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AN ABSTRACT OF THE THESIS OF

Coulter R. Rose for the degree of Master of Science in General Science presented on November 18, 1993.

Title: Relationships of Green-Tree Retention Following Timber Harvest to Forest Growth and Species Composition in the Western Cascade Mountains

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National Forest management in the Pacific Northwest is shifting from a focus on commodity production to ecosystem management, in which the health of the entire forest ecosystem is considered, rather than that of a few key species. Ecosystem management includes retention of some live trees following timber harvest (green-tree retention) to preserve biodiversity, imitating the natural fire regime of large, but patchy fires that leave many live trees. How ecosystem management will affect growth and species composition of future forests is an important question. This study takes a retrospective approach to this question by using past disturbance as an analogue to green-tree retention following timber harvest. Using USDA Forest Service timber inventory plot data from the Cascade Mountains of Oregon and SW Washington, 132 unmanaged stands were identified with a tree cohort of 70-110 years old (regeneration) or a tree cohort of 70-110 years old with an overstory of large trees 200+ years old (remnants). All stands were in the *Tsuga heterophylla* (Raf.) Sarg. zone (Franklin and Dyrness 1973). Single-aged stands represented clearcuts, while two-aged stands served as analogues to stands harvested with green-tree retention. Regeneration basal area/hectare (ba/ha) declined when remnant-tree densities exceeded about 15 remnant trees/ha ($R^2=0.51$) in a relationship roughly described by a sigmoidal curve. Conceptually removing remnant-tree space occupancy effects decreased remnant-tree density's value as a predictor of regeneration ba/ha by about 50% at management-level remnant densities

($\leq$45 remnant trees/ha). Thus, it appears that remnant "effects" were a result of both remnant-tree space occupancy and remnant resource use. Douglas-fir ba/ha in the regeneration also declined when remnant-tree densities exceeded about 15 remnant trees/ha (R^2=0.60). Western hemlock ba/ha in the regeneration increased slightly with increasing remnant-tree densities (R^2=0.19). Western redcedar ba/ha in the regeneration was apparently not related to remnant-tree density (R^2=0.02). The degree of aggregation in remnant trees did not appear to affect regeneration ba/ha, but few stands contained the isolated clumps of remnant trees likely under a management scenario. Neither measured site characteristics nor regeneration density was related to regeneration ba/ha across species. Remnant-tree density was apparently unrelated to tree-species diversity in the regeneration. Total-stand ba/ha remained relatively constant across remnant densities.

Relationships of Green-Tree Retention Following Timber Harvest to Forest Growth and Species Composition in the Western Cascade Mountains

by

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INTRODUCTION

Background

Pacific Northwest forests have some of the highest biomass accumulations of any forests in the world and are among the most productive temperate forests (Franklin and Waring 1979). Management of these magnificent forests is in a state of transition. Competition between commodity and non-consumptive uses of National Forests has illuminated the need to change forest management practices. Single resource management is slowly yielding to an ecosystem approach to forest management in which the health of the entire ecosystem is considered, rather than that of a few key species (Swanson and Franklin 1992). In this so-called "New Forestry" (Franklin 1989) or ecosystem management, forests are managed toward a desired future "natural" condition (Kessler et al. 1992), which has required that we understand and accept natural disturbance regimes. Forest management schemes that mimic natural disturbance regimes leave standing dead and green trees, as well as fine and coarse woody debris on site. Thus, in ecosystem management, what is left on a site may be as important as what is removed.

Managing forests toward a natural condition requires a value judgement that a natural condition is better than an alternative condition that can be achieved through silviculture. Because past management practices have diminished qualities such as biodiversity and aesthetics, as well as more tangible attributes such as water quality, salmonid stocks, and wood for sawmills, altered management strategies are being implemented. Ecosystem management involves recognizing that if we are to continue to reap the diverse benefits of forests, we must allow natural processes to occur or mimic natural processes through management.

In the Pacific Northwest, clearcutting has been traditionally justified by asserting that it mimics the stand-replacing fires typical of the region (Franklin and DeBell 1973). However, recent studies have shown that before about 1910 (when fire suppression began in earnest), fire regimes in the Pacific Northwest were variable, ranging from long-rotation, stand-replacing fires in the Olympic Mountains, to high-frequency, variable-intensity fires in southwest Oregon (Agee 1990). Historically, an average of about 30000 ha burned each year in the Douglas-fir region of Oregon and Washington (Agee 1990). However, even where stand-replacing fires are considered the norm, pockets of live trees are often left on a site following a fire. Other disturbances such as disease, insects, and wind storms are also important in the Pacific Northwest, but fire is probably the most frequent and widespread stand-level disturbance.

Fires in the central Oregon Cascades created numerous irregular patches of forest with different levels of tree mortality (Morrison and Swanson 1990). The presence of many two-storied stands with fire scars throughout the western Oregon Cascades attests that many trees survived even large forest fires. This natural regime of patchy fires that leave scattered live trees as individuals and in clumps is the basis for logging with green-tree retention on Federal lands as mandated in the Forest Ecosystem Management Assessment Team's (FEMAT) Preferred Alternative Plan (Option 9, President's Forest Plan) (1993a). Green-tree retention (leaving live large trees following timber harvest) is part of ecosystem management; green-tree retention alone does not necessarily include retention of snags and downed woody debris.

Some aspects of ecosystem management are hardly new. As Smith (1971, as quoted in Franklin and DeBell 1973) noted back in 1970:

> "If silviculture were a perfect imitation of natural processes leading to the ecological optimum for each species and site, a number of variants of the shelterwood method rather than clearcutting would be the most common kind of silvicultural management of the [Douglas-fir] region."

This statement recognizes the fact that Douglas-fir often regenerates naturally under the partial shade of trees left after a disturbance. Foresters and ecologists in the Pacific Northwest had long assumed that the dominant trees in Douglas-fir (Pseudotsuga menziesii (Mirbel) Franco.) old-growth forests were even-aged (Franklin and Waring 1979). Douglas-firs in these stands were assumed to have established in a short time following fire, hence part of the analogy to regeneration following clearcutting and broadcast burning. However, an age structure analysis conducted in the H.J. Andrews Experimental Forest in the central Oregon Cascades found that the ages of dominant old-growth Douglas-firs ranged from 275-540 years (Franklin and Waring 1979). Further, these old trees grew over a cohort of Douglas-fir about 100 years of age, indicating that the stand was probably disturbed about 100 years ago, allowing some shade-intolerant Douglas-fir to establish. The age structures observed in many stands in the Cascades fit Harper's (1978) hypothesized development sequence for western hemlock (Tsuga heterophylla (Raf.) Sarg.)/ Douglas-fir forests (Franklin and Waring 1979). Multiple disturbances after the first, stand-initiating disturbance destroy portions of a young stand, allowing survival of individual trees and small patches of trees while opening spaces for the establishment of even younger cohorts.

While these multiple-canopied forests are common in the Northwest, they are difficult to categorize. Above I refer to old trees left after a disturbance as "old-growth trees," but a young stand with a scattering of old trees is not an old-growth stand. Mixed-aged stands containing some old trees are not old growth in the classical sense, and these mixed-aged stands have led to much of the debate over how much old growth is left in the Pacific Northwest (FEMAT 1993a). Thus, I will avoid using the term "old growth" to describe old trees that are left standing after a disturbance over a clearly-defined younger cohort. Because these old trees are remnants of a previous stand, I will refer to these trees as "remnants" throughout this paper.

The Role of Remnant Trees in Stand Development

Remnant trees that survive a disturbance or that are retained following harvest probably have major effects on the recovering ecosystem. Together with dead wood, remnant trees bridge past and future forests (FEMAT 1993b). These trees provide a seed source, shade, and amelioration of temperature and surface desiccation for the post-disturbance, regenerating cohort. Remnants also compete with the regeneration for deeper soil moisture and nutrients. By providing a source for snags and promoting a multi-storied canopy, remnants provide protection and suitable habitat for many organisms that cannot exist in young, even-aged forests (FEMAT 1993b). Remnant trees also serve as a source for epiphytic lichens and mycorrhizal fungi, both of which play vital roles in nutrient cycling and in the diet of small mammals (Pike 1978, Raven et al. 1986). Patches of residual green trees also may promote diversity of lichens and fungi, as well as vascular plants and arthropods (FEMAT 1993b). Large remnant trees, snags, and logs provide protection from predators and temperature fluctuations and may serve as natal den sites for American martens and fishers (FEMAT 1993b). Remnants may also serve as roosting sites for bats, and nesting sites for many bird species (FEMAT 1993b). In addition, remnants may harbor potentially damaging forest pathogens.

Over decades, remnant trees will probably influence the species composition and growth rates of the developing tree cohort. It is logical to expect that stands with relatively great abundance of remnants will be associated with greater abundance of shade tolerant trees such as western hemlock and western redcedar (Thuja plicata (Donn.)) and lower abundance of less tolerant Douglas-fir. More shade may also slow the growth of the regenerating cohort, though remnant trees may have beneficial effects on seedling recruitment by lessening frost and sun damage, and serving as a reservoir for mycorrhizal fungi.

Objectives

The objectives of this study are to analyze the relationships of varying levels of green-tree retention to growth and species composition of regenerating conifer stands. This study uses natural disturbance as an analogue to timber harvest in an attempt to determine how leaving large green trees on a site will affect stand development over a typical rotation period of 70-110 years.

Justification

Green and dead standing trees and downed woody debris can strongly affect the rate of ecosystem recovery following disturbance (Swanson and Franklin 1992), however, we do not fully understand what effects these elements have on the recovering ecosystem. In particular, information on the effects decades or centuries into the future is lacking. Green-tree retention as part of timber harvest has been practiced recently on some National Forests in the Pacific Northwest and is mandated in the FEMAT Preferred Alternative Plan (FEMAT 1993a, USDA Forest Service 1990a,b,c,d), with unknown consequences for either biodiversity or for conifer growth and yield.

With new legal requirements for green-tree retention with timber harvest, the question of how a forest will be affected by leaving varying numbers of remnant trees is clearly an important management question. Any forest management plan is actually a large-scale experiment without strict controls. Managers have no direct way of determining the long-term impacts of different harvest methods on forest ecosystems without studies that would take at least several decades to complete. However, retrospective studies have potential utility for predicting the future result of different harvest regimes (Swanson and Franklin 1992). Retrospective studies are based on the assumption that a past disturbance (such as fire) can be used as an analogue for timber harvest.

While analogies between timber harvest and natural disturbances can be made, it is important to remember that fires differ from timber harvests in several ways. First, fires leave almost all large wood on the site, while timber harvests remove wood from the site. Fires generally increase the amount of fine and coarse woody debris on the forest floor (Agee and Huff 1987). The result of ecosystem management more closely resembles results of forest fires than traditional timber harvest methods, in that some live and dead standing trees and coarse woody debris are left on site following logging. Second, under conventional logging methods, compaction of the soil occurs from heavy equipment pulling logs across the ground (Brooks et al. 1991). Both compaction and removal of organic debris from the soil surface can result in higher erosion and nutrient losses following harvest than following fire (Brooks et al. 1991, USDA Forest Service 1990d), though particularly intense fires may also result in soil and nutrient losses (McNabb and Cromack 1990). Erosion and nutrient losses would be ameliorated in a management plan that retains green trees and coarse woody debris, even more so when coupled with aerial harvest methods. Third, planting of tree seedlings will likely follow harvest, as opposed to natural regeneration after a fire. Planted seedlings will often have an advantage over naturally-regenerated species and thus will influence the species composition of the future stand. However, the planted seedlings must survive in the same environmental conditions in which natural seedlings would have to survive. Thus, it is legitimate to compare the growth of stands that regenerated naturally under varying numbers of remnant trees to stands that will regenerate after planting. Finally, there is no natural process equivalent to the herbicide treatment of competing herbs and shrubs following harvest.

Despite imperfections in the analogy between timber harvest and fire, retrospective studies offer the only feasible means of obtaining a picture of the future of ecosystem management harvests without waiting decades for consequences from recent cuts to be observed. This study provides important information for timber managers on how their activities may affect species composition and tree growth rates of future forest stands. This project also helps fill a large hole in the literature relating to ecosystem management activities and forest succession in the western Cascades. The only information currently available on effects of remnant trees on conifer growth is in the form of rough estimates in reports by the Willamette National Forest (unpublished) and Washington Department of Natural Resources (Hoyer 1993), and a computer model for northern Idaho (Long and Roberts 1992). Finally, this study makes use of existing Forest Service timber inventory data, saving thousands of dollars and hours that would have been required to conduct this project as a field study. The timber inventory plot data are an underutilized resource that allowed me to increase greatly both my sample size and the generality of inferences from the data.

METHODS AND MATERIALS

Description of Study Area

The study area is the lower-to-moderate elevations (450-1250 m) of the western Cascade Mountains from southern Washington to central Oregon, including portions of the Gifford Pinchot, Willamette, and Umpqua National Forests (Figure 1). The area typifies the lower-to-moderate elevation coniferous forests common to the region, however, data are lacking from the Mt. Hood National Forest in northern Oregon and from the Columbia River Gorge. Little of the Gorge is National Forest land, while the Mt. Hood plots were excluded because of data incompatibility (See Plot Selection Criteria). The area encompasses much of the *Tsuga heterophylla* zone within the central part of the Western Cascades Province described by Franklin and Dyrness (1973).

The maritime climate is relatively mild and wet throughout the study area, with relatively dry summers receiving only 6-9% of the mean annual precipitation (Franklin and Dyrness 1973). Precipitation varies primarily along an elevational gradient ranging from approximately 150cm at the lower elevations to 250cm or greater higher in the mountains (Oregon Climate Service 1993). Moisture may be limiting to plant growth throughout much of the summer, especially on south-facing slopes. Average January temperatures range from about 0° C at Wind River, Washington (351 m) in the north part of the study area to about 2° C at McKenzie Bridge, Oregon (419 m) in the south (Franklin and Dyrness 1973). Mean July temperatures range from about 17° C to 19° C, while mean annual temperatures range from 9-10° C (Franklin and Dyrness 1973). Because weather stations are located only at the lower elevational extreme of the study area, average temperatures for the study area are actually lower.

