned plantation projections. These effects were most evident in the more intense thinning options such as the heavy thinning and the old-growth target thinning (See Figures 4.4a, 4.4b, and 4.4c).

Figure 4.4a. North Prairie diameter distribution by stand type projected to age 250. With (1) plantations unthinned and (2) plantations with site-specific target thinning and understory thinned. The largest plantation trees are 56 inches dbh in the unthinned plantation and 60 inches in the thinned plantation. Neither the unthinned nor the thinned plantations have many trees < 16 inches dbh. Thus thinning moved the overstory trees further into the upper diameter classes and understory trees into the middle diameter classes. Additional disturbances are necessary to recruit new trees into the lower diameter classes and to move overstory trees further into the large diameter classes to emulate the diameter distribution of the old-growth.

(1)



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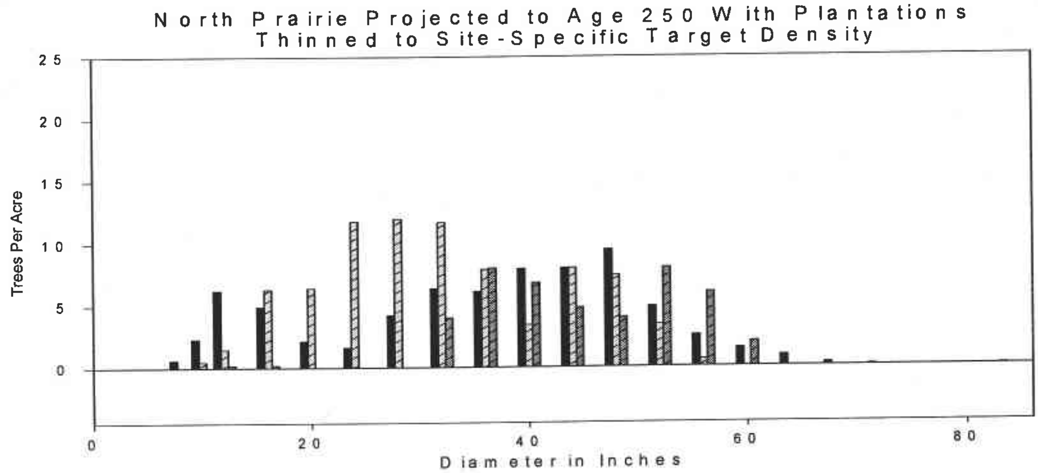
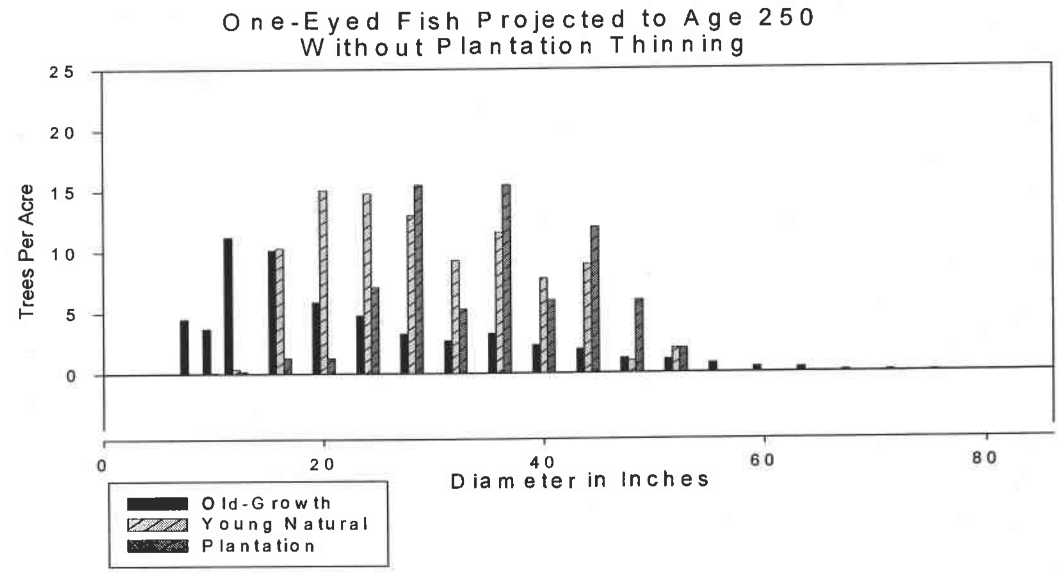


Figure 4.4b. One-Eyed Fish diameter distribution by stand type projected to age 250. With (1) plantations unthinned and (2) plantations with site-specific target thinning and understory thinned. The largest plantation trees are 56 inches dbh in the unthinned plantation and 64 inches in the thinned plantation. Neither the unthinned nor the thinned plantations have many trees < 20 inches dbh. Thus thinning moved the overstory trees further into the upper diameter classes and understory trees into the middle diameter classes. Additional disturbances are necessary to recruit new trees into the lower diameter classes and to move overstory trees further into the large diameter classes to emulate the diameter distribution of the old-growth.

(1)



