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Effects of pruning on growth of western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) and Sitka spruce (*Picea sitchensis* (Bong.) Carr.) in southeast Alaska

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Effects of Pruning on Growth of Western Hemlock (*Tsuga heterophylla* (Raf.) Sarg.) and Sitka Spruce (*Picea sitchensis* (Bong.) Carr.) in Southeast Alaska

by

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Abstract

Effects of Pruning on Growth of Western Hemlock (*Tsuga heterophylla* (Raf.) Sarg.) and Sitka Spruce (*Picea sitchensis* (Bong.) Carr.) in Southeast Alaska

by Markian Demetrius Petruncio

Chairperson of the Supervisory Committee: Professor Chadwick D. Oliver
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Permanent study plots were established in Southeast Alaska in 1990, 1991, and 1992 to monitor and quantify the growth responses of western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) and Sitka spruce (*Picea sitchensis* (Bong.) Carr.) to thinning and pruning. Young trees in mixed stands were thinned to 170 trees per acre (420 trees/ha) and pruned to three different heights -- 8, 12, and 17.4 feet (2.4, 3.7, and 5.3 m). Branch sizes and time-and-motion data were recorded and analyzed to determine the functional relationships between time required to prune and branch characteristics. Pruned height and stem diameter were significant variables for predicting time required to prune. Epicormic branching, sunscald, and tree mortality were monitored to determine how pruning to various heights affects stem quality and tree survival. Epicormic sprouts increased on spruces but differences in numbers of epicormics between treatments were statistically nonsignificant in the first two years after treatment. Stem diameter, basal area, and butt log volume growth differences between treatments were statistically significant in the first year; and diameter growth differences were significant in the second year after treatment. Height growth differences between treatments were statistically nonsignificant in the first two years after treatment. Percent live crown length removed in combination with initial stem diameter and live crown ratio in combination with initial stem diameter were significant variables in multiple regression models for predicting posttreatment stem diameter, basal area, and volume growth. Growth was significantly reduced when 40 percent or more live crown length was removed and when live crown ratios were reduced below 50 percent. Mean stem diameter growth in the 17.4-foot (5.3 m) lift was significantly reduced at 4.5 feet (1.4 m) above the ground but not at 17.4 feet (5.3 m) resulting in significant changes in stem taper after treatment.

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Dedication

To the "Pair of Aces," Adelaide and Andrew Petruncio, for their love and encouragement to explore dreams and possibilities.

Part I. Introduction to Forest Pruning

Forest pruning entails removing lower branches from crop trees to predetermined heights to promote growth of clear wood on the boles. The primary objectives of pruning are to improve wood quality and increase value of crop trees. Clear wood production in unpruned young-growth stands of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco[1]), western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), Sitka spruce (*Picea sitchensis* (Bong.) Carr.), and ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) may be minimal over 60- to 100-year rotations because of the inherent retention of branches by these conifers. Branch retention may be especially pronounced if the stands are planted and/or precommercially thinned to wide spacings. Wide spacing may increase volume growth of individual trees; however, as spacing increases, lower branches receive more light, stay alive longer, and increase in size. Consequently, growing trees at wide spacings delays natural pruning in young-growth timber and creates larger knots in sawn and sliced products. Knots are structural defects in lumber and veneer; accordingly, wood quality decreases as the size and number of knots increase.

Pruning is an accepted silvicultural method for improving wood quality; however, it has not been a common practice in the Pacific Northwest, British Columbia, or Southeast Alaska because abundant reserves of high-quality old-growth timber have historically provided a steady supply of clear wood. The old-growth forests have declined and harvesting is restricted in most remaining stands; therefore, if clear wood is to be produced in the region at all, future supplies will have to come from well-managed young-growth forests. Thinning and pruning

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[1] Tree species nomenclature conforms to that of Little (1979).

regimes will be necessary to ensure the production of significant volumes of clear wood in managed young-growth stands. Although some pruning trials have been installed and monitored in northwestern North America for some species, little is known about pruning western hemlock and Sitka spruce.