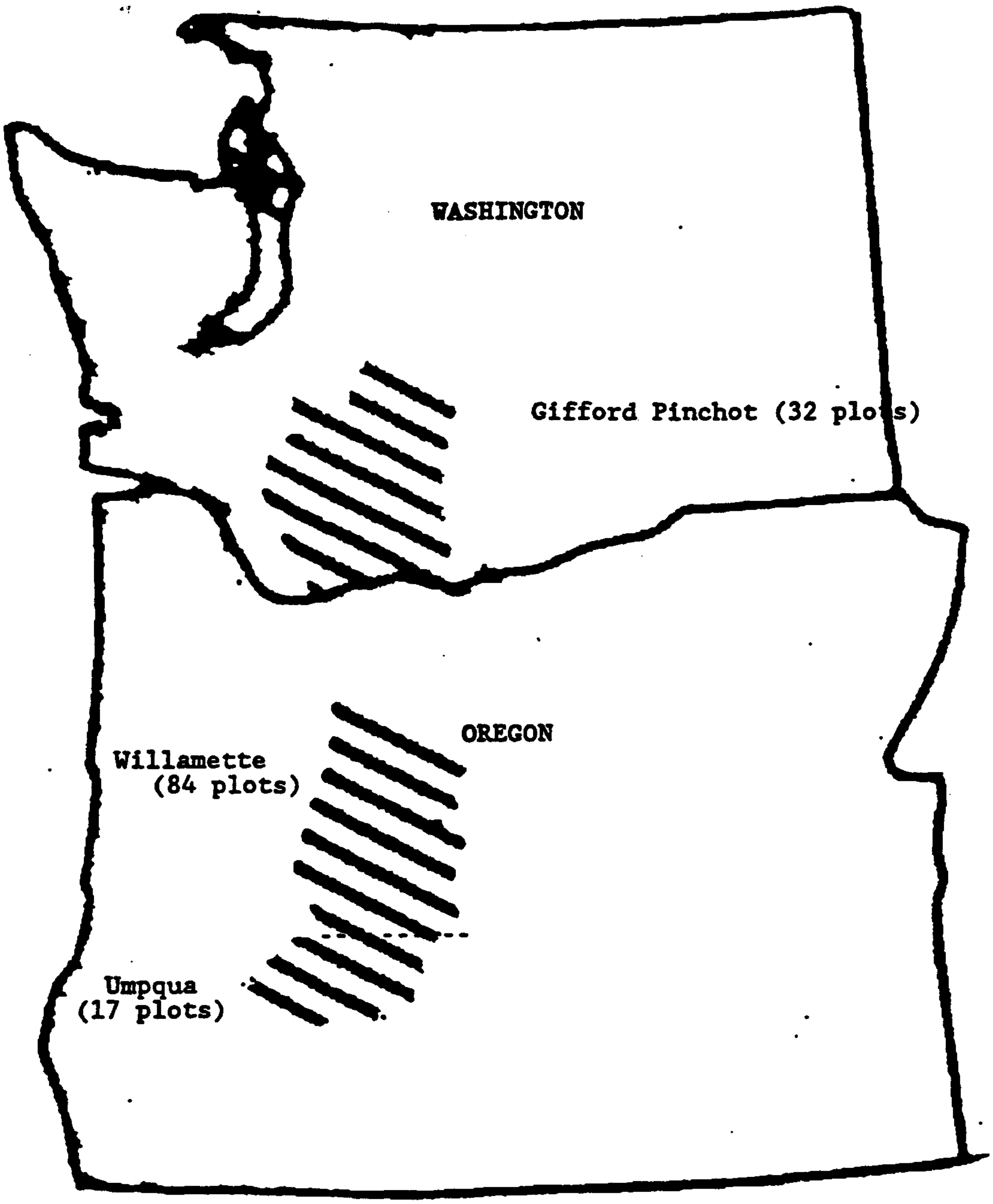

FIGURE 1: Map of study area

Typical soils tend to be moderately acidic with a well-developed organic layer (Franklin and Dyrness 1973). The porous and well-aggregated soils typical of the area are deeper and more productive on terraces in river bottoms than on the steep slopes that drain into the many rivers and streams. The great soil groups characteristic of the Cascades *Tsuga heterophylla* zone include Dystrochrepts, Haplumbrepts, Haplorthods, Xerumbrepts, and Vitrandepts (Franklin and Dyrness 1973).

Source of Data

The data for this study came from the timber inventories conducted every ten years on the National Forests of the Pacific Northwest. These inventories establish or revisit thousands of plots on which trees are measured and physiographic conditions (e.g. elevation, aspect, percent slope, etc.) are recorded. The purpose of these plots is to estimate timber volume available for harvest. This study utilizes data from four timber inventories: the 1981 inventories on the Gifford Pinchot and Willamette National Forests, the 1980 Umpqua National Forest inventory, and the 1970 Willamette National Forest inventory. For the 1980-1981 inventories, each National Forest was first stratified into specific vegetative strata and then enough inventory plots were established in each stratum to estimate timber volume within a 10% precision level. For the 1970 inventory, plots were chosen at random from a grid covering the entire forest, with no prestratification of vegetation (USDA Forest Service 1980, Pers. Comm.: Jim Mayo, Willamette National Forest).

Description of Timber Inventory Plots

Each plot consists of 10 sample points distributed over approximately 0.40 hectare (one acre) (Figure 2). For each new plot, point 1 was located at a point pricked on an aerial photo, then each plot was located and referenced on the ground so that it could be relocated and remeasured in subsequent inventories. Because each plot represents a relatively homogeneous unit of forest, I will use "stand" interchangeably with "plot". The overall shape of the plot might have been modified if one or more of the points would have been located on non-forested land. However, the area encompassed by each plot remained approximately 0.40 ha. A variable radius subplot was taken at each of the 10 points, in which a BAF 80 wedge prism or angle gauge was used to tally all trees 18 cm (7.0 inches) diameter at breast height (DBH) and larger. In addition, a 2.07-meter (6.8-foot) fixed-radius (13.46 m^2) subplot was established at each of the ten points in which trees up to 17.53 cm (6.9 inches) DBH were tallied. Data on tree quality, size, age, species, and other items were collected for every salvable tree (live and dead) at each point (Table 1). Age was derived by counting the rings on cores of a "representative number" of trees of each species (ie 10-20 per stand across all species); not every tree was cored. Years were added to the age at breast height to approximate more closely the true age of each species (Table 2).

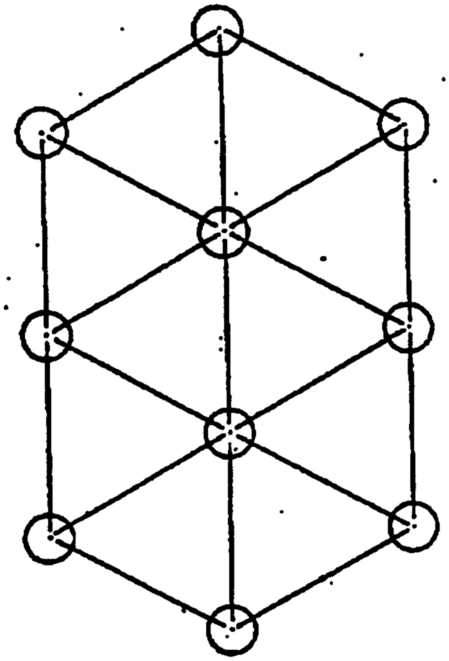

FIGURE 2: Timber inventory plot design. Source: USDA Forest Service, Timber Inventory Plot Procedures Guide, Region 6 (1980). Circles represent variable-radius subplots around each of the ten points.

TABLE 1: Summary of timber inventory tree measurements used in study (with comments).

Tree Measurements	Comments
Tree History	8 categories, summarized here in 3 categories: Live, Salvable (live and dead), and Nonsalvable.
Diameter at Breast Height (DBH)	Measured to 0.1 inch (2.54 mm), used to compute basal area.
Measured Height	Measured at first three points only, less in 1970 inventory. Considered unreliable and therefore not used.
Age Class	Recorded in 10-year increments up to 200 years, then 1 age class for trees 200-299 years, and 1 for age 300+. Number of years required to grow to breast height are added (see Table 2).
Species	18 across study stands.

TABLE 2: Years added to age at breast height to compute age class for the most common tree species.

Species	Years Added to Age at Breast Height
Douglas-fir (_Pseudotsuga menziesii_)	8
Pines (_Pinus_ spp.)	11
Hemlock (_Tsuga_ spp.)	7
Pacific-silver fir (_Abies amabilis_), grand fir (_A. grandis._), noble fir (_A.procera_)	8
Incense cedar (_Calocedrus decurrens_)	15
Western redcedar (_Thuja plicata_)	7

Plot Selection Criteria

The original plan for this project was to utilize data from a large (but relatively homogenous) stretch of the west side of the Cascade Mountains, from southern Washington to central Oregon. The USDA Forest Service Pacific Northwest Research and Experiment Station in Portland provided computerized data files of all timber inventory plot data from the 1980-1981 inventories on the Gifford Pinchot, Willamette, and Umpqua National Forests as well as the 1986 Mt. Hood National Forest data. Unfortunately, the 1986 Mt. Hood inventory data were incompatible with the data from the other Forests for the purposes of this project because of a lack of sufficient tree measurements, and no data were available from earlier timber inventories on the Mt. Hood National Forest. For these reasons, no data from the Mt. Hood National Forest were used in this study. Fortunately, paper copies of the 1970 Willamette National Forest inventory were available, substantially increasing my sample size.

Out of several thousand plots available, I selected only plots that were between 450 and 1250m elevation, and clearly in the Tsuga heterophylla (western hemlock) zone described by Franklin and Dyrness (1973), with Douglas-fir and western hemlock as dominant trees. Within this group, only even-aged stands between 70 and 110 years old, or those with an overstory of remnant trees greater than 200 years old over a cohort of trees 70-110 years old were selected. Although I considered remnants to be all trees over 200 years of age, in practice very few were younger than 300 years. Henceforth, I will refer to the cohort of trees 70-110 years old as the "regeneration." The stands with remnants were partially disturbed, while the even-aged stands with no remnants represent cases where the trees were completely destroyed 70-110+ years ago and are analogous in some ways to clearcuts. I assume that fire was the disturbance in most cases, and comments on several of the timber inventory data sheets indicate the presence of fire scars on trees or charcoal in the soil.

Stands with a regeneration cohort 70-110 years old were chosen because this age range encompasses rotation ages common on National Forests of the Pacific Northwest (USDA Forest Service 1990a,b,c,d) and is narrow enough to allow comparisons between stands. Trees in this age range are usually large enough to be considered merchantable timber. While there are seedlings, young saplings, and occasionally older trees mixed throughout these stands, the mean age of the dominant regeneration cohort is 70-110 years for almost every stand, and I avoided truly multiple-aged stands. In some stands, a few trees in the regeneration are included that are up to 150 years old. These trees may in some cases represent the true date of the disturbance and may reflect a lengthy establishment period for the regeneration. A 20-year lag time in tree establishment following disturbance has been assumed in the literature, but "full" establishment may take decades longer (Spies et al. 1988). I excluded seedlings and young saplings from most analyses because I am primarily interested in the effects of remnants on trees of merchantable size. However, it is important to note that seedlings and young saplings were present and probably competing for moisture and nutrients. One hundred thirty-two stands were included in analyses (see Table 3).

TABLE 3: Selected stand characteristics. Ba is in m^2. Grand fir=*Abies grandis* (Dougl.) Forbes, western white pine=*Pinus monticola* Dougl., sugar pine=*Pinus lambertiana* Dougl.

STANDS WITHOUT REMNANT TREES (N=51)

	Mean	SE	SD	Minimum	Maximum
Regeneration Density (Trees/ha)	40.64	3.13	22.12	7.52	125.18
Regeneration Ba/ha	60.88	2.47	17.47	23.82	108.09

Species	Douglas-fir	Western Hemlock	Grand Fir	Western White Pine	Sugar Pine
Species Ba/ha (% of Total Regeneration Ba/ha)	2705.52 (90.19%)	126.94 (4.23%)	38.87 (1.30%)	37.81 (1.26%)	20.15 (0.67%)

STANDS WITH LIVE AND DEAD SALVABLE REMNANT TREES (N=81)

	Mean	SE	SD	Minimum	Maximum
Remnant Density (Trees/ha)	29.31	3.09	27.94	0.77	125.39
Remnant Ba/ha	28.24	2.67	24.14	1.83	97.10
Regeneration Density* (Trees/ha)	54.65	6.16	55.75	6.82	468.80
Regeneration Ba/ha	39.99	2.16	19.55	3.66	81.31

Remnant Trees

Species	Douglas-Fir	Western Redcedar	Western Hemlock	Pacific Silver Fir	Incense Cedar
Species Ba/ha (% of Total Remnant Ba/ha)	1804.52 (77.93%)	252.82 (10.92%)	137.33 (5.93%)	42.14 (1.82%)	36.64 (1.58%)

Regeneration

Species	Douglas-Fir	Western Hemlock	Western Redcedar	Pacific Silver Fir	Grand Fir
Species Ba/ha (% of Total Regeneration Ba/ha)	4684.81 (73.74%)	901.14 (14.18%)	252.50 (3.97%)	142.10 (2.24%)	88.45 (1.39%)

* Includes one stand with an unusually high regeneration density of 468.80 trees/ha. With this stand removed, regeneration density = 49.54.

Relationship to FEMAT Preferred Alternative Plan

Under the guidelines of the FEMAT Preferred Alternative, the forest matrix (the site of most harvesting) includes retention of 15% of the volume of each cutting unit on the National Forests of the Oregon and Washington Cascades. While up to half of this volume can be left as individual trees, at least half the retained volume must be in 0.20 to 1.62 ha (1/2- to 4-acre) intact late-successional (or oldest available) stands. According to FEMAT (1993a), Bureau of Land Management (BLM) lands in northern Oregon will be managed with 150-year timber harvest rotations and green-tree retention of 30-45 trees/ha (12-18 trees/acre). On BLM lands south of Grants Pass, Oregon, 40-62 green trees per hectare (16 to 25 per acre) will be left on site (FEMAT 1993a), but this area is outside the study area. For my purposes, "management level" remnant densities range from 0-45 trees per hectare (0-18 trees per acre).

Conceptual Model of Factors Influencing Current-Stand Basal Area/Hectare

Factors influencing total-stand ba/ha and how total-stand ba/ha is apportioned between remnants and regeneration are represented in Model 1:

Current stand basal area (ba) = regeneration ba (A) + remnant ba (B) + error component (C)

B=remnant ba immediately after disturbance (B1) + remnant ba growth since disturbance (B2)-remnant death (B3)

Units are m^2/ha for all of these variables

Factor A

Regeneration ba/ha is the dependent variable in most analyses here. Remnant trees affect the regeneration in two ways: through simply making space unavailable to the regeneration, and through competition for resources. I attempted to distinguish space occupancy from other remnant effects through an adjusted regeneration ba/ha that statistically removed remnant-tree space occupancy (see Stand-Level Analyses). I also examined how the spatial patterns of remnant trees may modify the effects of remnant trees on the regeneration. For example, if remnants were clumped on one small part of a stand they would only shade that part of the stand, and probably have less effect on the regeneration than if the same number of remnants were evenly spaced across the stand. Remnant-tree distribution is examined with an "aggregation index" that is added to the regeneration ba/ha vs. remnant density regression. Regeneration density is investigated because spacing of the regeneration may affect competition for resources and consequently the regeneration ba/ha of a stand. (See Stand-Level Analyses for details.)

Factor B

B1 + B2 - B3 = measured remnant-tree density or ba/ha. Different stands had varying numbers of potential remnant trees before the regeneration-initiating disturbance left different numbers of remnants among stands. Varying numbers of remnants were left alive due to different disturbance intensities between stands, and then during the history of the regeneration, some remnants have died and fallen, while the survivors have grown. The trees left standing at the time of the timber inventories were included in this study as remnants. Remnant spacing may also have affected remnant growth.

Factor C

Error component: There are various other factors that affect ba/ha of both regeneration and remnants:

Propagule supply and quality

Propagule supply is probably not an issue for major species because remnants and trees from adjacent stands should provide ample seed source. There may, however, be genetic differences (propagule quality) between seeds that result in greater growth potential for some trees than others. This potential problem is partially addressed by comparing the mean regeneration ba/ha's of the three National Forests. Within-National Forest and within-stand genetic variability cannot be addressed here and probably add noise to the relationship between remnants and regeneration ba/ha. Propagule source may also have affected species composition, resulting in some stands having faster-growing species than other stands. This is addressed by examining the relationship between the Douglas-fir proportion of the regeneration and the regeneration ba/ha across species (see Stand-Level Analyses).