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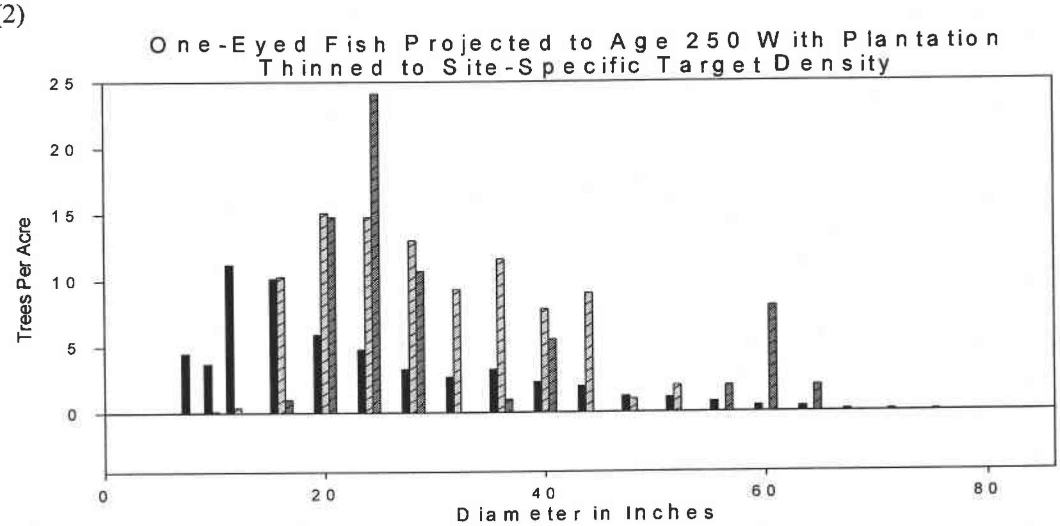
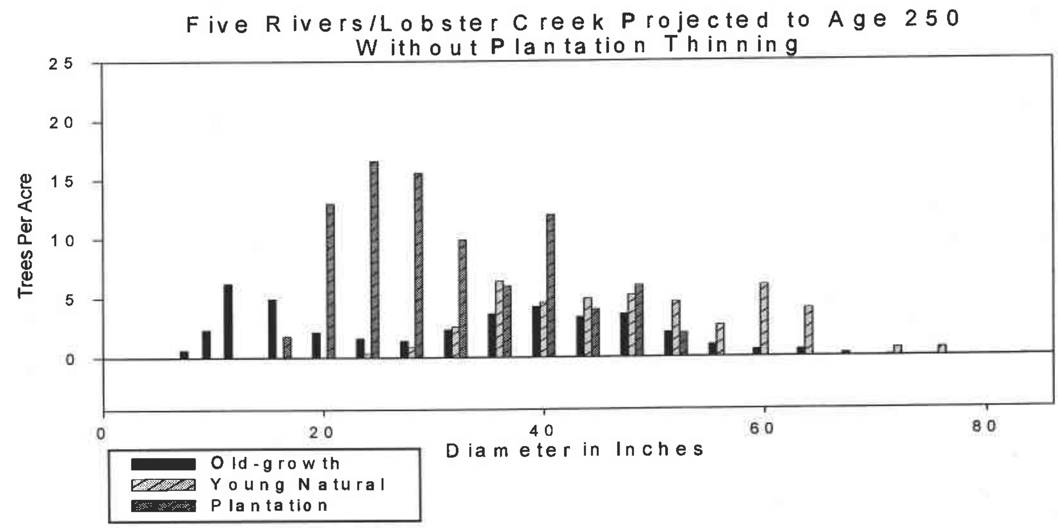


Figure 4.4c. Five Rivers diameter distribution by stand type projected to age 250. With (1) Plantations unthinned and (2) plantations with site-specific target thinning and understory thinned. The largest plantation trees are 56 inches dbh in the unthinned plantation and 64 inches in the thinned plantation. Neither the unthinned nor the thinned plantations have many trees < 20 inches dbh. Thus thinning moved the overstory trees further into the upper diameter classes and understory trees into the middle diameter classes. Additional disturbances are necessary to recruit new trees into the lower diameter classes and to move overstory trees further into the large diameter classes to emulate the diameter distribution of the old-growth.

(1)



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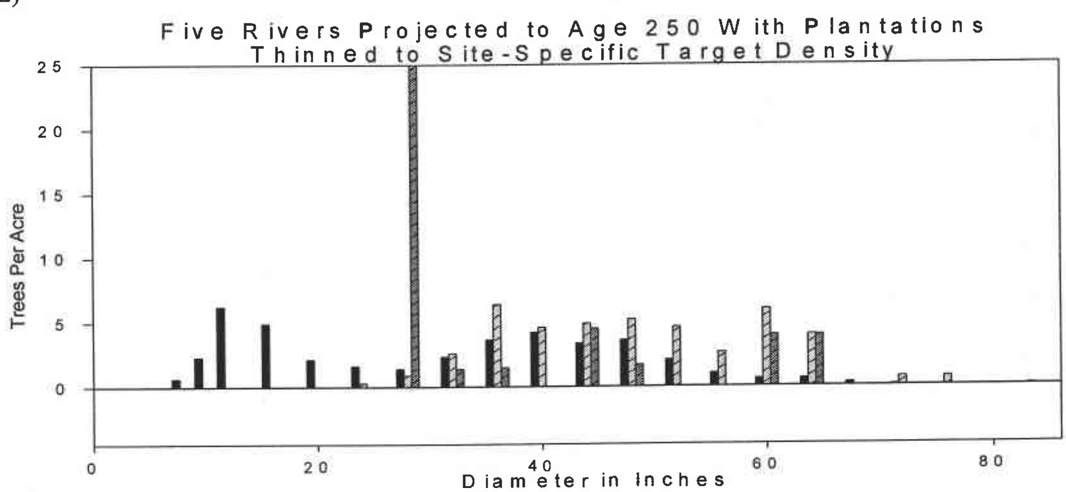


Height-to-Diameter Ratios

The current mean Douglas-fir height-to-diameter ratios (H:D) suggest that trees in the young natural stands (64 to 93) are more stable than in the plantations (81 to 98). H:D ratios ≥80 (Wonn and O'Hara 2001) indicate structural instability and H:D ratios >60 (Emmingham et al. 2000) or ≥70 (Cole and Newton 1987; Hughes et al. 1990) can indicate poor vigor/growth potential in young Douglas-fir trees. When projected to the age of the young natural stands, the plantations developed unstable mean Douglas-fir H:D ratios (82 to 99) but somewhat lower H:D ratios in the largest 24 trees per acre (60 tph) (65 to 74). Though lower, trees are still less stable and vigorous trees than the largest 24 tpa (60 tph) in the young natural stands (54 to 76) (See table 4.5).

The old-growth had mean height-to-diameter values from 46 to 50. These are nearly half as large as mean values for the plantations. Poage (2001) found similar low height-to-diameter ratios in 156 old-growth trees. They had H:D ratios as low as 28 up to 75. Projected to age 250 the young natural stands continued to have more structurally stable mean stand values (64 to 81) than the plantations projected to age 250 (83 to 91), however, both the young natural stands and the plantations continued to produce structurally stable height-to-diameter ratios in the dominant 24 trees per acre (60 tph) (54 to 57 and 58 to 71 respectively) (See table 4.5). The plantation height-to-diameter ratios projections are probably lower and thus indicate more stability than may actually develop, because the growth and yield model used was developed based on naturally regenerated stands that are able to differentiate at a faster rate than plantations (Wilson and Oliver 2000).