This study addresses some of the logistical and biological questions about pruning conifers. In 1990, the U.S.D.A. Forestry Sciences Laboratory in Juneau and the University of Washington College of Forest Resources began a cooperative study to develop pruning prescriptions for the Tongass National Forest. Permanent study plots were established in Southeast Alaska in 1990, 1991, and 1992 to monitor and quantify the biological responses of western hemlock and Sitka spruce to thinning and pruning. Young trees in mixed stands were thinned to 170 trees per acre (420 trees/ha) and pruned to three different heights -- 8, 12, and 17.4 feet (2.4, 3.7, and 5.3 m). Branch sizes and time-and-motion data were recorded and analyzed to determine the functional relationships between the time required to prune and branch characteristics. After pruning, epicormic branching, sunscald, and tree mortality were monitored to determine how pruning to various heights affects stem quality and tree survival. In addition, stem diameter and height growth were measured and analyzed to determine how removal of varying proportions of the live crown and resulting live crown ratios affect tree growth and stem taper.

In this dissertation, the terms "forest pruning," "artificial pruning," and "pruning" are synonymous and refer to the silvicultural operation of removing lower branches from crop trees. "Forest pruning" is a forestry practice, distinct from ornamental pruning, fruit tree pruning, and

Christmas tree pruning. Objectives of ornamental pruning are aesthetics and public safety. Fruit trees are pruned to increase fruit quality and improve access to fruit. Christmas trees are pruned for aesthetics. Forest pruning is done to maximize clear wood production and to increase value of managed stands. Forest pruning, in conjunction with thinning, can also be prescribed to perpetuate the growth of understory vegetation and thereby enhance wildlife habitat.

Forest pruning is an art and a science -- the art of pruning advanced by trial and error over many centuries; it was not until early in the nineteenth century when scientific foundations for pruning were established. General pruning theories evolved during the course of experimentation; these theories comprise a pruning paradigm with the following axioms and postulates:

Axioms

Axioms are basic propositions which are widely accepted as self-evident truths. The following axioms pertain to forest pruning and wood quality; detailed descriptions and citations are given in the literature review.

- Decreased stand density (*i.e.*, wide spacing) results in increased branch diameter growth and, consequently, increased branch retention.
- Knots are defects in sawn and sliced wood products. Softwood lumber is graded on the basis of the size, soundness, number, and distribution of knots; presence or absence of knots also determines plywood grade.
- Pruning trees early in a rotation minimizes the size of the defect core (i.e., the central portion of a tree containing knots) and maximizes clear wood production.
- Removing live branches (green pruning) reduces crown size and

results in changes in photosynthate allocation.

- Removing large portions of live crowns at one time causes reductions in stem diameter and height growth, or death of trees.

Postulates

The following postulates are propositions which have not yet been tested.

- Clear wood production in unpruned second-growth western hemlock and Sitka spruce stands may be minimal over a 60- to 100-year rotation because of persistent branches. If the stands are thinned to wide spacings, increased branch sizes may reduce wood quality.
- Some combination of thinning and pruning may ensure production of significant volumes of clear wood in managed stands.
- Performing the pruning in conjunction with thinning would minimize the number of stand entries and may significantly reduce operational costs.
- To produce a clear 16-foot (4.9 m) log, a tree must be pruned to a greater height, *e.g.*, 18 feet (5.5 m), to allow for stump height and trim at the mill. Pruning small trees, *e.g.*, 30 feet (9.1 m) tall, to a height of 18 feet (5.5 m) in one operation may significantly decrease diameter or height growth, or result in tree mortality.
- Young trees could be pruned to 18 feet (5.5 m) in two or three lifts (stages) to maintain a uniform defect core within the pruned portion of the stem without adversely affecting growth.

Hypotheses

Hypotheses are specific postulates which can be examined in relation to data and can be designated true or false with specified probabilities. It was hypothesized that the time required for pruning would be a function of number of branches, branch basal area, stem diameter, and pruned height. The null hypotheses were there are no functional relationships between the time required for pruning and branch number, branch basal area, stem diameter, or pruned height. It was also hypothesized that stem quality and growth response of hemlock and spruce would be a function of pruned height, percent live crown length removed, live crown ratio after pruning, and stem diameter at the time of pruning. The null hypotheses were there are no functional relationships between stem quality or growth and pruning.

Epicormic branching and incidence of sun scald were evaluated to assess pruning affects on stem quality. Parameters used to quantify the growth responses included survival, changes in tree height, stem diameter, taper of the first 16-foot (4.9 m) log, basal area, and volume. These parameters were evaluated individually and in combinations to determine the functional relationships between tree growth and pruning. The following hypotheses were tested:

- Pruning time may be a function of the number of cut branches.
- Pruning time may be a function of the sum of basal areas of cut branches.
- Pruning time may be a function of the diameter at breast height of the pruned tree.
- Pruning time may be a function of pruned height.
- Epicormic branching may be a function of pruned height.
- Incidence of sunscald may be a function of pruned height.
- Height growth may be a function of pruned height.
- Height growth may be a function of percent live crown length removed and stem diameter at the time of pruning.