Site differences

Different environmental conditions among stands, including elevation, aspect, soil, and available moisture, may confound the relationship between remnants and regeneration. I developed physiographic classes based on potential available moisture, which assumes that moisture is the most important limiting factor in the study area (see Grouping of Stands). The effects of elevation and aspect were examined using ordination and analysis of variance (see Stand-Level Analyses). Soil differences among stands cannot be addressed directly, although water-holding capacity is probably reflected in physiographic classes. Soil differences likely add noise to the relationships between remnants and the regeneration.

Stochastic factors

Higher incidence of disease, insect damage, and windthrow are examples of stochastic factors that may cause variability among stands but cannot be addressed here. None of the stands included for analysis were obviously disturbed since stand initiation, but excessive windthrow is a notable (and possibly hidden) factor that could have removed standing remnant trees from some stands, distorting the relationship between regeneration growth and remnant-tree density.

Grouping of Stands ("site differences" in error component of Model 1)

The primary goal of this study is to infer effects of remnant trees on the regeneration. Inference about the roles of remnants is most robust when all environmental variables (eg elevation, aspect) are standardized as much as possible. For example, comparing tree growth in a canyon bottom with tree growth on a ridge-top could be meaningless, because of different growing conditions on each site. A great deal of standardization was accomplished with the initial stand selection criteria as described above, but I felt more was needed. One way of grouping plots to avoid confounding remnant effects with site effects would be through the use of site potentials based on the height of the dominant trees on each plot (reported in the timber inventories). Such an approach would have been appropriate if all plots were even-aged, but the use of site potentials based on dominant height is invalid for multi-canopied stands with more than one species (Husch et al. 1972). Further, growth rates of the trees used for site potentials were probably influenced both by site potentials and by shading and resource use of nearby remnants, and thus do not provide a basis for grouping that is independent of remnants.

Because of the problems with using site potentials, I grouped plots into four physiographic classes, primarily on the basis of heat loading, or potential dryness of a plot (modified from Kessell 1979) (Table 4). Physiographic classes were based on a combination of aspect, slope position, and presence of indicator species. Occasionally, remarks by the workers who did the timber inventories allowed further characterization of a plot. I used indicator vegetation to modify a plot's class placement where necessary. For example, a north-facing plot with incense cedar (Calocedrus decurrens Kurz) and madrone (Arbutus menziesii Pursh.), both dry site species on the west side of the Cascades

(Franklin and Dyrness 1973), would be removed from Class 3 and placed in Class 1. This site might be drier than other north-facing slopes due to thin, rocky soil with little water holding capacity or some other unrecorded environmental factor. I also grouped stands by aspect and by National Forest to see if there were significant differences between the stands of each aspect or National Forest.

TABLE 4: Description of physiographic classes. Class 1=driest plots, class 4=wettest plots.

Class 1	Upper and middle west-, southwest-, and south-facing slopes
Class 2	Upper and middle southeast- and northwest-facing slopes
Class 3	Upper and middle north-, northeast-, and east-facing slopes
Class 4	Bottomlands: canyon bottoms and lower 1/3 of all slopes

Data Analyses

Analysis of the data began with conversion of diameter at breast height (dbh) measurements to basal area per hectare (ba/ha), with basal area in square meters. I ordinated plots in species space (matrix of plots by tree species ba/ha in the regeneration) to try to understand the basic patterns of species composition and relative abundance in the regeneration. The community data were strongly dominated by the overwhelming abundance of Douglas-fir, western hemlock, and western redcedar. The correlations (r) between these species and the first three axes extracted by Bray-Curtis ordination were 0.997 (Douglas-fir and axis 1), 0.841 (western hemlock and axis 2), and 0.953 (western redcedar and axis 3), respectively, while the first axis explained 85% of the variance in the data. This preliminary analysis pointed out the need to relativize the data so that the total ba/ha added up to one for each stand. Relativization greatly decreased the overwhelming dominance of the most abundant species so that the ordination axes reflected more than just the abundance of a single species.

I ran a principal components analysis (PCA), nonmetric multidimensional scaling (NMDS), and Bray-Curtis ordination after removing five multivariate outlier stands. The Bray-Curtis ordination using Euclidean distance measure and variance-regression endpoint selection produced the most clearly interpretable first and second axes. Also, compared to PCA or NMDS, the Bray-Curtis ordination showed the least distortion of the ordination space when outliers were included. I examined correlations between ordination axes and species, remnant density, and elevation, as well as overlays of the environmental factors of physiographic class, cluster group, and aspect on the ordination graph. Other multivariate analyses included cluster analysis (clustering plots based on tree species ba/ha) with city block (2W/(A+B)) distance measure and Ward's group linkage method, and multiresponse permutation procedure (MRPP) to test the significance of differences between groups defined by cluster analysis. The statistics package PC-ORD (McCune 1993) was used for all multivariate analyses.

Univariate methods included regression, analysis of variance, and correlation analysis to explore relationships of remnant trees and other factors to growth and species composition of the tree regeneration. The dependent variable in regressions was square-root transformed to help linearize the relationships between variables except where indicated. I also examined the distribution of the data to test the assumptions necessary for using parametric statistics and the need for data transformations. The statistics package SPSS/PC+ Version 4.0 (Norusis/SPSS Inc. 1988) was used for univariate analyses. Graphs were made with As-Easy-As Version 4.00c (Trius Inc. 1989).

Calculation of Stand Parameters

The timber inventories were designed so that each plot represented approximately 0.40 ha, but variable-radius sampling produces different-sized plots depending on tree size (Husch 1972 et al.). Larger trees will be sampled over a larger plot area than smaller trees, thus it is inappropriate to compare basal areas on two different plots in this data set without putting them both on the same area basis. For this reason, I summed the individual-tree basal area/hectare values for each stand instead of using the sum of the individual-tree basal areas. Different stands may have different ratios of basal area to basal area per hectare for the tallied trees, presumably because the actual area sampled is different between the stands. Variable radius sampling also results in each tree over a certain diameter representing the same basal area per land area ratio (Husch 1972 et al.).

The timber inventory system used a relatively high basal area factor (BAF) of 80, which made sampling less sensitive to small trees than would a smaller BAF. Because the probability of tallying any given tree is proportional to its basal area, there is a much higher probability of tallying larger trees (Avery and Burkhart 1983). With a BAF of 80 and ten sampling points, each tree greater than 17.8-cm dbh (7 inches) represents 1.83 m^2/ha, or 8 ft^2/acre (80/10) (Bell and Iles 1991, Spurr and Barnes 1980). Trees less than 17.8-cm dbh were tallied on ten, 13.51m^2 (1/300-acre) fixed-radius plots centered on each of the ten points. Thus, trees less than 17.8 cm dbh occupy a certain basal area per 1/30 of an acre, or 0.03 acre and the total ba/acre = ba(ft^2)/0.03 acre. Converting to metric: ba(m^2)/ha = ba(ft^2)/acre*0.229 (USDA Forest Service 1980, Spurr and Barnes 1980).

Summing the ba/ha of all sizes of trees in the regeneration cohort on a plot produced the basic unit that I used for most analyses (henceforth "regeneration ba/ha") except where noted. The regeneration ba/ha includes both live trees and salvable dead trees; salvable dead trees make up 6.49% of the regeneration ba/ha, or 5.7% of the total number of stems in the regeneration. I included the dead trees because they would likely be harvested in a timber sale, and I wished to focus on remnant effects on merchantable trees.

Ideally, I would have analyzed relationships of regeneration volume to remnants, but few heights were taken on the inventory plots, particularly in 1970. The 1980 and 1981 inventory plot data included calculated heights based on a regression equation using (probably) DBH and the few measured heights, but calculated heights were not available for the 1970 data. Different regeneration and remnant densities may result in different basal area to volume ratios across stands. On stands with the lowest regeneration densities, ba to volume ratios will likely be higher than on stands with medium-to-high regeneration densities, because free-growing trees put more photosynthate into diameter growth (and hence ba) than trees growing with side shade (Oliver and Larson 1990). However, because basal area is highly correlated with tree volume (Green 1992), conclusions based on analysis of basal area/hectare are probably generalizable to volume/hectare for most stands.

Remnant tree density (trees/ha) was calculated for each stand by the dividing the total ba/ha of all remnants on a stand by the mean ba of remnants on a stand (Bell and Iles 1991). I use remnant-tree density as the independent variable instead of remnant ba/ha for two reasons: First, guidelines for green-tree retention following timber harvest often specify a given number of remnant trees left per acre or hectare, rather than specifying a ba/ha to be left. Second, because each remnant represents the same ba/ha with Bitterlich sampling, the regeneration ba/ha to remnant ba/ha relationship is almost exactly the same as the relationship between regeneration ba/ha and remnant density (see RESULTS). Regeneration density (trees/ha) was calculated in the same way as for remnants.

I included dead remnants in most analyses because these trees were likely alive throughout much of the history of the regeneration. The remnants currently on a site were present at the initiation stage of the regeneration, but in the 70-110 years or more since the disturbance, many remnants may have died. Thus, the number of remnants present now may be far less than the number that survived immediately after the disturbance and may not provide a good indication of growing conditions for much of the life of the regeneration. For this reason, I calculated three different remnant densities: live remnants only; live remnants plus salvable snags; and the combination of live remnants, salvable snags, and nonsalvable snags (nonsalvable snags $\geq$ 60cm dbh). Large Douglas-fir snags in western Oregon may exist in decay class one or two (and are probably salvable) for up to 18 years (see Maser et al. 1988). Thus salvable remnants likely influenced the regeneration during most of its 70-110 years of development. Salvable dead remnants made up 8.72% of the ba/ha of the combined ba/ha of live remnants plus salvable dead remnants across stands. The heartwood of a large Douglas-fir snag may last 125 years or longer (Maser et al. 1988). Therefore, nonsalvable snags may or may not have lived during part of the development of the regeneration. Their inclusion may either improve the estimation of remnant effects on plots where nonsalvable snags were alive at stand initiation, or decrease the accuracy of estimated remnant effects where nonsalvable snags were dead at stand initiation. Nonsalvable snags ($\geq$ 60-cm dbh) made up 15.95% of the combined ba/ha of all remnants across stands when included.

Individual-Tree-Level Analyses

I examined the relationship between remnant density and individual-tree growth in the regeneration in each stand by first obtaining the unstandardized residuals from the regression of tree basal area vs. age for regeneration trees in each stand. Mean residuals (means calculated across species and for individual species in the regeneration of each stand) were then regressed against remnant density to determine how much of the deviation from the age/basal area relationship could be explained by remnant density.

Stand-Level Analyses

I used analysis of variance (ANOVA) to examine the regeneration ba/ha relationship to physiographic class, aspect, and National Forest. The relationship of National Forest to regeneration ba/ha was examined because regeneration ba/ha might have been greater on the warmer Willamette and Umpqua National Forests than on the Gifford Pinchot ("site differences" error component in Model 1), and because of potential genetic differences among National Forests ("propagule supply and quality" error component in Model 1). The ANOVA's provided a check to see if physiographic classes, aspects, or National Forests appeared similar enough to allow further analyses across these groupings, or if I should only analyze data within these groups. Most univariate stand-level analyses involved examining relationships of remnant density to regeneration ba/ha with regression (See Model 1). I also used regression to examine the relationships of regeneration to elevation ("site differences" error term in Model 1), regeneration density ("A" in Model 1), and proportion of Douglas-fir regeneration in the stand ("propagule supply and quality" portion of error component in Model 1). I included elevation in analyses because regeneration ba/ha might have decreased with increasing elevation and the corresponding shorter growing season. As regeneration densities increase, individual tree basal area typically decreases because of side shade from adjacent trees, but regeneration ba/ha for the entire stand may increase with density up to some optimal density (Oliver and Larson 1990). The density at which the upper limit of regeneration basal area is reached depends on species composition, site, and stand structure (Oliver and Larson 1990). Thus, it would seem that regeneration density would contribute "noise" to the relationship between remnant trees and the regeneration. However, there appears to be a systematic relationship between regeneration density and regeneration ba/ha: Table 3 shows that as regeneration density increases, regeneration ba/ha decreases (compare stands with remnants to those without remnants). (Regeneration density is not significantly correlated with remnant density R=0.01.) Thus, regeneration density may be an important independent source of variation in the regeneration ba/ha.

I defined the Douglas-fir proportion of the regeneration as Douglas-fir regeneration ba/ha / (Douglas-fir regeneration ba/ha+western hemlock regeneration ba/ha) because these species dominate every stand (Table 3) and are the most important trees from a management perspective. Seedlings and young saplings were not excluded from analyses involving individual species, because I thought that including the young trees would provide a more complete picture of regeneration species composition. Thus, it is possible for the ba/ha of individual species to add up to more than regeneration ba/ha across species. However, because of the stringent stand selection criteria, stands contained few trees younger than 70 years of age. Including younger trees adds less than 5% to the combined Douglas-fir and western hemlock ba/ha for most stands (up to 10% in one stand) and does not change R^2-values for any regression involving individual species more than 0.02. The rationale for using the Douglas-fir proportion is that Douglas-fir is a fast-growing tree that usually outgrows its coniferous competitors soon after a disturbance in the western Cascades (Wierman and Oliver 1979). Because Douglas-fir is a good competitor and dominates most stands, the amount of ba/ha in the regeneration across all species might simply reflect how much Douglas-fir is in the regeneration. The Douglas-fir proportion was arcsine-square root transformed to homogenize the variance in the data (Sokal and Rohlf 1981).

Another important factor I examined was remnant tree distribution (spacing), which may have modified remnant-tree relationships with the regeneration (see "A" and "B" in Model 1). For example, in western Washington, the heights of 60-year-old Douglas-firs decreased as their distance to overstory 120-year-old Douglas-firs decreased (Hoyer 1993).

I computed an aggregation index as a measure of how clumped or scattered the remnant trees were in a stand. This index was computed by dividing the variance in the number of trees per point on each plot by the mean number of trees per point on each plot (adapted from Greig-Smith 1983). A variance/mean ratio of one implies a random distribution, a ratio < one implies a regular, evenly-spaced distribution, and a ratio > one implies a clumped distribution. Dividing by the mean number of trees per point controls for the number of trees on a plot. Aggregation index was added into the regeneration ba/ha vs. remnant-tree density regression equation to see if aggregation index explained any of the residual variance.

One aspect of the remnant tree/regeneration relationship seems obvious: remnant trees affect the regeneration by simply taking up space and making part of a forest unavailable to the regeneration after a disturbance (see "A" in Model 1). To distinguish this space occupancy effect from other remnant effects (shading, water use, etc.), I created an adjusted regeneration ba/ha that controls for the different proportions of a stand occupied by remnants in each stand. By dividing the regeneration ba/ha by the proportion of the stand available (1-the proportion of old growth stand remaining), the space occupancy effect is diminished. Conceptually, this adjustment spreads the regeneration across the entire stand, giving each stand an equal proportion of remnants (zero), but preserving any apparent remnant effects other than those resulting simply from remnants' occupation of space.

I first identified 33 old-growth timber inventory plots to provide a baseline mean old-growth tree density. From this mean old-growth density, I derived an estimate of the proportion of old-growth stand remaining after the regeneration-initiating disturbance in each of the 132 stands used throughout this study, and thus the proportion of the stand available to the regeneration. Eighteen old-growth stands were from the Willamette National Forest, 9 from the Gifford Pinchot, and 6 from the Umpqua National Forests, reflecting the distribution of the two-aged stands used elsewhere in this study. I considered a stand "old growth" if almost all the trees on the plot were 200+ years of age, with no other clear cohort of trees (besides seedlings) on the plot. I found that the mean density of salvable trees (including live trees and snags) 200+ years of age was 144 trees/ha, with a standard deviation of 61 trees/ha. These values should not be confused with those in studies where densities are reported by tree size. For example, Hansen et al. (1991) reported a mean density of 19 trees/ha for live Douglas-fir >100cm DBH in old-growth stands in western Oregon and Washington. In the old-growth plots I identified, the mean density of live Douglas-fir >100cm DBH was 22 trees/ha.