The long recruitment period to reach full stocking, indicated by the 21, 66, and 102 year age ranges in the young natural stands, allowed these stands to differentiate at a rate high enough to maintain very stable H:D ratios of the largest 60 trees per hectare. At age 250 the H:D ratios of the largest 24 tpa (60 tph) in the young natural stands ranged from 54 to 57, compared to the old-growth that ranged from 46 to 50 between the study sites. (See table 4.5) The largest 24 tpa (60 tph) in the plantation, without any additional thinning, at age 250 were higher and much more variable in results, but still had reasonably stable H:D ratios, from 58 to 71. Without pre-commercial thinning they may have been much more unstable and similar to the Hoskin's control, with a mean H:D ratio of 116 and an H:D ratio of 82 in the largest 24 tpa (60 tph) at only age 55. The failure to maintain stable trees in high-density stands may significantly decrease the likelihood of stands of developing into old-growth. Even after being fully released trees are not likely to improve their H:D ratio very quickly (Wilson and Oliver 2000). Thinning may only prevent the H:D ratios from deteriorating further. In very dense plantations pre-commercial or commercial thinning can be significantly important in dense uniform stands for the stability of the dominant and codominant trees to develop into the large tree component of old-growth, but they must be implemented in a timely manner.

In the projected thinning treatments, the intensity of the treatments influenced future H:D ratios. The thinning treatments facilitated the development of shade tolerant western hemlock advance regeneration and ingrowth to survive and grow into the canopy. The western hemlock ingrowth and understory trees, over this long simulation period, apparently competed with the overstory Douglas-fir thus decreasing the mean H:D ratios of the Douglas-fir largest 24 tpa (60 tph) in the heavy thinnings and the site-specific target thinnings. Simulations suggest that the understory trees may affect the H:D of the largest 24 tpa (60 tph). The western hemlock, included in the projection as ingrowth and understory trees with thinning produced H:D ratios of 55 to 65 in the heavy overstory thinning and 56 to 68 in the site-specific overstory thinning. Without thinning the understory the resulting H:D ratios of the Douglas-fir largest 24 tpa (60 tph) were somewhat higher at 57 to 68 in the heavy overstory thinning, and 57 to 77 in the site specific overstory thinning (See Table 4.5). It is important to understand that this hemlock ingrowth was added artificially, based on the amount and size of hemlock ingrowth that regenerated in thinned western Oregon Douglas-fir stands 20 to 30 years after thinning.

Table 4.5. Douglas-fir mean height-to-diameter ratios (H:D) and the height-to-diameter ratios of the largest 24 trees per acre (60 tph) by stand type and plantation thinning prescription currently, projected to the age of the young natural stands, and projected to age 250.

		Mean H:D of largest 24 tpa	Mean H:D	Mean H:D of Largest 24 tpa	Mean H:D	Mean H:D of Largest 24 tpa	Mean H:D
Study Area	Stand Type	At Current Age		At Age of YN		At Age 250	
North Prairie	Old-growth	*	47	*	*	*	*
	Young Natural	63	68	63	68	54	76
	Plantation (no thinning)	73	81	65	82	58	83
	Light Thin	73	81	*	*	57	76
	Variable Density Thin	73	81	*	*	62	92
	Heavy Thin With Understory Managed	73	81	*	*	55	104
	Heavy Thin Without Understory Managed	73	81	*	*	57	114
	Site Specific Target Thinning with Understory Managed	73	81	*	*	56	66
	Site Specific Target Thinning without Understory managed	73	81	*	*	57	72
One-eyed Fish	Old-growth	*	46	*	*	*	*
	Young Natural	76	93	76	93	57	81
	Plantation (no thinning)	74	98	74	99	71	85
	Light Thin	74	98	*	*	69	84
	Variable Density Thin	74	98	*	*	72	98
	Heavy Thin With Understory Managed	74	98	*	*	65	116
	Heavy Thin Without Understory Managed	74	98	*	*	65	116
	Site Specific Target Thinning with Understory Managed	74	98	*	*	68	92
	Site Specific Target Thinning without Understory managed	74	98	*	*	76	102
Five Rivers	Old-growth	*	50	*	*	*	*
	Young Natural	54	64	54	64	56	64
	Plantation (no thinning)	59	84	66	97	66	91
	Two-Story	*	*	*	*	*	*
	Light Thin	59	84	*	*	66	90
	Variable Density Thin	59	84	*	*	89	91
	Heavy Thin With Understory Managed	59	84	*	*	60	90
	Heavy Thin Without Understory Managed	59	84	*	*	68	107
	Site Specific Target Thinning with Understory Managed	59	84	*	*	56	73
	Site Specific Target Thinning without Understory managed	59	84	*	*	77	93
Hoskins	Hoskins Control plots	82	116	*	*	78	142

* No data available. Note: H:D ≥ 80 (Wonn and O'Hara 2001) indicates structural instability in inland Douglas-fir and H:D ≥ 70 (Cole and Newton 1987; Hughes et al. 1990) indicates poor vigor/growth potential in very young Douglas-fir.

Total Tree Heights

Forests regenerating over a long recruitment period initially create a wide range in tree heights. Not only are their heights different, but so are their rates of height growth. This differentiation in height growth could have lasting affects on tree growth for a long time (250+ years). The height advantage of the trees that regenerated 20 to 100+ years before the rest of the trees clearly must give these trees a growth advantage and affect the range of trees heights found in a stand, depending on the timing and distribution of the initial colonizing trees. For example, based on King (1966), a stand with a 60 year recruitment period and a site index of 100 ft (30 m) could contain 90 year old dominant and codominant trees with heights nearly 67 feet (20 m) greater than dominant and codominat trees growing in a younger 30 year-old cohort in the same stand.

Unfortunately, it is difficult to separate age range influences on the range of trees heights in this study from other influences, though they should exist. Generally, more variability in tree height is found in the young natural stand compared to the plantations, but this is not always the case (See the coefficients of variation in table 4.6). The overstory species diversity and composition can also influence the variability in stand tree heights. Generally, higher species diversity increases overstory variability in tree heights, but not always. The plantation stand at North Prairie had a slightly higher CV among the overstory heights of the Douglas-fir than the overstory heights of all the species. (See table 4.6).

Table 4.6. Current overstory tree height coefficients of variation in percent within each stand type.