- Height growth may be a function of live crown ratio after pruning and stem diameter at the time of pruning.
- Stem diameter growth may be a function of pruned height.
- Stem diameter growth may be a function of percent live crown length removed and stem diameter at the time of pruning.
- Stem diameter growth may be a function of live crown ratio after pruning and stem diameter at the time of pruning.
- Change in taper of the first 16-foot (4.9 m) log may be a function of pruned height.
- Change in taper of the first 16-foot (4.9 m) log may be a function of percent live crown length removed and stem diameter at the time of pruning.
- Change in taper of the first 16-foot (4.9 m) log may be a function of live crown ratio after pruning and stem diameter at the time of pruning.
- Basal area growth may be a function of pruned height.
- Basal area growth may be a function of percent live crown length removed and stem diameter at the time of pruning.
- Basal area growth may be a function of live crown ratio after pruning and stem diameter at the time of pruning.
- Volume growth of the first 16-foot (4.9 m) log may be a function of pruned height.
- Volume growth of the first 16-foot (4.9 m) log may be a function of percent live crown length removed and stem diameter at the time of pruning.
- Volume growth of the first 16-foot (4.9 m) log may be a function of live crown ratio after pruning and stem diameter at the time of pruning.

Historical and contemporary forest pruning literature are summarized in the Literature Review; the study areas and field procedures are described in the Experimental Design and Procedures; analytical techniques and the effects of pruning on mortality, epicormic branching, sunscald, growth, and taper are presented in the Experimental Results and Discussion; and the implications of the research results are discussed in the Applications to Management.

Part II. Review of Forest Pruning Literature

Forest pruning, as an intermediate stand treatment, has been practiced and documented for many centuries. This review summarizes the literature pertaining to forest pruning. Lessons can be learned from the reported failures and successes of forest pruning operations conducted around the world. Historical pruning literature provides numerous illustrations of crude pruning techniques that failed to produce clear wood; yet other investigations confirm that proper pruning can improve wood quality and increase value. Investigations of pruning techniques and subsequent wood quality resulted in previously accepted pruning practices being discredited and even discontinued altogether. For example, in 1858, pruned fir (*Abies* spp.) and spruce (*Picea* spp.) trees were dissected in Baden, Germany; it was found that axe pruning left jagged stubs with accumulations of pitch and bark that delayed occlusion. As a result of those observations, forest ordinances prohibited axe pruning, and only saw pruning was permitted (Mayer-Wegelin 1936).

The art of pruning woody plants received early mention in the Old Testament of the Bible (e.g., Isaiah 2:4) The Romans recognized the utility of pruning trees in the third century A.D., and designated Coinquenda as the pruning goddess (Evelyn 1706; Dumézil 1966; Leach 1992). Fernow (1911) suggested that early Roman silvicultural ideas were adopted by German tribes in the fourth century. According to Curtis (1937), forest pruning was first practiced in Belgium and the Netherlands, was introduced in France and Germany; and then Poland, Italy, and Sweden followed Germany's examples.

European forests were seriously depleted during the Middle Ages as a result of the great demand for fuelwood, charcoal, and animal fodder.

Trees were coppiced as a means of meeting the demand for wood quantity rather than quality (Curtis 1937). By the sixteenth century, pruning was prescribed in forest ordinances (Mayer-Wegelin 1936) and was discussed in Carlowitz's (1713) "Wilde Baumzucht" (Wild Silviculture). Pruning became a widely practiced and specialized craft, leading to the development of a guild, or a pruning corps, in France and Belgium.

During the seventeenth century, Lawson (1623) and Evelyn (1706) recommended pruning in England to prevent decay and to enhance the vigor and appearance of trees. In France, the coppice-with-standards system was prescribed in a 1669 forest ordinance. By the eighteenth century, coppice with standards became the most commonly employed silvicultural system. Widely-spaced standards were managed for sawtimber while the coppiced understory produced fuelwood. The open-grown standards, however, developed stems with short boles, coarse branches, and wide crowns above the understory. Pruning the standards was then prescribed to improve the quality of the timber for building purposes; pruning also allowed more light to reach the coppiced understory, thereby increasing fuelwood production. Among other documented benefits, pruning provided employment opportunities for villagers.