For each two-aged stand, I calculated the proportion of old growth remaining based on the mean density from the old-growth stands. For example, a plot with a density of 37 trees/ha was said to have a 0.25 of an old-growth remaining, because 1/4 (37/144) of the old-growth stand remained. In this example, an adjusted regeneration ba/ha would be computed by dividing the regeneration ba/ha by 0.75, (1 - 0.25), because the regeneration essentially had only 75% of the stand available in which to develop. This calculation assumes that the mean-density old-growth stand represents the maximum amount of space that can be occupied by trees on a plot. Adjusted regeneration ba/ha was then regressed against remnant density to infer remnant effects relatively independent of space occupancy.

Clearly, the adjusted ba/ha is a rough estimate of remnant space-occupancy effects because of the large standard deviation of the old-growth density. A sensitivity analysis showed that using a density of mean old-growth tree density minus one standard deviation in the above calculations produced largely meaningless results because this density is equal to or lower than remnant-tree densities in some of the two-aged stands in the data set. An adjustment based on mean old-growth density plus one standard deviation produced qualitatively and quantitatively similar results to using the mean density. While imperfect, this method should diminish the effects of simple space occupancy by the remnants.

Cases where regeneration ba/ha were adjusted are specified below, all other regeneration ba/ha values are unadjusted.

RESULTS AND DISCUSSION

Grouping of Stands

I initially grouped stands to see if there were enough differences between physiographic classes, aspects, or National Forests to warrant analyzing data within these groups. The species composition of the regeneration was apparently more strongly influenced by factors other than aspect and slope position (as used in physiographic classes), as indicated by the fact that stands grouped on the basis of physiographic classes and aspects were intermixed on the ordination graph (Figures 3 and 4). There was no grouping of plots according to aspect or physiographic class as would be expected if the aspects or classes had similar species or productivities. An analysis of variance conclusively put the importance of dividing stands into physiographic classes to rest by showing that there was no significant difference in the regeneration ba/ha between plots of different classes (Table 5). There are two possible interpretations of these results. First, the physiographic classes may not have been as homogenous as they appeared, in that they might have contained stands with different growth potentials and consequently might have been poor groupings of the data. Second, initial plot screening may have been stringent enough to make the entire data set relatively homogeneous, as the formation of only two cluster groups suggests.

TABLE 5: Results of one-way ANOVA with physiographic class as main effect and remnant density as covariate. See Table 4 (p. 20) for description of classes.

Source of Variation	F	Significance of F
Remnant Density (Salvable, Live and Dead)	104.74	0.00
Physiographic Class	0.97	0.41

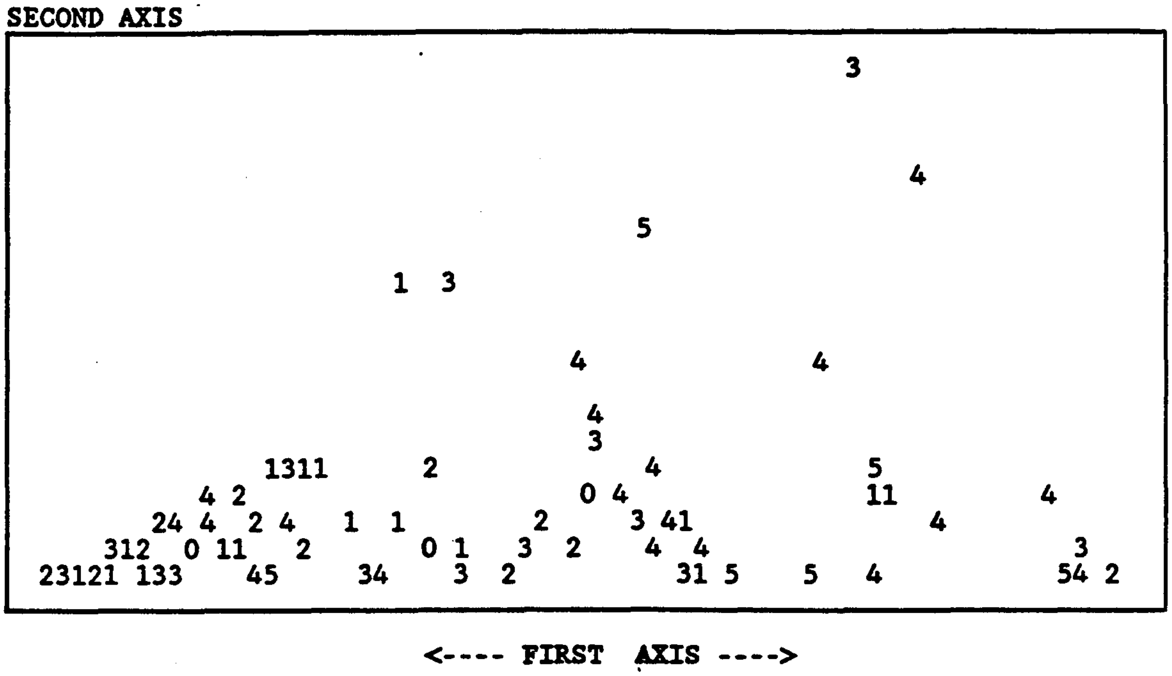

FIGURE 3: Overlay of aspects on Bray-Curtis ordination. Aspect codes: "0"=Flat or bottomlands, "1"= SW, "2"=S or W, "3"=NW or SE, "4"=E or N, "5"=NE. (Modified from Kessell 1979).

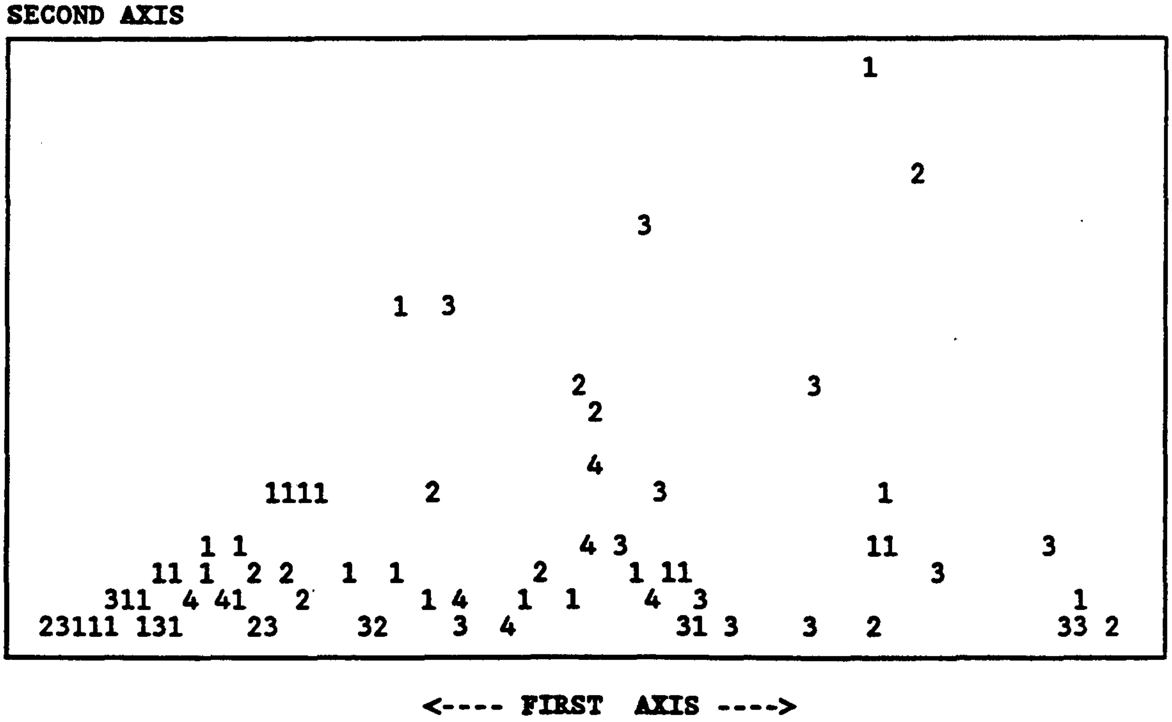

FIGURE 4: Overlay of physiographic classes on Bray-Curtis ordination. Class codes (1-4) indicate the moisture condition of the site. The higher the number, the wetter the site. See Table 4 for details.

There was no significant difference between the regeneration ba/ha of the different aspects (F=0.36, p=0.88). However, there were significant differences (F=3.45, p=0.01) between remnant-tree densities of the different aspects (Table 6). This may be due to different growing conditions or different disturbance regimes on the different aspects.

TABLE 6: Mean remnant-tree densities by aspect.

Aspect	Flat bottomlands	SW	W or S	SE or NW	N or E	NE
Mean Remnant-Tree Density	9.17	15.04	8.48	16.38	32.87	18.23
Number of Plots	4	31	32	21	33	11

The potential existed for greater growth in the warmer forests of the Umpqua and Willamette National Forests than on the Gifford Pinchot, but there was no significant among-National-Forest difference in regeneration ba/ha (ANOVA: Main effects (National Forest) F=105.36, p=0.29 with remnant density as a covariate). Regeneration ba/ha was slightly lower on the Willamette National Forest, but this was related to the fact that the Willamette had the highest mean remnant density of any National Forest (Table 7). Elevation was also unrelated to regeneration ba/ha (R^2=0.01).

TABLE 7: Mean remnant and regeneration densities by National Forest.

National Forest	Mean Remnant Density (Trees/ha)	Mean Regeneration ba/ha (meters^2/ha)
Gifford Pinchot	8.82	57.84
Willamette	24.13	43.06
Umpqua	6.96	52.85

These results indicate that were no apparent differences between the regeneration growth of the different physiographic classes, aspects, and National Forests, thus, all analyses were conducted across all stands rather than within groups of stands. Comparing stands with different site growth potentials may have added some "noise" to analyses, but the large sample size increases the probability of extracting meaningful patterns from the data.

Stand-Level Responses

Community Composition

A shade gradient was apparently the main trend in the data, as plots were ordered from high relative abundance of relatively shade-intolerant Douglas-fir to high relative abundance of relatively shade-tolerant western hemlock on the first axis of the ordination graph (TABLE 8). Remnant density was positively correlated with the first axis, and thus negatively correlated with shade-intolerant species in the regeneration. Elevation was a minor trend in the data, as shown by the positive correlations of the second axis to elevation and Pacific silver fir (Abies amabilis (Dougl.) Forbes), a high-elevation tree relative to this data set. The third axis was strongly correlated with western redcedar abundance. Interestingly, while producing nearly the same first axis, Principal Components Analysis (with relativized data) gave much more importance to minor species in the second axis. For example, incense cedar and madrone were both negatively correlated with axis two. This appears to reflect a moisture gradient, as these species tend to grow on drier sites in the western Cascades (Franklin and Dyrness 1973).

TABLE 8: Pearson correlations with ordination axes. Species names from Hitchcock and Cronquist (1973). N=127 Stands.

AXIS (Variance Explained)	1 (83.03)		2 (5.26)		3 (5.96)	
Species	R	R^2	R	R^2	R	R^2
Abies amabilis	-.982	.963	-.433	.188	-.275	.076
Abies concolor	-.037	.001	.073	.005	.128	.016
Abies grandis	-.037	.001	.140	.019	-.013	.000
Abies procera	-.042	.002	.113	.013	.069	.005
Acer macrophyllum	.155	.024	-.001	.000	-.008	.000
Alnus rubra	.276	.076	.913	.834	-.108	.012
Arbutus menziesii	.136	.018	.342	.117	.079	.006
Calocedrus decurrens	.025	.001	.264	.070	-.015	.000
Castanopsis chrysophylla	.961	.923	.102	.010	-.053	.003
Picea engelmannii	.224	.050	.067	.005	.194	.038
Pinus lambertiana	.034	.001	.126	.016	.170	.029
Pinus monticola	.423	.179	.094	.009	.912	.831
Pseudotsuga menziesii	-.036	.001	-.025	.001	.001	.000
Populus trichocarpa	.001	.000	.082	.007	.035	.001
Taxus brevifolia	-.008	.000	.064	.004	.208	.043
Thuja plicata	-.070	.005	.009	.000	-.021	.000
Tsuga heterophylla	-.047	.002	.040	.002	.095	.009
Tsuga mertensiana	-.073	.005	.071	.005	.041	.002
Remnant Density	.669	.448	.189	.036	.223	.050
Elevation	.121	.015	.362	.131	.015	.000

There were two clear groups in the data (Cluster Analysis), apparently based on the ratio of Douglas-fir to western hemlock (in species space) and remnant density (environmental space). These groups significantly differed in terms of remnant density (MRPP: p=0.00). Group one contained plots with relatively little Douglas-fir in the regeneration and high remnant density, while group two had high amounts of Douglas-fir, little or no western hemlock, and for the most part, low remnant densities (Figure 5). Removing the high-density remnant stands (RD $\geq$ 45 trees/ha) did not change these groupings.

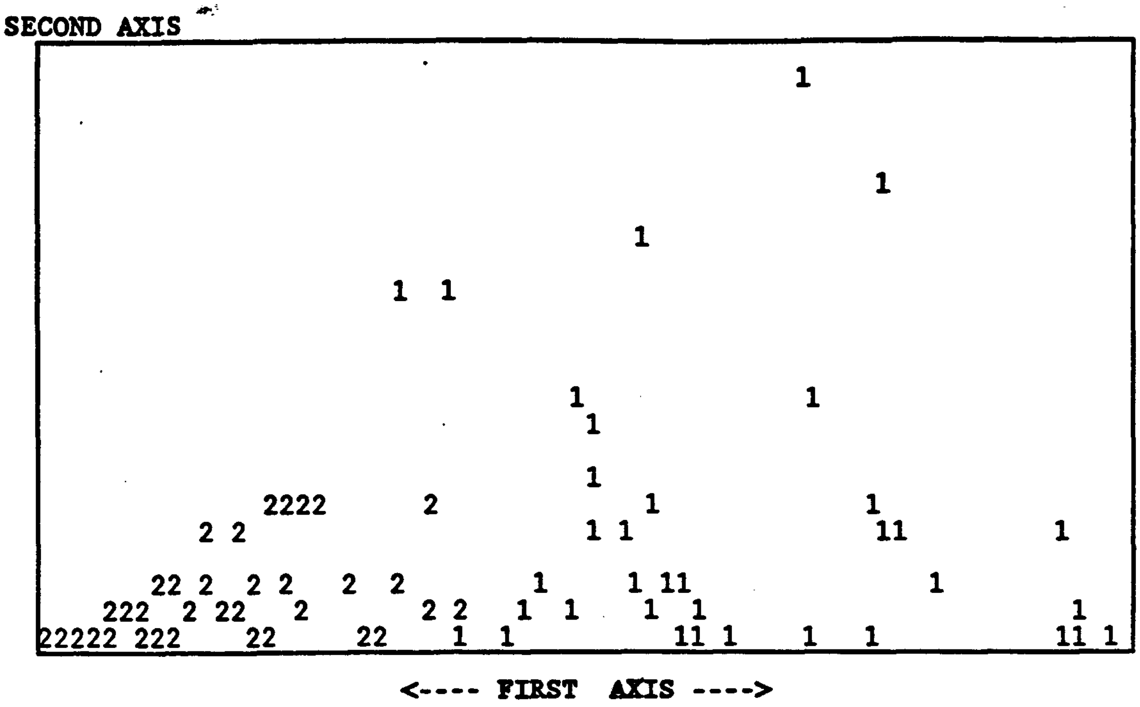

FIGURE 5: Overlay of groups formed by cluster analysis on Bray-Curtis ordination."1"= cluster one, "2"= cluster two.