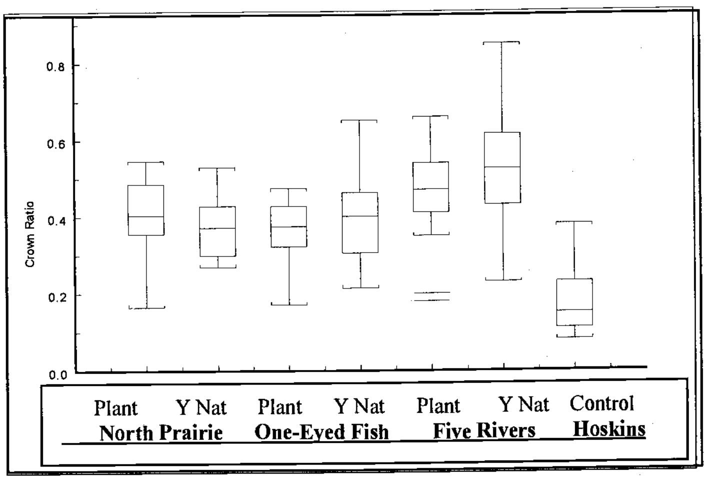
Site	Young Natural All Species	Young Natural DF Only	Plantation All Species	Plantation DF Only
North Prairie	20.90	14.43	17.06	18.50
One-Eyed Fish	36.25	15.28	24.32	8.73
Five Rivers	12.47	12.47	17.66	17.66

Note: The tree species composition at Five Rivers was nearly 100% Douglas-fir

Live Crown Ratios

The live crown ratios of the largest 24 Douglas-fir trees per acre (60 tph) between young natural stands and the plantations at their current age are similar. With pre-commercial thinning and regeneration practices the plantations have been able to maintain live crown ratios (0.30 to 0.38) comparable to those currently found in the young natural stands (0.26 to 0.37). The pre-commercial thinning may have only postponed crown recession, however, and additional thinning in the future may be necessary to maintain live crown ratios to sustain growth for large tree development. (See Figure 4.6 and Table 4.7) Maintaining crown ratios are important for maintaining growth for large tree development, maintenance of low H:D ratios, and for providing other values such as wildlife habitat structure. The mean live crown ratios in nearby old-growth stands range from 0.20 to 0.40 and Poage (2001) found mean crown ratios in 156 old-growth trees of 0.36.

Figure 4.5. Current live crown ratios of all trees by stand type and study site. The box represents the middle 50% of the distribution around the median and the whiskers represent the upper and lower 25% of the distribution.



Projections suggest that by the time the plantations are the age of the young natural stands, their crowns are receding; the decrease in mean tree live crown ratios in the plantations are (0.14 to 0.25) compared to the young natural stands (0.26 to 0.37).

The young natural stands and the site-specific old-growth target thinnings (with understory and ingrowth thinned) generally produced the highest live crown ratios. (See Table 4.7) In other words, these produced the stands with the greatest potential for sustained future growth and vigor. In general, the plantation thinning options in comparison to the unthinned plantations have increased both the mean live crown ratios to 0.17-0.23, 0.11-0.27, and 0.11-0.41

from 0.22, 0.11, and 0.11 and the live crown ratios of the dominant 24 Douglas-fir tpa (60 tph) to 0.19-0.27, 0.12-0.26, and 0.15-0.39 from 0.25, 0.12, and 0.15 by age 250 in North Prairie, One-Eyed Fish, and Five Rivers respectively (See Table 4.7).

The live crown ratios, like H:D ratios, appear to be influenced by understory trees over the long projection period. The largest 24 Douglas-fir tpa (60 tph) increased in the plantations that had their understories and ingrowth thinned to the western hemlock densities found in nearby old-growth stands. In general, the reduced competition over the projection possibly allowed the dominant Douglas-fir trees to maintain larger crowns to age 250. Understory thinning in the heavy thinning option increased crown ratios to 0.26, 0.17, and 0.29 from 0.22, 0.17, and 0.17 and in the site-specific thinning option it increased crown ratios to 0.22, 0.26, and 0.39 from 0.21, 0.17, and 0.17 in North Prairie, One-Eyed Fish, and Five Rivers respectively (See Table 4.7).

Table 4.7. Mean crown ratios and the crown ratios of the largest 24 Douglas-fir trees per acre (60 tph) by stand type and plantation thinning prescription currently, projected to the age of the young natural stands, and projected to age 250.

		Mean Crown Ratios Largest 24 tpa	Mean Crown Ratios	Mean Crown Ratios Largest 24 tpa	Mean Crown Ratios	Mean Crown Ratios Largest 24 tpa	Mean Crown Ratios
Study Area	Stand Type	At Current Age		At Age of YN		At Age 250	
North Prairie	Old-growth	*	0.25	*	*	*	*
	Young Natural	0.38	0.26	0.38	0.26	0.25	0.21
	Plantation (no additional thinning)	0.57	0.38	0.35	0.25	0.26	0.22
	Light Thin	0.57	0.38	*	*	0.27	0.22
	Variable Density Thin	0.57	0.38	*	*	0.19	0.17
	Heavy Thin With Understory Managed	0.57	0.38	*	*	0.26	0.23
	Heavy Thin Without Understory Managed	0.57	0.38	*	*	0.22	0.19
	Site Specific Target Thinning with Understory Managed	0.57	0.38	*	*	0.22	0.19
	Site Specific Target Thinning without Understory managed	0.57	0.38	*	*	0.21	0.17
One-eyed Fish	Old-growth	*	0.40	*	*	*	*
	Young Natural	0.49	0.32	0.49	0.32	0.26	0.21
	Plantation (no additional thinning)	0.44	0.30	0.28	0.17	0.12	0.11
	Light Thin	0.44	0.30	*	*	0.12	0.11
	Variable Density Thin	0.44	0.30	*	*	0.13	0.11
	Heavy Thin With Understory Managed	0.44	0.30	*	*	0.17	0.19
	Heavy Thin Without Understory Managed	0.44	0.30	*	*	0.17	0.19
	Site Specific Target Thinning with Understory Managed	0.44	0.30	*	*	0.26	0.27
	Site Specific Target Thinning without Understory managed	0.44	0.30	*	*	0.17	0.18
Five Rivers	Old-growth	*	0.32	*	*	*	*
	Young Natural	0.50	0.37	0.50	0.37	0.40	0.32
	Plantation (no additional thinning)	0.53	0.38	0.23	0.14	0.15	0.11
	Light Thin	0.53	0.38	*	*	0.16	0.11
	Variable Density Thin	0.53	0.38	*	*	0.15	0.14
	Heavy Thin With Understory Managed	0.53	0.38	*	*	0.29	0.29
	Heavy Thin Without Understory Managed	0.53	0.38	*	*	0.17	0.19
	Site Specific Target Thinning with Understory Managed	0.53	0.38	*	*	0.39	0.41
	Site Specific Target Thinning without Understory managed	0.53	0.38	*	*	0.17	0.20
Hoskins	Hoskins Control plots	0.34	0.17	*	*	0.11	0.12