Mayer-Wegelin (1936) described three periods of intense pruning activity in Germany. The first pruning period occurred from 1780 to 1800; the second from 1860 to 1890; and the third period began in 1920. The first two periods ended rather abruptly and were followed by reactionary periods during which pruning fell into disrepute. Pruning was rejected because incorrect pruning had caused damages which became evident after the trees were harvested and processed. The inability to provide expert supervision during the first attempts to prune on a large scale may have been the reason pruning was discontinued (Curtis 1937). Interest in pruning was revived when it was shown that proper pruning techniques resulted in improved wood quality and increased value.

Pruning was carefully practiced in the early part of the nineteenth century by a few foresters in Bohemia and various German provinces. Where firewood gathering was permitted, pruning was done to prevent damage to the trees that would otherwise be caused by peasants breaking off the branches for fuel. The increased mining of coal gradually decreased the fuelwood demands. Pruning became more important in the nineteenth century as the demand for quality timber increased. The idea of pruning to produce clear wood was introduced in England by Pontey (1805). He recognized that some tree species did not self-prune very well; and, consequently, much of the wood had defects caused by large branches. In his "Forest Pruner," Pontey proclaimed that "knottiness in timber is an evil of immense magnitude," and that pruning should be done to increase wood value. Gillanders (1887) and Michie (1888) also promoted pruning in estate plantations in England.

Beginning in 1863, knowledge and efficiency were improved through experimental and operational pruning carried out at the newly established forest experiment stations in Germany. By 1890, however, interest in pruning declined; and, again, improper pruning was blamed as the cause of wood defects. Forest experiment stations also shifted research priorities from pruning to thinning methods. It was thought that increased tree volume growth obtained by thinning would eliminate the need for pruning.

During the third pruning period, in the first half of the twentieth century, the practice spread to New Zealand, Australia, and North America. Pruning was not widely accepted though, because there were still plentiful supplies of clear wood in high-quality old-growth timber, especially in northwestern North America. A steady increase in pruning research and operations since the 1980's may well represent a fourth pruning wave. Pruning has become an accepted practice in South Africa, New Zealand and Chile; and interest in operational pruning has been aroused in the southeastern United States, the Pacific Northwest, British Columbia, and Southeast Alaska.

Recent changes in economic and social conditions in the Pacific Northwest, British Columbia, and Southeast Alaska have made pruning a more attractive and viable silvicultural practice. A number of private forest industry firms, public agencies, and nonindustrial private forestland owners have begun operational pruning programs. On National Forests in Oregon and Washington, trees were pruned on 5768 acres (2334 ha) in 1991 and 4400 acres (1781 ha) in 1992, up from 244 acres (99 ha) in 1987 (Fight 1993; Fight *et al.*, in press).

Natural Pruning and Clear Wood Production in Conifers

Natural pruning refers to the process in which branches die and eventually break off of standing trees. Lower branches gradually become shaded and die as forest stands develop through the stand initiation and the stem exclusion stages. Branches die when photosynthate production drops below a minimum required for maintenance respiration. The dead branches become inhabited by insects, fungi, and bacteria and eventually break off through the actions of precipitation, wind, or whipping by understory trees. Dead branches may persist, however, if they are large or if decomposers are inhibited by excessive dryness or chemical barriers. Live crowns may recede to considerable heights over time but dead branches remain protruding from the lower portion of the boles for many decades. After the branches finally break off, the remaining branch stubs are grown over and clear wood is produced.

Bransford and Munger (1939) dissected trees from a 100-year-old stand of even-aged Douglas-fir to examine natural pruning patterns. Branches from the lower 16 feet (4.9 m) of the boles died before the trees were 30 years old, however, the dead branches were not shed readily -- it took, on average, an additional 54 years from the time a branch died until it fell off and the stub was completely occluded. Kachin (1940) quantified natural pruning in stands of different ages, site qualities, and stocking classes. In well-stocked stands the live crowns receded to a height of 18 feet (5.5 m) in 30 years; yet disintegration of the dead branches was reported to occur very slowly. In 100-year-old stands, the heights to the bases of the live crowns were 75 to 80 feet (23 to 24 m) but only the lower 5 to 12 feet (1.5 to 3.7 m) of the boles were completely free of branch stubs. It took an average of 60 years from the time a branch died until the time when the stub was completely occluded.