To investigate the biological basis for the differences between clusters, I regressed the Douglas-fir proportion (Douglas-fir ba/ha in the regeneration divided by western hemlock ba/ha+Douglas-fir ba/ha in the regeneration) against remnant density (Figure 6). (Note that this is not the proportion of Douglas-fir in the regeneration across all species, but only across Douglas-fir and western hemlock). Based on preliminary calculations, I suspected that the cluster groups were based on different amounts of Douglas-fir relative to western hemlock, the two species that dominate every stand. In fact, stands in cluster group two tend to have a higher mean proportion of Douglas-fir than stands in cluster group one. The Douglas-fir proportion declines as remnant density increases ($R^2 = 0.46$, Douglas-fir proportion data arcsine-square root transformed) (Figure 6, Table 9).

TABLE 9: Regression equations and R^2 values for the relationship between Douglas-fir proportion (with arcsine square-root transformation) and remnant-tree density (live and dead salvable remnants). Y=arcsine square-root Douglas-fir proportion, X=remnant tree density.

Regression Equations	Remnant Density(Trees/ha)	R^2
Y=0.91 - 0.02X	$\le$45	0.42
Y=0.87 - 0.01X	All	0.46

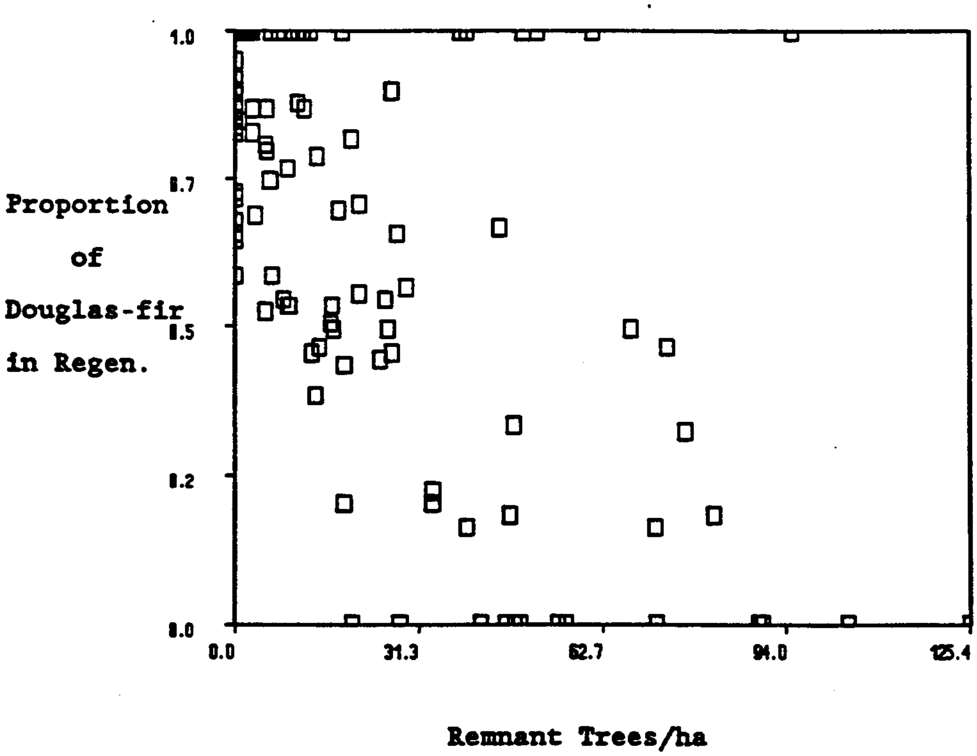

FIGURE 6: Douglas-fir proportion in the regeneration vs. remnant-tree density. Untransformed data, salvable live and dead remnant trees.

Regeneration Ba/ha vs. Remnant-Tree Density

Regeneration ba/ha declined with remnant density, whether or not salvable and/or nonsalvable dead remnants were included (Table 10). The overall trend was a apparently a negative exponential relationship between the regeneration and remnant density, with a relatively large variance in the regeneration ba/ha for most remnant densities (Figure 7). However, closer examination of the curve reveals a sigmoidal curve (Figure 8), indicating that regeneration growth does not significantly decline until remnant-tree densities above about 15 remnants/ha are reached. The overall trend of the data was expected, as remnants usurp increasing amounts of water, nutrients, and sunlight with increasing density. While conifers do not greatly extend their branches into gaps like some trees at lower latitudes, a conifer growing in a forest opening will not self prune its lower branches like a tree growing in a clump of trees. Consequently, a denser crown will result when conifers grow in the open, and because shade is cast at an angle, the tree growing by itself will cast more shade than a comparable tree growing in a clump (Oliver and Larson 1990). This may help to explain why each additional remnant appears to have more effect on the regeneration growth at moderate remnant densities (ie 15-45 remnants/ha) than at high densities, resulting in a sigmoidal rather than linear relation. Apparently, remnants do not cast enough shade to impact regeneration growth at the stand level at remnant-tree densities below about 15 remnants/ha.

TABLE 10: Regression equations and R^2 values for relationships between regeneration ba/ha (Y) and remnant-tree density or remnant ba/ha (X). All remnant densities, dependent variable square-root transformed in each case.

Type of Remnants	Regression Equation	R^2
Live Remnants Only (Density)	Y=7.52-0.05X	0.50
Salvable, Live and Dead (Density)	Y=7.55-0.05X	0.51
Salvable, Live and Dead +Nonsalvable $\geq$ 60cm dbh (Density)	Y=7.64-0.04X	0.42
Salvable, Live and Dead (Ba/ha)	Y=7.52-0.05X	0.52

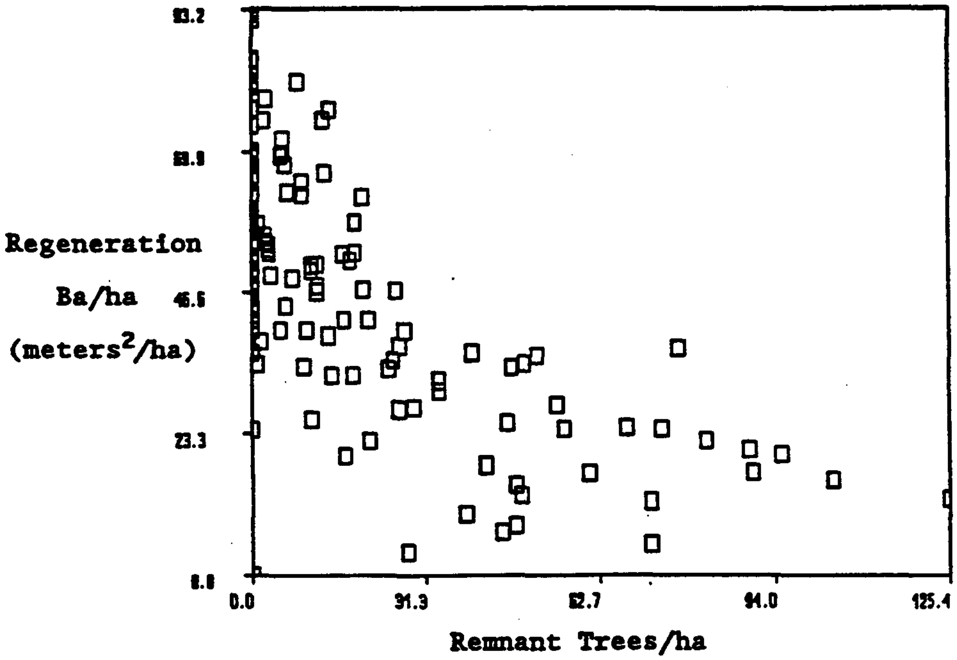

FIGURE 7: Regeneration ba/ha vs. remnant-tree density (all remnant densities). Salvable live and dead remnants, untransformed data.

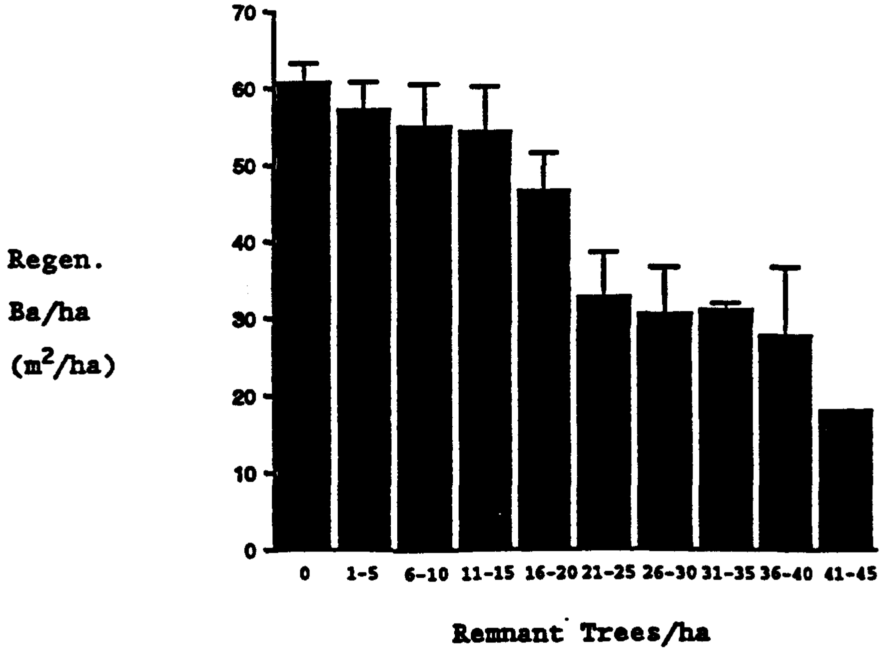

FIGURE 8: Regeneration ba/ha vs. remnant-tree density ($\leq$45 remnant trees/ha). Salvable live and dead remnants, untransformed data.

I had hypothesized that density of all salvable remnants (live and dead) would be more strongly related to regeneration ba/ha than would the density of live remnants alone, assuming that salvable snags were living for much of the time since the regeneration-initiating disturbance. However, there was little difference between these relationships (Table 10). There was an average of 6 salvable snags on 39 stands, and the number of snags ranged from one to 26 per stand. This compares with the 6 snags/ha (all decay classes, over 50-cm DBH) that Spies et al. (1988) found in old-growth stands in the Oregon Cascades. The number of salvable snags is generally small enough to have little influence on the regeneration when compared to the much larger number of remnants that are still living. Out of the 132 stands, 61 had nonsalvable snags over 60-cm DBH. In several cases, there are nonsalvable snags without any salvable live or dead remnants. When these nonsalvable snags are added to the total number of remnants, R^2 for the relationship between remnant density and regeneration ba/ha drops from 0.51 to 0.42 (Table 10). I suspect that the remnant/regeneration relationship weakens with the addition of nonsalvable snags because these snags have been dead for decades and thus had minimal impact on the growth of the regeneration. The maximum age of the regeneration is generally 110 years and decaying snags may last over 125 years (Spies et al. 1988), thus many nonsalvable snags probably predate the regeneration. Because of this fact, henceforth "remnant density" includes only salvable, live and dead remnant trees.

Several factors add "noise" to the relationship of the regeneration to remnants. First, what appears to be open space available to the regeneration actually may be influenced by remnant effects below the soil surface. Remnants may expand their roots following a disturbance into areas vacated by killed trees (Oliver and Larson 1990). Second, especially at our temperate latitudes, trees do not shade directly beneath their crowns because the sun is always to the south. Trees cast shadows to the north, east, and west, an effect that becomes increasingly important in the period from late fall to early spring (Oliver and Larson 1990). Thus, the regeneration on the south side of a stand may actually be shaded by large trees adjacent to the stand on the south. Finally, it is possible for different numbers of remnants to cast the same areal extent of shade, depending on their spacing and distribution.

The fact that there are clear relationships between remnant density (or ba/ha) and regeneration growth 70-110 years following disturbance, despite these confounding factors, shows the strength of the relationship between remnant trees and the regeneration. Up to 52% of the variance in regeneration ba/ha was apparently explained by remnant density or remnant ba/ha. To determine if other structural features of the forest help to explain any more of this variance, I added several other variables to the regeneration ba/ha vs. remnant density regression equation.

Other Factors Related to Regeneration Growth

No factor other than remnant density was significantly related (increased R^2 by more than 0.05) to the regeneration ba/ha when added to the regression equation in a stepwise manner after remnant density, whether the variables were untransformed, or log (base 10), square-root, or angular transformed (the last in the case of Douglas-fir proportion in the regeneration).

The Douglas-fir proportion in the regeneration (with angular transformation) added little to the regression equation, probably because Douglas-fir proportion (with angular transformation) was highly correlated with remnant density ($R=-0.68$). Thus, once remnant density was entered into the regression equation, little additional explanatory power remained for the Douglas-fir proportion. It has been noted in the literature that mixed stands of Douglas-fir and western hemlock may produce more wood than pure stands of either species, and that western hemlock consistently out-yields Douglas-fir on comparable sites (Richen 1976, Wierman and Oliver 1979). However, these studies for the most part address even-aged stands, not the two-aged stands that are of interest here. In this study, stands with pure Douglas-fir regeneration had higher ba/ha than any other stands (Figure 9), but most pure Douglas-fir stands also had no remnant trees, making it impossible to separate effects of species mix in the regeneration from those of remnant density.

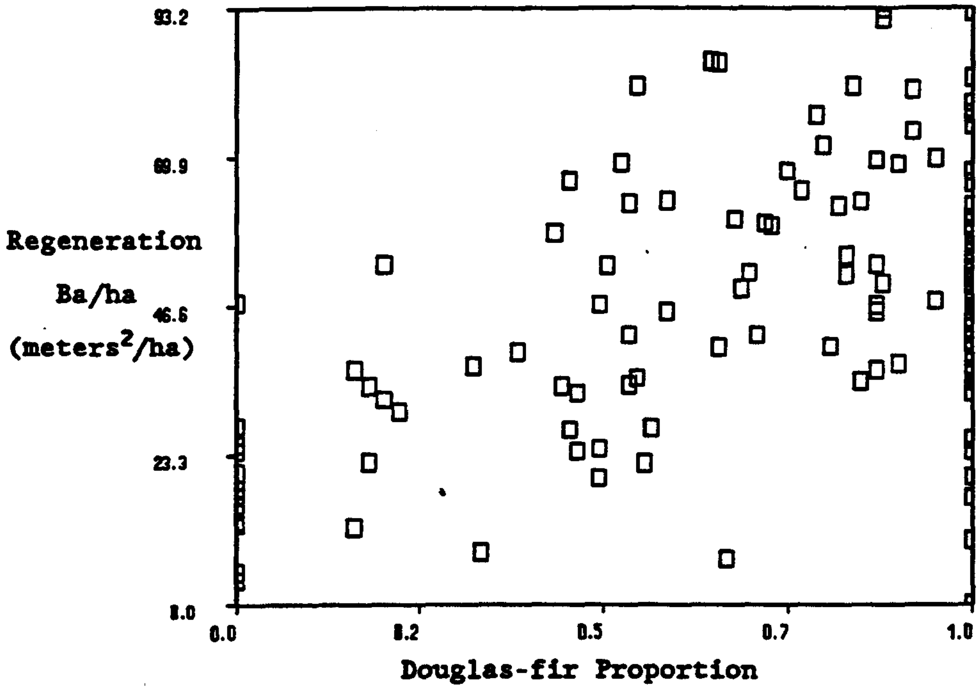

Figure 9: Regeneration ba/ha (untransformed) vs. Douglas-fir proportion in the regeneration (arcsine square-root transformation).