* No data available

The development of high crown ratios, particularly in the larger trees (the largest 24 tpa (60 tph) of the diameter distribution in table 4.7), may be important for long term sustained tree growth for the development of large Douglas-fir trees characteristic of old-growth forests. The large crown ratios allow dominant and codominant trees to sustain higher growth rates and give these trees a competitive advantage over their smaller neighbors. The large age ranges created by low initial stand densities in old-growth trees allowed the initial regeneration (after a stand replacing disturbance or cessation of native American burning) to acquire a height advantage, allowing the trees to maintain large crowns for sustained growth late in age.

Crown length in relation to total tree height (live crown ratio) is also often used as an indicator of tree vigor (Ritchie 1999). Trees with longer crowns tend to respond more readily to thinning with higher growth rates than trees with short crowns, and they generally are more predictable in response (Ritchie 1999). Shade intolerant Douglas-fir crown ratios are strongly influenced by current densities. The pre-commercial thinning in the young plantations has maintained the crown ratios. I predict, and the model indicates, that as these plantations continue to fill the available growing space, begin stem exclusion, and decrease in crown size and diameter growth. In contrast, the larger trees in the young natural stands that had established at low densities were able to maintain reasonable crown ratios and grow at rates similar to those of nearby old-growth. If the plantations had not been thinned and were high-density stands, they may have developed smaller crowns and lower growth at rates similar to the unthinned Douglas-fir control plots at the Hoskin's Level of Growing Stock study (LOGS) (See Figure 4.3 and the bottom of Table 4.7). Hoskins, at age 55, currently has mean crown ratios of 0.17 and crown ratios of the largest 24 tpa (60 tph) of 0.34. Hoskins is projected the mean crown ratios at age 100 near 0.18 and at age 250 near 0.12, and mean crown ratios of the largest 24 tpa (60 tph) of 0.11 at age 250.

Historic and Current Forest Cover

The forest landscape in western Oregon has undergone significant changes in distributions of stand types since European settlement and harvesting began almost two centuries ago. The changes in types of forest cover within each of the study sites illustrate this and identify possible targets for management. (See Table 4.8) Although in some circumstances, such as wildlife habitat requirements, management goals may require exceeding historical quantities or historical stand attributes of a particular stand type, the identification of historical reference conditions can serve as starting points and provide valuable information regarding the feasibility of managing toward pre-harvest forest conditions. Not all the study sites have all the stand types that may need to be managed for, and not all the stands in the earliest photos available will be in pre-harvest condition (as in North Prairie and One-Eyed

Fish). The Fiver Rivers site in the 1860's burned as part of the Yaquina fire with few patches of old-growth surviving and visible in the historical photos. Harvesting since the photos were taken has also resulted in no local patches of old-growth to use as management targets and for understanding local old forest development. Target structures and landscapes may need to be based on other nearby old-growth forests, such as Lobster Creek, or on other objectives, such as wildlife species-specific target habitat.

The forest landscape in the three study sites has changed considerably since harvesting and timber management began in these areas (See Table 4.8). Plantations (or stands regenerating after harvest) were relatively rare compared to the amount of old-growth present. Plantations and old-growth have since shifted places from primarily old-growth to primarily plantations. The percentage of the study sites composed of young natural stands has remained relatively the same, though they have decreased in land area. Open areas such as grassy balds, brush fields, or bracken prairies have also declined possibly due to aggressive afforestation and natural conifer colonization. This information regarding changes in stand types from historic may also be valuable for managing areas to provide other forest and non-forest habitats and structures historically present on the landscape besides old-growth forests.

Table 4.8. Current and historical forest cover by stand type in each of the study sites. Not only old-growth has decreased but also two-story and open/prairie.

Study Area	Stand Type	Current			Historical		
		Acres	Hectares	% of Project Area	Acres	Hectares	% of Project Area
North Prairie	Old-growth	112.6	45.6	10.5%	675.3	273.4	62.7%
	Young Natural	191.9	77.7	17.8%	259.5	105.0	24.1%
	Plantation	676.8	274.0	62.8%	31.4	12.7	2.9%
	Open / Prairie	96.1	38.9	8.9%	111.2	45.1	10.3%
One-eyed Fish	Old-growth	155.4	62.9	24.8%	468.4	189.6	69.0%
	Young Natural	93.9	38.0	15.0%	62.5	25.3	9.2%
	Plantation	378.2	153.1	60.3%	148.2	60.0	21.8%
	Open / Prairie	0.0	0.0	0.0%	0.0	0.0	0.0%
Five Rivers	Old-growth	0.0	0.0	0.0%	38.3	15.5	4.1%
	Young Natural	471.0	190.7	51.0%	802.1	324.7	86.9%
	Plantation	417.7	169.1	45.2%	0.0	0.0	0.0%
	Two-Story	19.8	8.0	2.1%	63.8	25.8	6.9%
	Open / Prairie	14.8	6.0	1.6%	19.1	7.7	2.1%

CHAPTER FIVE: GENERAL SUMMARY AND CONCLUSION

Study Site Differences

Some significant dissimilarities existed both among study sites, between stand types, and among stand types.

On the local scale, the stands at Five Rivers contained visibly much greater quantities of understory vegetation, especially salal and vine maple, but shade tolerant western hemlock was nearly absent compared to the other two study sites. Stands at both Five Rivers and North Prairie were located in a moister, milder climate in the Oregon Coast Range as opposed to the stands at One-Eyed Fish, which is in the lower elevations of the central Oregon Cascades. The One-Eyed Fish stands were also located in a landscape with steeper topography and scattered rock outcrops compared to the other two study sites.