In another study of knot formation in Douglas-fir stands, Paul (1947) reported that dead branches extended through the bark along the entire merchantable length of most trees in stands ranging in age from 70 to 150 years. Kotok (1951) examined natural pruning of Douglas-fir in stands ranging from 20 to 150 years old. It took an average of 22 years for the live crowns to recede to 17 feet (5.2 m), and a total of 32 years for the live crowns to recede to 33 feet (10 m). Natural pruning of the dead branches up to 17 feet (5.2 m) did not occur until age 77, and by age 107 the lower 33 feet (10 m) of the boles were clear of branch stubs. An unspecified additional number of years was required for branch stub occlusion and clear wood production. Results from these four studies indicate clear wood production in stands of Douglas-fir less than 100 years old will be minimal.

On the Tongass National Forest in Southeast Alaska, western hemlocks and Sitka spruces grow in natural stands which range in species composition from pure stands of either species to mixed stands. Density of young natural stands is typically high and precommercial thinning is prescribed to stimulate growth of selected trees and to increase financial returns (Ruth and Harris 1979). Wildlife biologists advocate wide spacing of trees in critical deer winter range to promote the growth and development of understory vegetation; wider spacings between trees may increase light levels in the understory and perpetuate the growth of understory vegetation (Hunter 1990). Silviculturists prescribe wide spacing (*e.g.*, 16 x 16 feet, 5 x 5 m), in areas where no future thinning treatments are planned before the next harvest (Smith 1986).

Thinning operations usually increase merchantable yields by redistributing volume growth on fewer, larger stems (Daniel *et al.* 1979; Smith 1986). Trends toward establishing and maintaining lower stand densities have raised concerns among silviculturists worldwide that wide spacings result in larger, more persistent branches and, hence, reduced wood quality (Cieslar and Janka 1903; Paul 1932; Bransford and Munger 1939; Kachin 1940; Kotok 1951; Eversole 1955; Harris 1966; Gallagher 1984; Carter *et al.* 1986). Branches of Sitka spruce and western hemlock are very persistent in widely spaced stands. Sitka spruce branches (or branch stubs) are generally very persistent even in dense stands where branches may be relatively small and short-lived. When young stands are precommercially thinned to wide spacings, lower live branches receive more direct sunlight and become larger and more persistent, resulting in an increase in the size and number of knots in the wood. Knots are the most common defects that normally cause losses in value in lumber and veneer. In softwood lumber grading rules, knots are classified as to form, size, quality, and distribution (West Coast Lumber Inspection Bureau 1993). Likewise, plywood grading is based on the size and frequency of knots in the face veneer layers (American Plywood Association 1992). Clear material is preferred, while presence of knots characterizes the medium and lower grades of lumber and plywood. Thinning to wider spacings may become more common in future silvicultural prescriptions; and since wider spacing results in larger branches, a combination of thinning and pruning may be necessary to ensure the production of significant volumes of clear wood in managed young-growth stands.

Developments in Pruning Equipment

Forest pruning is accomplished using a combination of equipment and labor. Early equipment developments were nonmechanized and labor intensive. Recent developments in mechanization have the potential for reducing the labor intensity of pruning operations. Equipment costs increase in relation to the amount of mechanization and range from approximately $60.00 for a quality polesaw to $44,000 for the Treewitch®[2] and Multimax® combination. The increased productivity

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[2] Use of trade names in this dissertation is for the reader's convenience and does not constitute an official endorsement.

of mechanized equipment has the potential to offset the initial equipment costs to yield a pruning cost of $2.00 to $3.00 per tree. Costs of manual pruning are dependent on pruning height and range from approximately $1.00 to $3.00 per tree.

Early Equipment Developments in Europe

Early pruning operations were performed using various types of clubs, chisels, pruning hooks, knives, and hatchets. Pruning techniques were improved in 1865 by the Vicompte de Courval with the introduction of pruning saws that enabled branches to be cut flush with the bole (Mayer-Wegelin 1936). The first polesaw, the Flügelsäge, was introduced in Germany by George Alers in 1874 (Curtis 1937); Alers also promoted the financial benefits of pruning.

Early Equipment Developments in North America

Forest pruning was not practiced in North America until early in the twentieth century. Pruning operations were restricted to removing dead branches and were accomplished using clubs or pruning hooks; saws were used only on the largest branches (Graves 1911; Curtis 1937). Pruning activity increased during the 1930's in the eastern white pine stands of New England.