I had anticipated that given the same numbers of remnants, regeneration ba/ha would be greater when remnants were highly clumped than when they were scattered, because shade and other remnant effects would be more concentrated near the clump of remnant trees. However, the degree of remnant aggregation apparently had no relation to the growth of the regeneration (R^2 increased by 0.04 when aggregation index was added into regression equation after remnant-tree density). These results must be interpreted cautiously, however, because this data set contained few stands with a clump of several trees (ie five or more) remnants on one small section of the plot and no remnants on the remainder of the plot, as could occur under a management scenario. No stands resembled the prescription outlined for the matrix in FEMAT's Preferred Alternative (1993a), in which at least one-half of the green trees retained after harvest must be in intact late-successional stands of 0.2-1.6 ha (0.5-4 ac). In most cases, stands with higher aggregation indices had several trees on one or more points in the plot, but also a scattering of remnants on the remainder of the plot. These scattered remnants may have had suppressive effects on the regeneration that obscured any differences between stands with relatively clumped remnants and stands with completely scattered remnants.

Because mean ages of the regeneration differed somewhat among stands (minimum mean age class of the regeneration: 70-79 years, maximum: 120-129 years, mean: 90-99 years), it seemed that there could have been relationships between mean age of regeneration and regeneration ba/ha that potentially confounded interpretation of remnant effects. However, there was no relationship between mean regeneration age and growth (R^2=0.01). Consequently, age of the regeneration does not appear to account for any of the "noise" in the relationship of regeneration ba/ha to remnant density.

Adjusted Regeneration Ba/ha vs. Remnant-Tree Density

As discussed earlier (see Stand-Level Analyses in METHODS) the adjusted regeneration ba/ha attempts to eliminate conceptually the space occupied by remnants on each stand to allow clarification of remnant effects beyond those attributable to space occupancy. This adjustment probably overestimates the proportion of a stand unavailable for the regeneration because the mean old growth density probably does not represent the highest potential level of stocking in these stands. Therefore, regeneration ba/ha values may have been adjusted upward too high, overestimating remnant space effects and possibly losing biological meaning, particularly at the highest remnant densities. When comparing Figure 10 with Figure 11 it appears that the adjusted regeneration ba/ha values are little different from unadjusted values at management-level densities (0-45 remnant trees/ha). However, the fit of the regression line for regeneration ba/ha vs. remnant-tree density declined markedly when the regeneration ba/ha was adjusted to remove the effect of remnant space occupancy (Table 11). While the space-occupancy effect may be overestimated, these results indicate that at management-level remnant densities, the strength of the linear relationship between regeneration ba/ha and remnant density is reduced after accounting for space occupancy by remnants.

TABLE 11: Regression equations for adjusted regeneration ba/ha (X) vs. remnant-tree density (Y) and unadjusted regeneration ba/ha (X) vs. remnant-tree density (Y). Live and dead salvable remnants, only plots with densities $\leq$ 45 remnant trees/ha included in analyses.

Dependent Variable (Square-root Transformed)	Regression Equations	R^2
Adj. regeneration ba/ha	$Y=7.78-0.05X$	0.18
Regeneration ba/ha	$Y=7.77-0.07X$	0.34

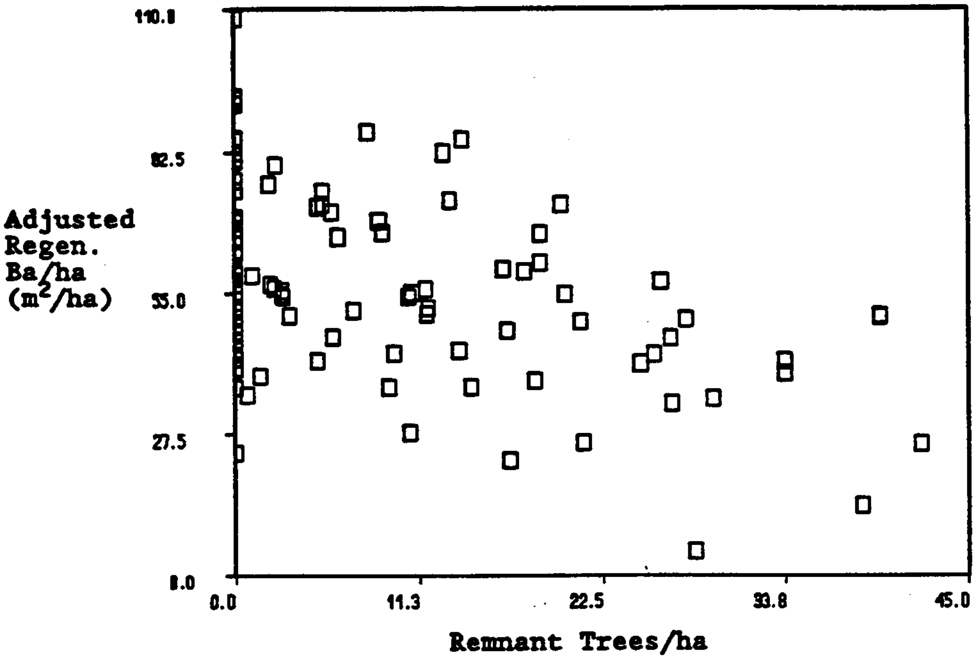

FIGURE 10: Adjusted regeneration ba/ha vs. remnant-tree density (≤45 remnant trees/ha). Salvable live and dead remnants, untransformed data.

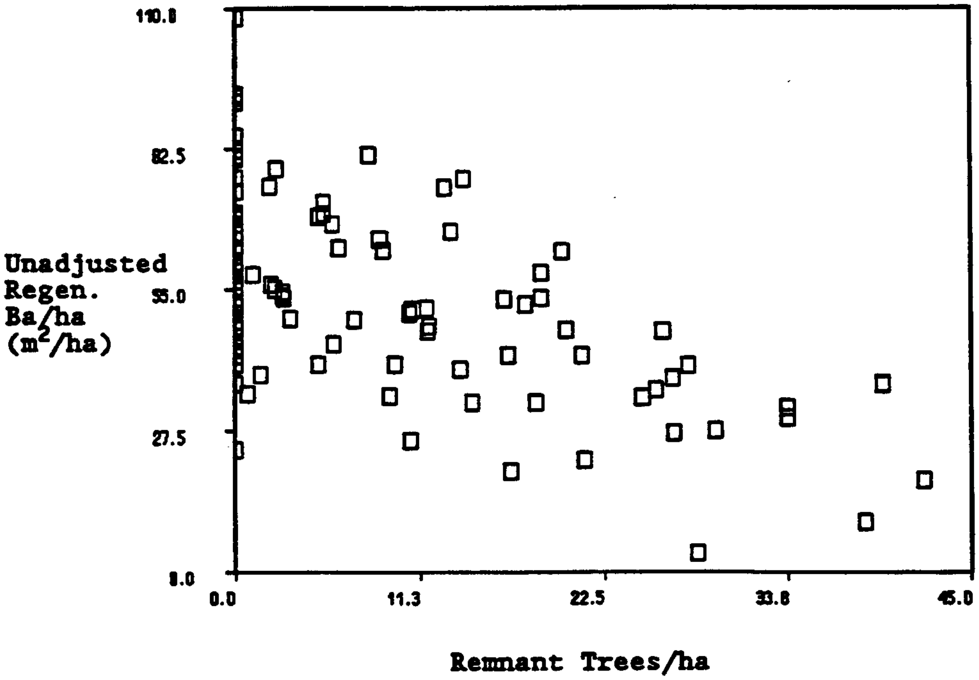

FIGURE 11: Unadjusted regeneration ba/ha vs. remnant-tree density (≤45 remnant trees/ha). Salvable live and dead remnants, untransformed data.

Another way to test the influence on regeneration ba/ha of space freed after disturbance is to regress the percentage of old growth remaining (remnant density divided by mean old growth density) against regeneration ba/ha (unadjusted). The result is almost exactly the same as the relationship of regeneration ba/ha to remnant-tree density, as expected (R^2=0.50, Y=7.52-0.71X, regeneration ba/ha square-root transformed, all remnant-tree densities). The FEMAT Preferred Alternative Plan calls for leaving at least 15% of the volume of a stand after harvest on most unreserved National Forests of the Pacific Northwest (FEMAT 1993a). I have no way of knowing the true proportion of volume or basal area that remained on each of the study stands after disturbance, however estimates for stands in this data set ranged from 0 to 71% of remnant-tree density left after the regenerating-initiating disturbance. These results provide an indication of the productivity of the regeneration when different percentages of an old growth forest are left standing, and suggest that regeneration ba/ha declines with increasing remnant-tree ba/ha in a negative-exponential relationship (Figure 7 closely approximates this curve).

Total Stand Ba/ha vs. Remnant-Tree Density

Thus far, all discussion has been limited to how leaving various numbers of remnant trees is related to the regeneration. Another interesting question is if there is any relationship between remnant density and the total ba/ha of stands, including both regeneration and the remnants. With an R^2 value of 0.13 for the regression (untransformed), I concluded that there was no interpretable relationship between the total ba/ha of a stand and remnant density (salvable live and dead remnants). This result corresponds to the concept that a site can sustain a certain ba/ha, whether this wood is in remnants, regeneration, or a combination of both. For most remnant densities, the mean total ba/ha is higher than the mean adjusted regeneration ba/ha (Figure 12). If space occupancy were the only remnant effect, adjusted regeneration ba/ha would be closer to the total ba/ha for all remnant densities, because conceptually removing remnants from a stand would allow the regeneration to fully occupy the site. Instead, the adjusted regeneration ba/ha is less than the total ba/ha, indicating that there are other suppressive remnant effects besides space occupancy.

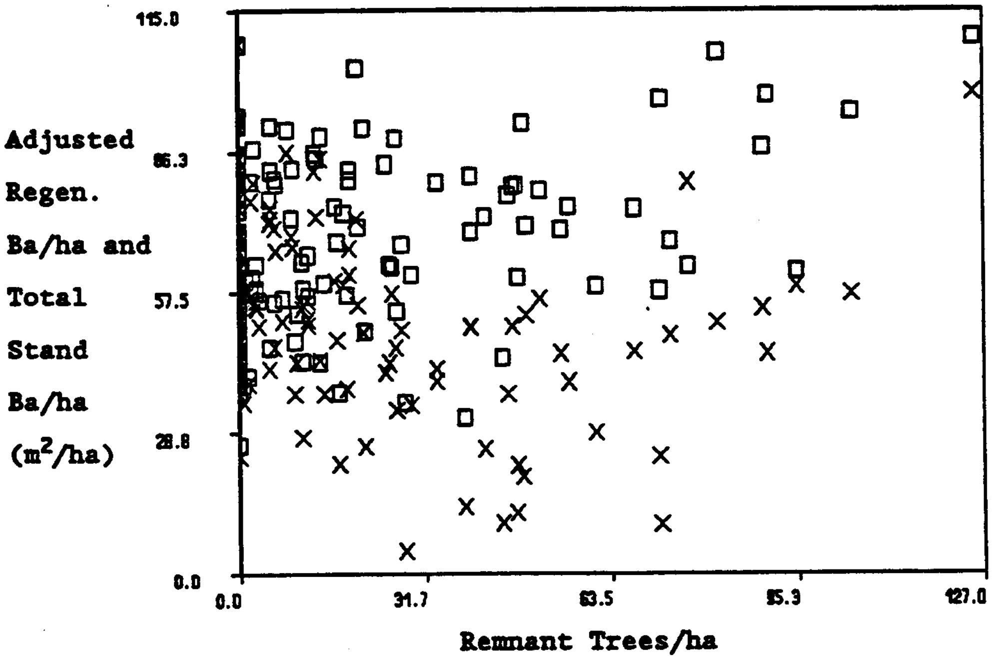

FIGURE 12: Adjusted regeneration ba/ha and total stand ba/ha vs. remnant-tree density. Variables untransformed, Square=total stand ba/ha, X=adj. regeneration ba/ha.

Douglas-fir Ba/ha vs.Remnant-Tree Density

As the most valuable lumber-producing tree in the Pacific Northwest, the impact of leaving large live trees after timber harvest on Douglas-fir production is of great interest to managers. I looked at the Douglas-fir regeneration ba/ha vs. remnant-tree density relationship in several ways but I came to the same conclusion in all cases: There was a marked decrease in Douglas-fir regeneration ba/ha above remnant densities of approximately 15 remnant trees/ha (6 trees/ac) (Figures 13 and 14).

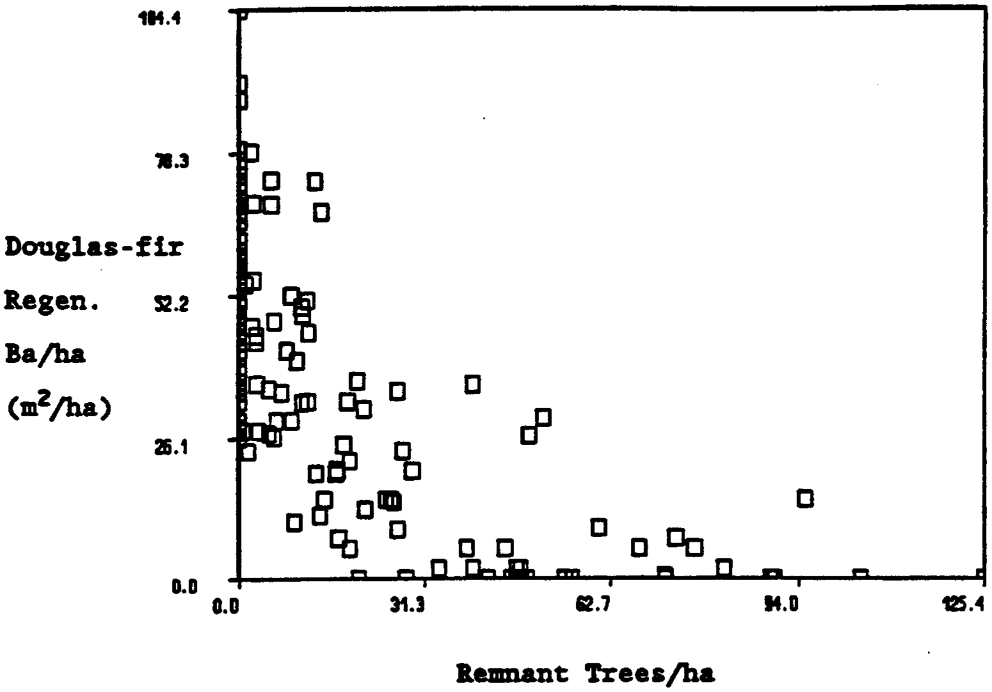

FIGURE 13: Douglas-fir regeneration ba/ha vs. remnant-tree density (live and dead salvable remnants, all remnant-tree densities). Untransformed data.