There were several differences among stand types and locations. The young natural and the old-growth stands contained more understory vegetation than the plantations (although this may partially be a result of age). The overstory tree species diversity was the highest in the old-growth stands among the three stand types at all three locations. The old-growth stands at North Prairie contained nearly twice as many overstory Douglas-fir trees per acre compared to the other two old-growth sites. The plantations at North Prairie contained significant amounts western hemlock advance regeneration in contrast to the other two plantations. Although there were these dissimilarities, important generalizations among sites can still be made.

Overstory Trees

In all three study sites wide age ranges of trees within each of the natural stands appear to have had lasting effects on the development and composition. Disparate tree ages have resulted in large live crowns and significant height advantages of some dominant and codominant trees. These trees have sustained rapid diameter growth rates and stable height-to-diameter ratios to survive and develop into the large tree component of old-growth. The large trees in the young natural stands generally have larger mean diameters, greater live crown ratios, and lower H:D ratios than would the large trees in plantations projected to the same ages. In addition, young natural stands regenerated after natural disturbance are growing at rates similar to nearby old-growth stands in their first 100 years, indicating similarities in initial stand densities and growing conditions. Density reducing disturbances appear to have occurred in old-growth stands over time (indicated by their age structure and sustained growth) influencing their structure and development. Additional density-reducing disturbances are likely necessary for these young natural stands to increase variability in tree size, widen age ranges, develop old forest crown characteristics, such as large epicormic branches, and further sustain growth similar to nearby old-growth forests. In contrast to the young natural and old-growth stands, the plantations appear to be growing and developing differently in their first 100 years. The plantations had produced higher early growth rates enabling earlier development of large diameters, but according to stand simulations they will not sustain high growth rates, eventually dropping below the rates found in the old-growth and young natural stands (See Figures 4.2 and 4.3 and Table 4.3). These plantations' growth may not have risen so high early on, and likely would have dropped sooner, if the plantations had not been pre-commercially thinned at 10 to 20 years of age. This is indicated when comparing the growth rates to the Hoskins control plots (See Figure 4.3). In addition, the plantations would probably have greater H:D ratios indicating instability and smaller crown sizes if not pre-commercially thinned (See Table 4.5).

Simulations of plantations suggest that when the plantations are left unthinned they generally would develop less structurally stable codominant and intermediate trees with lower mean diameters, but produce reasonably stable dominant overstory trees compared to young natural and old-growth stands. Projected plantation thinning options indicate that overstory thinning, particularly the more intensive thinning of overstory trees by diameter from below, can improve overstory tree size, including the dominant overstory tree size and improve individual tree stability.

Old-growth trees in the three study areas sustained rapid early growth rates similar to those measured in the young natural stands. Old-growth trees probably had delayed initial establishment like the young natural stands, but the ages found in the old-growth also indicate that conditions for additional cohorts to establish and develop must have been created repeatedly through some forms of disturbance such as wind, fire, pathogens, insects, and/or weather that could have reduced stand densities to allow additional tree establishment. Morris (1934) described a relatively high occurrence of landscape-altering fires, most less than 2,000 acres in size, in western Oregon in the mid-1800's and early 1900's. He described the resulting forest structure in that period as "a maze of young age classes which have been established after fires, and the effect of countless repeated burns makes it impossible to determine the extent of early fires." A study by Sensenig (2002) identified the repeated occurrence of low intensity fires in southwestern Oregon. Disturbances such as repeated fires of low and moderate intensity were likely essential to the development of the wide age ranges observable in many old-growth forests.

Understory Trees

Bailey and Tappeiner (1998) found significant quantities of understory trees present 10 to 24 years after commercial thinning in young stands. These quantities of understory trees were similar to the quantities found in old-growth stands that likely regenerated there following natural disturbances. My projections indicate that shade tolerant western hemlock understory trees and ingrowth can have an influence on the rate of growth and the structure of the overstory trees over extended periods of time (200+ years). These understory trees were influential only in the projected thinning regimes of low or significantly reduced overstory density. Simulations indicate that managing the density of these understory trees through thinning would increase the diameter growth in the overstory, including the dominant overstory trees, and generally decrease H:D ratios and increase overstory live crown ratios. Other than affecting the growth of the large Douglas-fir trees, other species such as western hemlock are an important component of old-growth forests. Though they have been found to generally make up only about 25% of an old-growth stand's basal area, these trees on average were found by Poage (2001) to account for most of the structural variation among old-growth forests.

Modeling suggests in two of the three plantations in this study, that if no thinning or only a single thinning entry is implemented, the development of tree size distributions like these found in nearby old-growth may take over 250 years in the absence of disturbance. The presence of shade tolerant species can accelerate or slow the development the tree size distributions found in nearby old-growth depending on their quantity, distribution, and timing of regeneration.

Density Reduction of Plantations

The plantations are growing and developing differently than the young stands observed by Tappeiner et al. (1997) and Poage and Tappeiner (2002), who found that trees in young stands were growing at rates slower than those of old-growth trees in their first 50 years. The young stands in these two studies are much different from the plantations I studied: a) they are young stands naturally regenerated after logging rather than planting; b) they were not pre-commercially thinned; and c) they were higher in initial density. Their young stands were also dissimilar to the young natural stands I used because the young natural stands were never harvested and regenerated after fire. Tappeiner et al. (1997) and Poage and Tappeiner (2002) also concluded that harvested young stands are on a different developmental trajectory than old-growth. My findings suggest that plantations are neither developing similar to old-growth nor developing similar to dense unmanaged young stands naturally regenerating after timber harvest. My findings support the hypothesis of Tappeiner et al. (1997), Poage (2001), and Sensenig (2002) that stands established after timber harvest are developing at much higher initial densities than the old-growth that preceded them. In addition, my evidence supports the conclusion by Tappeiner et al. (1997) that thinning is necessary in many plantations in order to change their developmental trajectory, otherwise the plantations would require a much longer time to develop typical old-growth structural characteristics. Also, it may be that without some sort of structural influencing disturbance, many densely stocked plantations may never achieve old-growth.

Thinning Prescriptions

Pre-commercial thinning in the plantations at all three study sites appear to have allowed for early rapid diameter growth and maintenance of large crowns and low H:D ratios by postponing crown closure. Unfortunately, these growth trends are not projected to continue, thus further thinning may be necessary.