Forest pruning equipment can be grouped in four categories: 1) clubs; 2) shears; 3) impact cutting tools; and 4) saws (Hawley 1946). The Hebo Club was developed to prune dead branches (Kachin 1940; Zach 1941). A steel ferrule was attached to the end of a wooden club; a 33-inch (84 cm) long club was swung with two hands and an 18-inch (46 cm) club was swung with one hand. Club pruning was limited to dead branches and, when properly executed, created a wound that reportedly healed more rapidly than cut branches (Hawley 1946; Anderson 1951). This advantage was negated by damage to the main stem and subsequent reductions in wood quality caused by unskilled operators (Hawley 1946; Smith 1962). Finnis (1953) found pruning with a Hebo Club faster than a saw but the results were unacceptable because of the jagged stubs left by the club.

Typical pruning shears ranged from 20 to 36 inches (51 to 91 cm) long and required two-handed operation (Hawley 1946). When pruning to 7.5 feet (2.3 m), Finnis (1953) found the 20-inch (51 cm) Porter Pruner® to be as fast as pruning saws and was preferred by operators. Effective use of shears without ladders was limited to a height of 8 feet (2.4 m) and to branches with diameters less than 1 inch (2.5 cm) (Hawley 1946; Smith 1962).

Impact cutting tools included axes, chisels, and pruning hooks (Mayer-Wegelin 1936; Curtis 1937; Hawley 1946). Axes in the hands of unskilled workers were dangerous to the trees as well as to the operators (Hawley 1946; Smith 1962) and generally produced poor results (Curtis 1937; Warrack 1948; Finnis 1953; Smith 1962); brushhooks and billhooks were equally dangerous (Hawley 1946). Chisels were used to sever branches from below by driving a sharp blade upward with force generated by the operator or with a blow from a mall (Williamson 1939; Smith 1962).

Rich (1935) devised a pruning tool with two cutting edges which was a combination chisel and pruning hook (Smith 1962). The tool was used by pushing one edge upward or by pulling the other edge downward through branches. Use of chisels, hooks, and the Rich pruning tool was limited by the amount of strength required to sever branches; small dead branches were easiest to prune (Hawley 1946; Smith 1962). Stem damage was also a problem when impact cutting tools were used by unskilled workers.

Handsaws and polesaws were the most widely used pruning tools in North America. Handsaws typically had a rigid, concave blade between 10 and 16 inches (25-41 cm) long. The blades had between 5 and 8 teeth per inch that would cut on both the push and pull strokes (Hawley 1946; Warrack 1948). Polesaws were fabricated by attaching saw blades to poles of various lengths. Polesaw blades were rigid, concave, and between 14 and 18 inches (36-46 cm) long. The blades typically had 5 teeth per inch and cut on the pull stroke only (Hawley 1946).

Hawley and Clapp (1935) developed a three-lift method of pruning eastern white pine using a handsaw in combination with 8-foot and 12-foot (2.4 and 3.7 m) ladders. Time required for pruning ranged from 8 to 13 minutes per tree (Hawley 1946). Warrack (1948) tested polesaws against a handsaw-ladder combination for pruning Douglas-fir to a height of 18 feet (5.5 m). The handsaw-ladder combination yielded the best average time of 11.5 minutes per tree. Finnis (1953) reported average times between 7.5 and 12.4 minutes per tree when using a handsaw-ladder combination for pruning Douglas-fir to a height of 20 feet (6 m); pruning to 24 feet (7.3 m) required 27.6 minutes. Finnis found that a one-lift operation was faster and more economical than the three-lift method.

Winn (1950) used an axe and polesaw combination to prune Douglas-fir to 18 feet (5.5 m) in 4.5 minutes per tree. The pruned trees were later removed for poles during an intermediate thinning, indicating that mid-rotation returns from pruning may be obtainable (Trautman 1965). Bull (1937) reported that, after a learning period, a polesaw was faster than a handsaw-ladder combination for pruning longleaf pine (*Pinus palustris* Mill.). In general, polesaws reportedly required more skill than a handsaw-ladder combination (Bull 1937). Polesaws were more fatiguing to use but easier to transport in dense underbrush (Moss 1937).