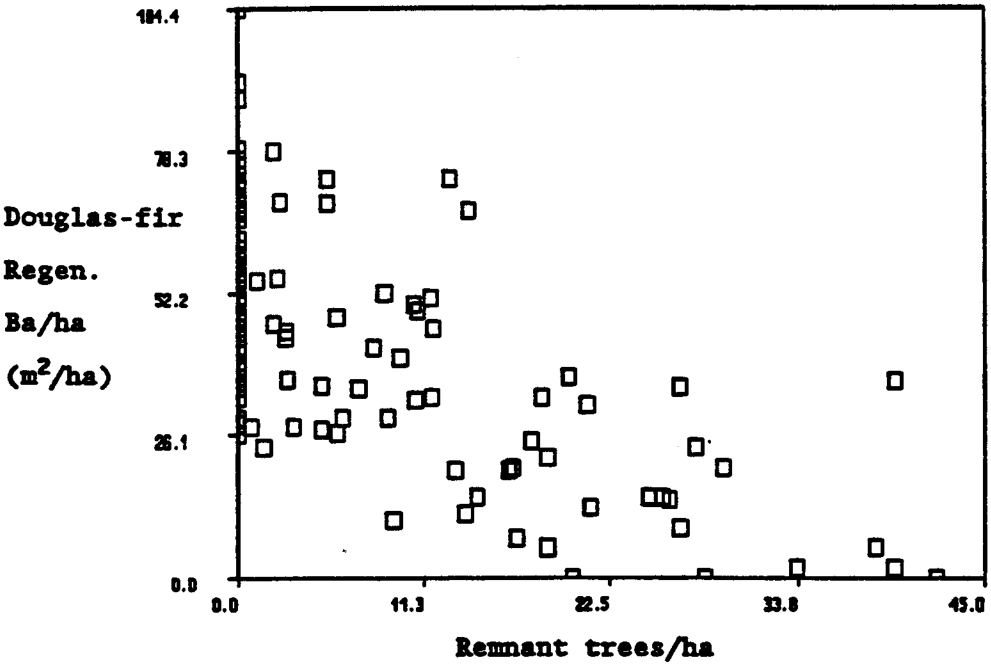

FIGURE 14: Douglas-fir regeneration ba/ha vs. remnant-tree density (live and dead salvable remnants, ≤45 remnant trees/ha). Untransformed data.

TABLE 12: Regression equations and R^2 values for the relationship between Douglas-fir ba/ha (square-root transformed) and remnant-tree density (live and dead salvable remnants).

Remnant Densities	Regression Equations	R^2
All	$Y=6.83-0.08X$	0.60
≤ 45 trees/ha	$Y=7.29-0.14X$	0.55

Remnant density apparently explained 60% of the variation in the Douglas-fir ba/ha (Table 12). There were fewer stands with remnant densities between about 12 and 18 trees per hectare than for other densities, somewhat confusing interpretation. However, Douglas-fir regeneration ba/ha was consistently above 25 m^2/ha (except in the case of one plot) until remnant-tree densities exceeded 12 trees/ha.

There was clearly a strong relationship between the amount of Douglas-fir in a stand and the number of remnant trees. However, the spatial distribution of remnants as reflected in the aggregation index apparently had no relationship to Douglas-fir regeneration ba/ha. Aggregation index added only 0.04 to the R^2 value of the Douglas-fir regeneration ba/ha vs. remnant density relationship. As was the case for regeneration across all species, no tested factor other than remnant density (eg elevation, mean age class of the regeneration) was related to Douglas-fir regeneration ba/ha (highest $R^2=0.05$). There was a significantly lower mean Douglas-fir regeneration ba/ha on the Willamette National Forest than on the Umpqua or the Gifford Pinchot, but this is because of the much higher mean remnant density on the Willamette (see Table 7).

Douglas-fir often regenerates naturally after fire because its seeds need mineral soil or a light litter layer on which to germinate (Hermann and Lavender 1990). Under the canopy of remnants, litter would be restored quickly after a fire, potentially inhibiting Douglas-fir reproduction. However, light is probably the main inhibitor of Douglas-fir regeneration under remnants. First-year seedlings survive and grow best under light shade, but older seedlings require nearly full sunlight, indicating an intermediate shade tolerance (Hermann and Lavender 1990). The decrease in Douglas-fir regeneration ba/ha shown here may be a result of shading by remnants. Above about 15 remnant trees/ha, there may often not be enough light for most seedlings to survive past the seedling stage.

Other Species vs. Remnant Density

I expected a positive relationship between abundance of shade-tolerant species and remnant density. I also assumed that as the proportion of Douglas-fir in the regeneration decreased, the proportion of the shade-tolerant species would increase. However, western hemlock ba/ha increased only slightly with increasing salvable (live and dead) remnant density (R^2=0.16, square-root transformation of both western hemlock ba/ha and remnant density to increase homogeneity of variances) (Figure 15). The addition of nonsalvable snags to remnant density lowered the R^2 values for relationships of Douglas-fir regeneration and regeneration across all species to remnant density. However, the R^2 for the regression of western hemlock regeneration ba/ha on remnant density increased slightly (R^2=0.19) with the addition of nonsalvable snags, probably because of western hemlock's tendency to establish on rotting wood. There were many plots with small amounts of western hemlock ba/ha (Figure 15), but only a few plots with relatively high amounts of western hemlock, creating a skewed distribution of western hemlock ba/ha across stands. Hence, parametric statistics involving western hemlock should be interpreted with caution.

There was some evidence of western hemlock replacing Douglas-fir in the regeneration as remnant density increased (correlation: R= -0.45 between Douglas-fir regeneration ba/ha and western hemlock regeneration ba/ha). However, as Douglas-fir regeneration ba/ha decreased, the ba/ha of the entire regeneration decreased as well (R=0.87 for correlation of

Douglas-fir regeneration ba/ha with regeneration ba/ha across species).

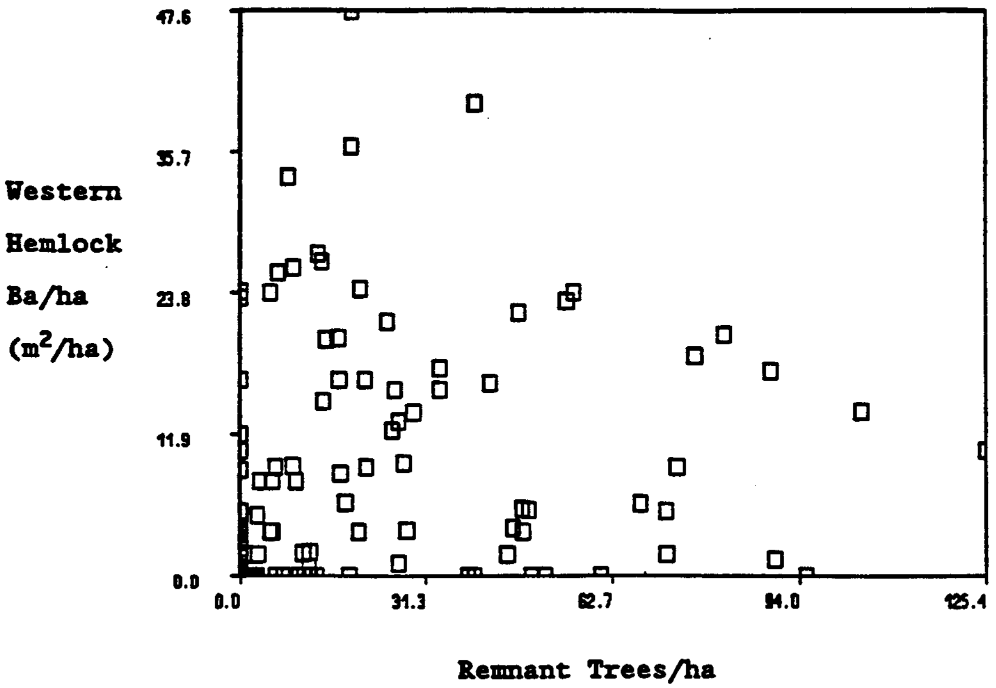

FIGURE 15: Western hemlock regeneration ba/ha vs. remnant-tree density (live and dead salvable remnants). Untransformed data.

Most of the remnants in this study were Douglas-fir; there were few old-growth western hemlock trees indicative of Franklin's and Dyrness's (1973) climax state that is more common further north in Washington (Scott et al. 1976). Disturbance may be too frequent in the Cascades of Oregon and SW Washington to allow extensive old growth western hemlock development. The regeneration in most study stands appeared too young to be dominated by hemlock growth, except where the stand was only lightly disturbed. However, judging from the seedlings and young saplings (trees <19 years old), the future belongs to western hemlock in these stands. The ratio of western hemlock seedling and sapling ba/ha to Douglas-fir seedling and sapling ba/ha across all stands was about 9000:1, while the western redcedar to Douglas-fir ratio was about 30:1.

The western redcedar abundance is probably too small to obtain close to a normal distribution of ba/ha values across stands. Forty-three out of 132 stands (33%) contained western redcedar with a mean ba/ha of 5.87 m^2/ha on those 43 stands. I can reach no conclusions about the relationship between western redcedar ba/ha and remnant density other than to say that there appears to be little relationship in the age classes and forests I studied.

Western hemlock reproduction is overwhelmingly dominant beneath canopies (Scott et al. 1976). Young western redcedar often sunburn severely when foliage is exposed to the direct sun (Minore 1983). For these reasons, I expected western hemlock and western redcedar to be nearly absent, except as seedlings (most of which will not survive), from stands with zero to low remnant densities. While this is true for the most part, there were zero to low remnant-density stands with western hemlock and western redcedar in the same age class as associated Douglas-fir, implying that all established when the stand was opened by disturbance. In such cases, brush or downed woody debris may have have provided microsites where wester redcedar and western hemlock could grow, even on a plot otherwise better suited for Douglas-fir. Looking at the regeneration across all stands, the mean age class for Douglas-fir was 90-99 years, while the mean age class for western hemlock and western redcedar was 80-89 years (excluding seedlings and young saplings for all species). Thus, it appears that Douglas-fir tended to be older in the regeneration, indicating that it was probably the first species to establish after disturbance. When seedlings and saplings were included, the mean age class for Douglas-fir remained 90-99 years, but mean age classes for western hemlock and western redcedar dropped to 70-79 and 50-59 respectively, reflecting the great number of seedlings of these species.

Western hemlock growth is probably more influenced by shade and moisture depletion caused by other western hemlocks and by faster-growing Douglas-fir in the regeneration than by remnant density. In even-aged stands ranging from 35 to 80 years of age in western Washington, western hemlocks were unable to exist beneath other western hemlocks but survived under Douglas-fir crowns, and a hemlock was rarely able to outgrow and over-top Douglas-fir when both species were the same age (Wierman and Oliver 1979). Thus, Douglas-fir and western hemlock did not segregate into crown classes because of age differences either between or within species, but because of faster Douglas-fir growth (Wierman and Oliver 1979). In summary, the small increase in western hemlock regeneration ba/ha with increasing remnant density was probably a result of the higher remnant densities causing lower Douglas-fir regeneration ba/ha, and hence reduced competition for light and moisture with Douglas-fir in the regeneration.

Diversity and Remnant-Tree Density

There was no interpretable relationship of either species richness or Shannon diversity index of trees in the regeneration to remnant density (R^2=0.01 and 0.07, respectively, neither variable transformed). The Shannon diversity index ranged from 0 to 1.50 across plots, and there were 32 stands with 0 remnants and Shannon diversity index ≤ 0.375, reflecting the relatively large number of stands with only Douglas-fir. Removing stands with no remnants did not change the regression equation significantly (R^2=0.02, untransformed); there was still a range of diversities across remnant densities. I had expected that diversity would be highest at relatively low (but nonzero) to medium remnant densities, because of the potential for a variety of microclimates under canopies, canopy edges, and full sun. The relationship of species diversity to remnant density would be better tested if herb and shrub species were included. However, with a maximum of seven tree species on a plot, and typically only three or four, diversity cannot vary much between stands. The slight among-stand differences in species richness and diversity were probably the result of different environmental conditions between plots largely unrelated to remnant density.

Individual-Tree-Level Responses

Growth rates of individual trees were only weakly related to remnant-tree density as shown in the relationships between the mean residuals (from the regeneration ba/ha vs. regeneration age regressions) and remnant density. At management-level remnant-tree densities (≤ 45 remnant trees/ha), R^2 equalled 0.17 for the regression of the western redcedar residuals (from western redcedar regeneration ba/ha vs. age regression) against remnant-tree density (untransformed data). The same procedure using Douglas-fir regeneration at management-level densities produced an R^2 of 0.11, while the maximum R^2=0.05 for regressions using all remnant-tree densities. However, this attempt to look at regeneration responses at the individual-tree level was flawed by not considering stocking level within the regeneration. That is, the same mean residuals could result from wildly different numbers of remnant trees in the regeneration, and thus the information is useless from a management perspective, where a stand's merchantable volume is of primary interest. Using the median residual has the same problem, and the mode is inappropriate because there are many modes in the data distribution.

I suspect that any method that attempts to infer remnant "effects" using average tree measurements in the regeneration will have the same problems. While larger trees may be more valuable than smaller ones, and in some cases time required to reach merchantable size may be of interest, a manager will probably be more interested in how remnants impact the amount of wood available for harvest in an entire stand. For these reasons, I used stand-level data only for the bulk of this study.

SUMMARY/CONCLUSIONS

The results presented here demonstrated a strong decline in the ba/ha of stands 70-110 years old as the number of remnant trees (over 200 years old) in the overstory increased above about 15 remnants/ha; most of this decline came from less Douglas-fir ba/ha on a stand at these remnant densities. The decline in regeneration ba/ha across all species and in Douglas-fir was probably a combined effect of shading (or other suppressive effects) by the overstory remnants and space occupancy by remnants (at least at management-level remnant-tree densities of ≤ 45 trees/ha). Western hemlock ba/ha increased slightly as remnant density increased, probably because of the corresponding decline in Douglas-fir. Western redcedar had no apparent relationship with remnant density. No significant relationship was found between any other stand feature and regeneration ba/ha, most notably in the cases of aggregation index and diversity. However, aspect may indirectly affect the regeneration by affecting the number of remnant trees on site.

Further research is needed to form generalizations about the relationship between green-tree retention and conifer growth throughout the region. However, the scope and sample size of this study should provide a reasonable prediction of effects of green-tree retention in the Pacific Northwest. The decline in Douglas-fir with increasing remnant density will probably be of most concern to managers who are charged with timber production, assuming that Douglas-fir continues to be the most valuable timber-species. However, these results indicate that about 15 large trees can be left on a site without a significant reduction in regeneration growth. In addition, total stand ba/ha remained fairly constant with increasing remnant density.

Creative silviculture might lessen the decrease in ba/ha of both Douglas-fir and regeneration across all species with increasing remnant densities. For example, planting Douglas-fir in the most open areas of a site harvested with green-tree retention and allowing natural hemlock regeneration in the shade may facilitate fuller use of available growing space and result in higher yields coupled with higher species diversity. Greater amounts of side shade from shorter hemlocks in the regeneration should keep Douglas-fir branches small and well-pruned, but allow crown expansion and larger diameter growth of the taller, faster-growing Douglas-fir (Wierman and Oliver 1979). Finally, a good mix of western hemlock, Douglas-fir, and other species may make stands more resistant to wind, insect, and disease damage than the near-monospecific stands that result from clearcutting (Wierman and Oliver 1979).