The thinning options modeled in this study have generally enhanced many of the tree characteristics found in old-growth forests. They accelerated the development of large trees, maintained or increased crown size, and decreased H:D ratios thus maintaining tree stability. The more intensive thinnings, in addition, have increased survival and accelerated the growth of understory trees and advance regeneration. Some thinning strategies were more effective in some study sites than others, depending on the characteristics of the target structure (old-growth) and the existing characteristics of the plantation stands. For example, the plantation thinning strategies at North Prairie resulted in stands of high similarity to old-growth stands because both stand types were primarily composed of Douglas-fir, thus producing much more similar tree size (diameter) distributions. The two most successful thinning options in all three study sites were the heavy thinning and the site-specific old-growth target thinning options.

Old-growth forests with a greater composition of shade tolerant species, such as western hemlock, had greater variability in tree size; therefore, plantations being managed toward these structures will likely require multiple density-reducing disturbances to develop similar ranges in tree size and to allow shade tolerant species to establish and grow.

The young natural stands appear to be developing similarly to nearby old-growth, but disturbance may be necessary for them to continue along the same trajectory. Similar to plantations, thinning may also be used in these stands to assist or accelerate development toward site-specific old-growth structure; however, the age structure of these stands has provided much more flexibility, giving these stands a much greater window of opportunity for a density-reducing disturbance to occur and promote old-growth development.

Though difficult to model effectively, variable density retention thinning may hold promise as a possible single entry correction or reduce the need for multiple thinning entries to adjust the development trajectory of plantation stands; however, the results indicate that multiple entries may be necessary to provide other old forest structural characteristics besides large Douglas-fir trees.

Also, variable density does not appear to produce some of the old-growth characteristics as quickly as the other thinning treatments such as large diameter trees.

Achieving historical old-growth structure requires more than reducing densities in plantations to a site-specific historical level, it requires directly managing for structural heterogeneity in tree size. This can be managed for by thinning to create new opportunities for tree regeneration to establish, to release advance regeneration, to increase tree growth, or by thinning to create a range of tree densities (variable density thinning) where trees will grow at various rates.

Use of Site-Specific Prescriptions

Using nearby old-growth as site-specific structural management targets for plantations may be more realistic and accurate than using a general regional definition of old-growth structure. This study demonstrated the use of retrospective methods such as cruise records, historical aerial photographs and other available data supplemented with onsite sampling to describe the desired structures and site-specific historical reference conditions. This study also described the use of growth and yield modeling to project management options and identified some basic tools for comparing the structures produced in each option. These tools are important because without understanding unique site-specific stand structure, composition, and regeneration patterns of old-growth forests, it may be difficult to develop silvicultural practices that meet biodiversity and old forest habitat goals.

Summary of Principal Results

1. Disturbance as Part of Old-growth Development

a) Not all thinning will always enhance tree size distributions in similarity to those found in local old-growth forests, but thinning generally does enhance some old-growth tree and stand characteristics, i.e. large live crowns, large diameters, low H:D ratios, and development of understory trees.

b) Wide age ranges may be needed for the development of tree size distributions or heterogeneity found in old-growth. But this may not be essential for the development of the large Douglas-fir tree component of old-growth. Multiple thinning entries can be used and may be necessary for age/size range development.

c) Young natural stands, developed after fires with low initial stand densities as indicated by wide age ranges, are developing at the same growth rates as nearby old-growth, but will not result in the same final structure and composition without future disturbance (natural or human caused).

d) Early thinning, such as pre-commercial thinning, may be more influential to stand development than later thinnings, particularly in high-density plantations.

e) Dominant trees in plantations that have been pre-commercially thinned are growing at faster rates than nearby old-growth in the first 20 to 30 years, but are projected to drop in growth rates below those found in old-growth when it was at the same age. It is uncertain whether the plantations will maintain rates of growth. The slower rate of differentiation created by plantation uniformity will likely cause plantation growth rates to drop further in the future rather than maintain the rates found in young natural and old-growth stands.

f) The growth rates in the thinned plantations of this study may possibly allow for the development of the large tree component in old-growth, but additional thinning or density-reducing disturbance may be necessary for the development of tree size ranges similar to nearby old-growth.

2. Importance of the Understory (as Suggested by Modeling)

a) When managing for structural characteristics in stands at low densities over long time periods, the advance regeneration and ingrowth of shade tolerant trees, such as western hemlock, in the understory can have an affect on the diameters, H:D ratios, and live crown ratios of the overstory.

b) Advance regeneration and ingrowth can play a significant role in mid-story and understory structural development, especially when composed of shade tolerant tree species, such as western hemlock, in stands thinned to a low overstory density. (This is based only of the modeling and additional research for verification is needed)

c) Greater impact on understory tree structure and development may be made through subsequent thinning entries or natural disturbances.

d) Managing only stand density and species composition may not improve the similarity in tree size distributions to nearby old-growth forests. Managing for ranges in tree sizes through repeated thinnings to create opportunities for conifer regeneration and advance regeneration release may be necessary.

3. The heavy thinning treatment and the site-specific old-growth target thinning treatment in plantations were projected to make the greatest improvements in the rates of development of old-growth characteristics and similarity to nearby old-growth stands.

4. Retrospective methods are useful for determining and describing nearby old-growth as a site-specific management target. These structural management targets or goals can provide useful information regarding differences among sites that can be accounted for by adjusting thinning prescriptions. Using these site-specific targets should produce forests that develop structures and characteristics more similar to local old-growth forests than using general regional definitions of old-growth as management targets.

5. Forest modeling can be useful for evaluating and comparing possible thinning prescriptions to get the desired target stand structures and characteristics. Care must be taken to consider all the assumptions and limitations of using growth and yield models.

Conclusion

The findings of this study provides useful forest development information and a methodology for forests in Late-successional Reserves and other areas where forests with old-growth characteristics are major objectives. I provide information on old-growth, young natural stand, and plantation development that can be used to determine if young stands will attain old-growth characteristics and if management is necessary. The results support the hypothesis that old-growth developed at low initial stand densities, likely related to prolonged stand establishment. This establishment pattern appears to have provided tree height and crown size advantages among trees that facilitated growth of dominant and large co-dominate trees long into the life of the stands. The results stress the importance of density-reducing disturbances that may often be necessary for the development of many characteristics. This includes forest stands over 80 years of age in Late-successional Reserves. These characteristics include a wide range of tree sizes, well-developed understories, and large old trees with long live crowns, large epicormic and meristematic branches, and low height-to-diameter ratios. Many dense plantations and managed stands may never achieve old forest characteristics similar to nearby old-growth forests without disturbance. Disturbance includes fire, wind, ice storms, and other natural disturbances as well as thinning. Many thinning approaches can be applied to attempt to achieve desired historical old forest conditions but it is likely that no single prescription is appropriate for all plantations and site-specific details regarding historical structures may be crucial for success.