Recent Developments in Pruning Equipment

Handsaws and polesaws remain popular tools in the 1990's. Numerous saw designs have been developed over the last century; an example of a recent design is the Oregon Prozig® pruning saw which has curved teeth and cuts on the pull stroke. Most blades can be mounted on an axe handle or on longer wooden or fiberglass poles. A handsaw can easily be used to prune to a height of 9 feet (3 m), a 6-foot polesaw can reach to 14 feet (4.3 m), and a 12-foot polesaw (*i.e.*, two interconnecting 6-foot sections) can be used to prune to 18 feet (5.5 m). The combination of the Oregon Prozig® saw and two 6-foot fiberglass poles costs approximately $60.00. The average time to prune Sitka spruce and western hemlock to 17.4 feet (5.3 m) using the handsaw-polesaw combination was 9 minutes per tree (including travel time between trees) (Petruncio 1992).

The main advantages to using handsaws and polesaws are that trees can be pruned at an early age to minimize the size of the defect core; saws are readily available, affordable, and require little maintenance. A major disadvantage is the height limitation -- polesaws become very difficult to control above 20 feet (6 m).

Pruning shears are the preferred pruning tools in New Zealand and British Columbia, Canada. Several design modifications have recently been made in attempts to improve the ergonomics of pruning operations (Hall and Mason 1988). More efficient shears with modified blades and handles are described by Hall and Mason (1988), Reutebuch and Hartsough (1993), and Knowles (in press).

The Husqvarna Highcutter® is a hydraulic pruning saw made in Sweden; it consists of an engine pack and a telescoping fiberglass shaft with a hydraulically driven chain saw mounted at the end. The 49 cc engine pack weighs 16.3 pounds (7.4 kg) and is carried on the back using a harness that provides a low center of gravity.

Telescoping shafts are available in sizes ranging from 6.6 to 19.7 feet (2 to 6 m) with respective weights of 6.6 to 11.7 pounds (3.0 to 5.3 kg). A shaft extending to 13 feet (4 m) is sufficient for pruning to a height of 18 feet (5.5 m), and weighs 9.3 pounds (4.2 kg). A throttle lever clips on to the shaft and can be moved up or down to a comfortable operating position. Hydraulic hoses run from the power pack through the shaft to the hydraulic motor at the end of the shaft. The hydraulic motor drives a chain on a 6.3-inch (16 cm) bar.

The power pack with the 13-foot (4 m) shaft costs approximately $2060.00. During a recent trial of the Husqvarna Highcutter® at the Charles Lathrop Pack Experimental Forest (Pack Forest 1992), the average time to prune Douglas-fir to a height of 18 feet (5.5 m) was 9.5 minutes per tree (including travel time between trees). Some problems were encountered during the trial -- the hydraulic hoses extending from the power pack to the shaft often got caught on slash when moving between trees, causing time delays; and the chainsaw easily scarred the stem.

"Tree monkey" is the common name for the KS 31® self-propelled mechanical pruner developed by Paul Meier in Switzerland in 1963. Several companies have since manufactured variations of the original machine, but the basic designs are similar.

The Swiss machine consists of a steel tubular frame, eight diagonally-oriented wheels (four of which are drive wheels), a 56 cc Stihl® engine, and a plane-toothed chain saw. The machine is carried between trees by two people. Branches must first be cleared from the lower portion of the stem (up to approximately 5 feet, 1.5 m) before the machine can be attached. The hinged tubular frame clamps around the tree, putting the wheels in contact with the stem; holding pressure is maintained with tension springs. The engine drives the wheels and the chainsaw. A ratchet-wheel gear-train system is integrated with the drive wheels to regulate climbing height. The chainsaw bar is positioned vertically above the frame and follows the contour of the stem; branches are cut off as the machine spirals up the tree. Spacers on the chainsaw bar maintain a set distance between the bark and the bar. When the machine reaches the set height, the transmission shifts into reverse and the machine descends to the base of the tree.

Tree monkeys range in price from approximately $3000.00 to $8000.00. A remote-controlled KS 31® has recently been developed by Paul Meier. The original and recent models work best on stems ranging from up to

12 inches (30 cm) diameter at the base to a 4-inch (10 cm) top diameter. During operational pruning in Oregon (Dew 1992), the average time to prune Douglas-fir to a height of 43 feet (13 m) was 6 minutes per tree (including travel time between trees). An advantage to using the tree monkey is that it provides an opportunity for pruning higher than would be possible using handsaws and polesaws. The disadvantages are the machines are heavy, 65 pounds (30 kg), and require two people to carry between trees; the machines were not designed for North American species and often get stuck on branch collars or ramicorn branches. Furthermore, since machine operation is limited to a 4-inch (10 cm) top diameter, breast height diameters have to be between 8 and 12 inches (20 to 30 cm) at the time of pruning; if the pruning is done in one lift, large defect cores would result.