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APPENDIX

APPENDIX A

Species codes used in Appendix A:

011 Pacific silver fir (*Abies amablis*)
015 White fir (*Abies concolor*)
017 Grand fir (*Abies grandis*)
022 Noble fir (*Abies procera*)
081 Incense cedar (*Calocedrus decurrens*)
093 Englemann spruce (*Picea engelmannii*)
117 Sugar pine (*Pinus lambertiana*)
119 Western white pine (*Pinus monticola*)
202 Douglas-fir (*Pseudotsuga menziesii*)
231 Pacific yew (*Taxus brevifolia*)
242 Western red cedar (*Thuja plicata*)
263 Western hemlock (*Tsuga heterophylla*)
264 Mountain hemlock (*Tsuga mertensiana*)
312 Bigleaf maple (*Acer macrophyllum*)
351 Red alder (*Alnus rubra*)
361 Madrone (*Arbutus menziesii*)
431 Chinkapin (*Castanopsis chrysophylla*)
747 Black cottonwood (*Populus trichocarpa*)
920 Willow (*Salix* spp.)

Abbreviations:
NF: National Forest
RD: Remnant-tree density, salvable live and dead trees (trees/ha)
REGD: Regeneration density (trees/ha)
RBAPH: Regeneration basal area/hectare
PBAPH: Douglas-fir regeneration basal area (m^2)/hectare
TBAPH: Western hemlock regeneration basal area (m^2)/hectare
ASP: Aspect
ELEV: Elevation
SNAGS: Salvable (≥ 200 years old) and nonsalvable (≥ 60 cm dbh) snags/hectare
SPP: Species

PLOT	NF	RD	REGD	RBAPH	PBAPH	TBAPH	ASP	ELEV	SNAGS	SPP
1	WIL	104.47	76.25	15.60	0	13.77	N	1109	3.10	263 17
2	UMP	12.80	61.07	74.93	73.10	0	SW	832	0	117 202
3	UMP	0	61.14	52.37	39.51	0	N	1170	5.47	15 17 117 202 431
4	GIP	10.63	62.39	50.20	50.09	1.86	SW	986	23.67	011 202 242 263
5	GIP	0	68.43	84.88	60.46	23.43	NW	1109	0	202 242 263

PLOT	NF	RD	REGD	RBAPH	PBAPH	TBAPH	ASP	ELEV	SNAGS	SPP
6	GIP	0	57.27	92.57	90.91	0	W	832	4.60	202 312
7	GIP	10.83	28.06	50.95	48.77	0	SW	1109	28.60	011 022 202
8	GIP	0	40.61	47.20	47.20	0	NE	585	76.17	202
9	UMP	0	28.51	40.40	34.81	0	S	832	18.68	117 202 312 431
10	UMP	2.89	24.89	53.75	45.09	0	S	832	6.15	081 117 202
11	WIL	0	34.54	42.14	36.64	0	E	862	0	117 202 242
12	WIL	16.45	468.80	52.97	19.62	20.03	NW	862	14.59	119 202 242 263
13	WIL	0	18.32	36.68	34.84	1.83	NE	493	0	202 263
14	WIL	56.27	26.63	23.82	0	23.82	SE	955	16.05	242 263
15	UMP	0	47.59	76.94	75.78	0	SE	1170	51.01	119 202 431
16	WIL	0	63.85	62.36	51.37	0.26	N	1263	8.01	011 022 119 202 263
17	WIL	81.66	50.78	22.14	1.83	20.31	S	1078	4.68	011 202 242 263
18	WIL	5.98	28.14	67.78	47.63	9.16	E	1232	27.35	011 022 119 202 263
19	WIL	16.69	16.68	42.14	20.15	16.49	S	585	1.00	202 242 263 312

PLOT	NF	RD	REGD	RBAPH	PBAPH	TBAPH	ASP	ELEV	SNAGS	SPP
20	WIL	13.14	52.88	66.26	19.62	27.13	SW	955	1.32	117 202 242 263 264
21	WIL	67.47	37.93	24.17	5.50	6.00	N	1047	17.24	022 202 242 263
22	WIL	14.50	72.77	32.98	14.66	19.85	NW	616	0	202 242 263
23	WIL	0	33.34	47.46	46.95	0.51	W	832	3.53	202 263
24	UMP	49.15	63.07	34.78	26.45	0	N	708	0	015 081 117 202
25	WIL	11.79	27.25	47.74	45.50	0	W	1078	0	015 202
26	WIL	0	49.92	43.97	50.99	3.19	E	678	18.42	202 263
27	WIL	2.38	39.50	55.03	55.03	0	W	493	0	202 263 351
28	WIL	13.76	125.99	39.49	11.64	26.47	NE	739	13.81	202 263 242
29	WIL	21.16	73.62	42.14	31.57	16.53	SW	986	3.26	202 263 242
30	WIL	0	20.76	56.79	56.96	0	W	986	0	202 263 312 431
31	WIL	0	24.23	58.62	53.13	0	S	1047	0	017 022 081 202 263 431
32	WIL	0.77	52.84	34.81	27.48	1.83	S	924	0	017 119 202 231 242 263 431

PLOT	NF	RD	REGD	RBAPH	PBAPH	TBAPH	ASP	ELEV	SNAGS	SPP
33	WIL	2.17	16.04	55.96	46.65	0	N	862	16.04	015 119 202 431
34	WIL	18.37	25.31	32.98	32.98	0	SW	862	0	081 202 312 431 492
35	WIL	11.71	30.12	46.80	32.98	2.00	W	1016	0	022 202 242 263
36	WIL	46.11	43.08	24.97	0	4.05	SW	801	0	242 263
37	WIL	29.28	5.98	27.48	20.03	13.70	NW	554	11.41	202 263 312 431
38	WIL	5.11	15.60	40.30	35.14	3.73	NW	616	1.71	202 263 312
39	WIL	51.45	36.70	36.07	29.75	0	E	862	2.95	081 202 312 361
40	WIL	0	11.99	23.82	26.15	0	SW	893	0	202
41	WIL	0	22.02	36.64	38.19	0.60	E	832	0	202 263 312
42	WIL	0	27.45	67.68	67.78	0.67	SW	862	0	202 263
43	WIL	18.73	41.67	58.19	21.98	36.21	NE	1201	0	017 202 242 263
44	WIL	0	30.70	51.63	45.80	3.83	NW	924	0	011 119 202 242 263 312
45	WIL	16.91	27.89	19.63	7.33	8.57	E	678	23.44	202 242 263

PLOT	NF	RD	REGD	RBAPH	PBAPH	TBAPH	ASP	ELEV	SNAGS	SPP
46	WIL	0	15.12	80.61	78.78	1.83	S	1232	0	202 263
47	WIL	2.12	21.56	75.11	78.39	0	SE	1201	0	202
48	WIL	0	9.22	45.80	42.14	0	N	832	0	081 202 263
49	WIL	28.18	77.77	3.66	0	3.84	N	739	3.19	202 242 263
50	WIL	47.61	29.61	8.14	1.83	5.65	E	924	0	202 242 263
51	WIL	39.57	61.65	36.64	1.83	39.79	NE	832	0	202 242 263
52	WIL	0	64.08	69.62	65.95	3.66	W	1109	0	017 202 263 431
53	WIL	21.34	11.83	21.98	12.82	9.16	S	708	24.71	202 242 263
54	WIL	26.72	14.88	37.66	34.81	1.09	S	739	0	202 231 242 263
55	WIL	42.09	13.07	17.99	0	16.15	W	493	3.11	242 263
56	GIP	27.63	42.18	40.23	23.82	9.42	FLAT	585	64.47	011 202 242 263
57	UMP	0	33.60	54.96	54.97	0	W	678	21.36	202
58	WIL	2.50	52.21	78.59	68.95	0	E	1078	0	202 242
59	WIL	0	50.83	45.80	38.47	2.33	FLAT	862	8.33	242 263
60	GIP	90.02	64.01	16.82	0	1.36	NW	770	40.21	011 263
61	WIL	0	35.08	76.94	76.94	0	FLAT	893	0	202
62	WIL	0	10.65	58.62	58.62	0	SE	893	0	202

PLOT	NF	RD	REGD	RBAPH	PBAPH	TBAPH	ASP	ELEV	SNAGS	SPP
63	GIP	3.00	34.92	53.13	36.21	1.83	S	924	23.61	202 242 263 351
64	WIL	2.88	38.90	54.54	43.84	5.04	SW	832	4.85	202 242 263
65	WIL	24.84	35.64	34.02	14.69	21.36	SW	493	9.99	202 263 312
66	WIL	0	38.86	59.63	47.72	11.91	NE	986	9.60	202 263 431
67	WIL	18.73	31.31	53.13	5.50	47.63	NE	1016	26.28	202 263
68	UMP	0	37.64	45.87	29.31	16.49	NW	1232	38.16	015 202 263
69	UMP	0	62.99	50.37	50.37	0	NW	924	0	202
70	UMP	45.06	165.46	7.10	5.48	1.83	SW	1016	9.31	202 263 431
71	UMP	0	25.50	62.47	51.22	0	SW	739	0	015 081 117 202 431
72	UMP	1.10	94.52	57.96	54.40	0	NE	770	0	202 361
73	UMP	0	69.10	52.01	48.88	0	SE	893	26.84	015 081 117 202
74	UMP	0	47.45	47.72	50.97	0	W	708	5.78	202
75	GIP	1.56	9.89	38.47	23.82	0	SW	770	0	015 119 202
76	GIP	0	7.52	40.30	32.98	0	S	1078	0	015 202
77	GIP	11.64	19.90	51.30	51.30	0.67	W	647	2.40	015 202 263 312

PLOT	NF	RD	REGD	RBAPH	PBAPH	TBAPH	ASP	ELEV	SNAGS	SPP
78	WIL	19.99	43.87	62.29	36.64	3.66	SW	1263	0	081 202 242 263 431
79	WIL	9.80	25.88	40.30	40.30	0	SW	801	7.84	081 202
80	WIL	73.65	38.48	23.82	7.33	9.16	E	1016	11.62	117 202 242 263
81	UMP	0	125.18	56.64	51.68	0	W	1232	7.00	015 202 431
82	WIL	89.34	49.94	20.56	0	17.24	N	832	0	242 263
83	WIL	60.87	49.85	16.61	9.28	0	SW	955	0	202 231 242 431
84	GIP	10.74	8.69	25.65	32.54	0	NE	493	12.11	202
85	UMP	0	82.31	81.19	72.90	5.44	SW	770	38.29	202 242 263
86	WIL	47.71	10.15	14.66	0	3.66	N	924	0	242 263 312
87	UMP	7.32	103.17	48.98	34.58	0	S	647	2.68	081 202 361
88	WIL	33.74	21.36	31.95	1.83	17.48	SW	986	9.76	015 081 117 202 242 263 264
89	WIL	71.78	126.22	11.97	0.34	5.44	NE	832	0	081 202 242 263
90	GIP	0	46.12	91.60	87.94	3.66	SE	770	4.60	202 263

PLOT	NF	RD	REGD	RBAPH	PBAPH	TBAPH	ASP	ELEV	SNAGS	SPP
91	WIL	38.47	46.12	9.91	5.67	0	SW	708	0	017 081 202 312 361
92	WIL	33.74	18.70	30.12	1.83	15.65	SW	986	9.76	015 081 117 202 242 263 264
93	WIL	6.04	61.25	44.40	26.35	0	SE	986	0	081 117 202
94	WIL	0	52.90	108.90	104.42	0	SW	1355	0	022 119 202
95	WIL	9.42	54.91	34.27	10.49	8.00	N	832	1.94	017 202 242 263
96	GIP	20.23	80.66	47.19	0	24.14	E	1324	10.03	011 022 242 263
97	GIP	0	46.45	74.19	72.36	1.83	SW	955	5.34	202 263
98	WIL	39.61	53.56	36.52	36.03	0	SW	1047	0	081 202
99	WIL	55.06	7.60	27.81	0	23.06	N	1201	0	011 017 081 242 263
100	GIP	0	27.88	58.62	58.62	0.17	SW	986	36.32	202 263
101	WIL	0	45.01	93.25	71.45	3.54	W	1201	8.02	015 081 119 202 263
102	GIP	0	27.35	59.26	43.97	10.47	W	1109	24.65	119 202 263
103	GIP	13.93	66.42	76.70	67.35	14.66	SW	924	54.99	202 263

PLOT	NF	RD	REGD	RBAPH	PBAPH	TBAPH	ASP	ELEV	SNAGS	SPP
104	GIP	5.39	57.81	71.87	68.88	7.99	SW	832	32.67	202 242 263 747
105	GIP	6.34	82.89	63.11	29.31	25.23	SE	986	21.83	011 202 242 263 351
106	GIP	3.35	83.79	49.34	27.48	7.99	SW	1232	27.63	011 202 263
107	GIP	0	76.99	85.09	58.50	23.94	E	801	13.91	202 242 263
108	GIP	8.86	129.42	64.72	52.23	9.28	E	739	8.81	202 263 242
109	GIP	0	35.87	54.96	53.13	0	SE	616	0	202 351
110	GIP	0	22.26	65.95	65.95	0	SW	801	12.74	202
111	GIP	0	10.43	36.64	36.64	0.33	S	678	0	202 263
112	GIP	0	58.62	69.00	67.17	2.83	S	986	0	011 202 263
113	GIP	26.09	90.83	46.91	14.27	15.65	NE	1078	0	011 202 242 263
114	GIP	9.04	99.68	62.68	29.31	26.00	FLAT	862	5.47	011 202 242 263 351
115	GIP	0	51.20	60.24	28.15	8.90	NW	1232	46.02	011 022 093 119 202 263
116	WIL	76.72	54.54	37.31	5.50	18.52	N	1232	12.94	011 022 119 202 263

PLOT	NF	RD	REGD	RBAPH	PBAPH	TBAPH	ASP	ELEV	SNAGS	SPP
117	GIP	5.12	44.23	69.18	27.05	23.82	E	1016	16.44	011 202 242 263
118	WIL	5.42	69.70	69.62	73.20	3.66	S	1263	29.14	202 263
119	WIL	8.18	88.56	81.31	42.14	33.68	W	1140	12.96	011 202 263
120	GIP	17.76	79.37	51.88	25.03	6.16	W	801	76.05	011 015 022 202 263
121	WIL	0	17.98	60.46	58.62	0	SW	1263	24.88	015 202
122	WIL	71.94	15.68	4.98	0	1.83	N	1232	25.21	011 263
123	WIL	0	35.61	82.44	69.62	0	S	1386	4.26	015 202
124	WIL	0	34.87	69.95	62.29	0.33	NW	893	39.02	202 263 312
125	WIL	46.85	46.39	34.07	1.83	22.08	N	1170	26.91	202 263 242
126	WIL	0	40.85	60.46	60.46	0	NW	708	22.32	202 312
127	WIL	95.18	21.32	19.83	14.70	0	N	1355	27.22	015 081 202
128	WIL	0	42.01	63.00	59.29	3.97	SW	862	68.97	202 263
129	WIL	48.65	6.82	12.99	0	5.50	SE	1324	13.88	011 263
130	WIL	125.39	24.96	12.51	0	10.51	SE	1078	24.96	011 242 263
131	WIL	26.75	44.98	27.17	9.16	13.01	N	862	0	202 242 263

132	WIL	25.65	40.11	35.35	14.66	12.20	E	1324	0	011 022 119 202 263