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APPENDIX

APPENDIX: Current Stand Tree Size and Structural Characteristics.

Site	Overstory TPA	Diameter Range in Inches	Mean Diameter (SE%)	% Coefficient of Variation of Diameter	Breast Height Age Range in Years	Height Range in Feet	Mean Height (SE%)	BA in sqft per acre (SE%)	RD	Mean Height to Diameter Ratio (SE%)	Mean HLC (SE%)	Mean Live Crown Ratio (SE%)	Site Index 50 years
NP OG Douglas-fir	23.3-60.7 (>8")	8-84"	35.5 (3.35)	67.46	101-434	178-246	215.5 (7.36)	473.8 (6.08)	0.71	47.0 (1.84)	116.7 (5.80)	0.25 (0.03)	*
NP OG All Species	45.5-88.6 (>8")	8-84"	30.8 (2.56)	73.05	46-434	NA	NA	567.9 (6.68)	0.91	NA	NA	NA	*
NP YN Douglas-fir	76-140 (>8")	8-40"	20.5 (.62)	34.70	70-125	94-166	135.0 (3.50)	269.3 (7.81)	*	68.0 (2.99)	86.5 (2.86)	0.38 (0.02)	100.6
NP YN All Species	120-160 (>8")	8-40"	19.5 (0.59)	35.63	NA	70-166	125.0 (4.69)	315.2 (4.33)	1.04	81.0 (3.84)	NA	NA	100.6
NP YN THIN Douglas-fir	56-100 (>8")	10-39"	27.1 (0.91)	25.45	70-125	102-189	171.2 (3.66)	330.4 (40.17)	*	75.0 (3.29)	113.3 (3.66)	0.34 (0.02)	117.0
NP YN THIN All Species	184-252 (>8")	8-39"	19.7 (0.69)	41.86	NA	NA	NA	366.4 (30.20)	1.23	NA	NA	NA	117.0
NP PLNT Douglas-fir	120-250 (>5")	5-26"	14.6 (0.29)	26.69	29-44	43-110	92.4 (1.60)	244.9 (35.89)	*	80.8 (5.40)	54.3 (2.21)	0.40 (0.03)	117.3
NP PLNT All Species	230-380 (>5")	5-26"	13.3 (0.30)	30.69	NA	43-110	92.4 (4.42)	308.6 (6.71)	1.08	NA	NA	NA	117.3
OF OG Douglas-fir	7.3-20.4 (>8")	8-76"	46.8 (1.34)	28.55	175-475	105-265	183.8 (5.63)	125.2 (1.31)	0.20	45.5 (1.64)	70.8 (4.94)	0.40 (0.02)	*
OF OG All Species	41.5-87.4 (>8")	8-76"	38.3 (1.52)	46.82	NA	NA	NA	221.1 (1.55)	0.43	NA	NA	NA	*
OF YN Douglas-fir	152-776 (>8")	8-23"	12.5 (0.26)	29.26	61-82	69-135	104.5 (3.74)	257.0 (41.49)	*	89.9 (7.50)	62.0 (2.80)	0.40 (0.11)	100.0
OF YN All Species	320-888 (>8")	8-23"	12.3 (0.22)	28.95	NA	64-135	95.1 (4.92)	307.2 (42.84)	0.99	90.1 (2.88)	56.8 (3.08)	0.42 (0.02)	100.0
OF PLNT Douglas-fir	190-260 (>5")	5-21"	13.3 (0.16)	27.90	36-43	88-127	111.7 (1.82)	221.2 (7.86)	*	97.8 (6.98)	59.3 (2.89)	0.41 (0.02)	134.2
OF PLNT All Species	190-260 (>5")	5-21"	13.0 (0.34)	29.13	NA	88-127	100.6 (4.08)	236.5 (7.47)	0.76	NA	NA	NA	134.2
LC OG Douglas-fir	14.1-18.5 (>8")	8-94"	45.6 (2.21)	31.36	180-534	215-266	246.2 (4.72)	182.7 (2.20)	0.27	50.2 (2.03)	114.8 (4.31)	0.32 (0.02)	*
LC OG All Species	39.7-42.8 (>8")	8-94"	32.3 (2.78)	55.82	NA	NA	NA	268.3 (2.78)	0.46	NA	NA	NA	*
FR YN Douglas-fir	48-108 (>8")	12-64"	34.9 (1.05)	24.71	47-149	130-238	204.4 (5.20)	473.0 (24.09)	1.00	64.4 (1.82)	95.2 (5.57)	0.52 (0.03)	121.0
FR YN All Species	48-108 (>8")	12-64"	34.9 (1.05)	24.71	47-149	130-238	204.4 (5.20)	473.0 (24.09)	1.00	64.4 (1.82)	95.2 (5.57)	0.52 (0.03)	121.0
FR TS Douglas-fir	172-208 (>8")	8-41"	15.9 (0.47)	35.42	45-80	39-160	124.9 (5.00)	290.3 (16.47)	0.83	77.5 (3.57)	74.7 (3.55)	0.39 (0.02)	122.0
FR TS All Species	172-208 (>8")	8-41"	15.9 (0.47)	35.42	45-80	39-160	124.9 (5.00)	290.3 (16.47)	0.83	77.5 (3.57)	74.7 (3.55)	0.39 (0.02)	122.0
FR PLNT Douglas-fir	100-260 (>5")	5-23"	12.9 (0.42)	32.86	29-41	65-108	93.2 (3.00)	203.2 (9.24)	0.63	84.3 (6.28)	51.2 (2.45)	0.45 (0.02)	123.0
FR PLNT All Species	100-260 (>5")	5-23"	12.9 (0.42)	32.86	29-41	65-108	93.2 (3.00)	203.2 (9.24)	0.63	84.3 (6.28)	51.2 (2.45)	0.45 (0.02)	123.0

(Note: the SE% given above are the standard errors of the mean in percent.)
(Note: the Five Rivers YN, TS, and PLNT were Douglas-fir only stands, no western hemlock was present)