The Treewitch® is a hydraulic pruning machine made in Germany (FERIC 1991). The Treewitch® head attaches to the bole and is hydraulically driven by rubber belts. The cutting edges of the head surround the bole and can shear branches up to 1.5 inches (4 cm) in diameter. The head is connected to a power source by a 115-foot (35 m) double hose. The Treewitch® can be connected to a tractor with a minimum 50 horsepower (37.3 kW) and a three-point hitch, or it can be attached to the Multimax® 40 horsepower (30 kW) minicaterpillar tractor.

The Treewitch® works best on stems ranging from up to 12 inches (30 cm) diameter at the base to a 4-inch (10 cm) top diameter. The unit has a remote control and can prune trees at a rate of 9.8 feet (3 m) per second. During operational pruning on Vancouver Island, B.C. (Robertson 1992), the average time to prune Douglas-fir to a height of 43 feet (13 m) was 2.1 minutes per tree (including travel time between trees). Lower branches are usually clubbed off before attaching the machine; although this method is fast it usually results in jagged stubs, damaged cambiums, and delayed occlusion. Additional time should be allowed for proper pruning of the lower branches. The Treewitch® (PTO model) costs $16,685.00. The Treewitch® and the Multimax®, sold together, cost $44,600.00. The main advantage of the Treewitch® is that it is fast. The disadvantages are that it is expensive and heavy (110 pounds, 50 kg); also, the bark can be easily stripped off if there are any irregularities in stem form.

A comparison of production rates for the various types of pruning equipment is presented in Figure 1. The graph shows the time required to prune to 18 and 43 feet (5.5 and 13.1 m), including travel time between trees.

Choosing the Right Equipment

A land manager choosing equipment for operational pruning needs to consider the following factors: tree size; marketing objectives; pruning height; pruning time-and-motion; operating costs; equipment service facilities; and quality control (condition of stems and branch stubs). Tree size at the time of pruning is the single most important factor for selection of the proper equipment. Tree size at the time of pruning determines the size of the defect core and drives profitability. Currently, no mechanical systems compete with manual equipment for pruning small diameter stems.

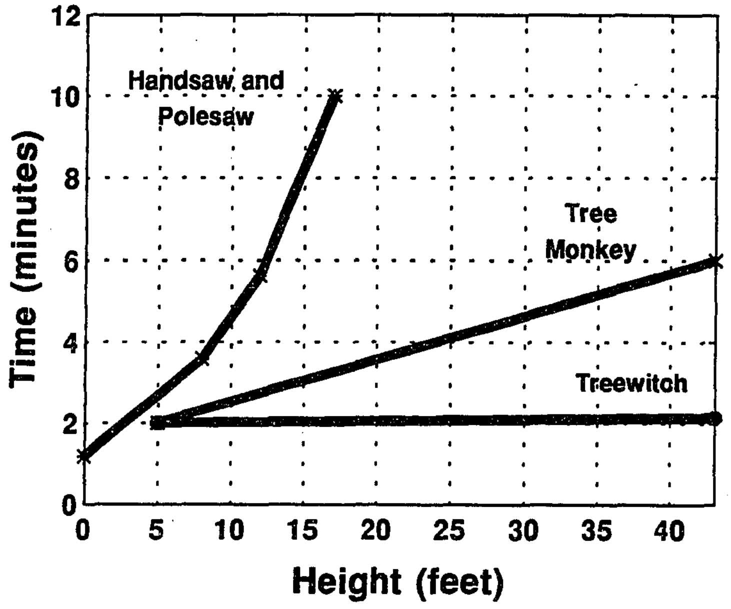

Figure 1. Comparison of pruning production rates for three types of equipment: a) manual saws; b) Tree Monkey; and c) Treewitch®. The time to prune to different heights includes travel time between trees. Manual saws can be used up to 20 feet (6 m); branches must first be cleared from the lower portion of the stem (5 feet, 1.5 m) before the Tree Monkey or Treewitch® can be attached.

The lengths of logs to be sold (*e.g.*, 16-foot or 40-foot (4.9 or 12.2 m) will be influenced by markets; and log lengths will determine pruning heights. Pruning time and operating costs will vary with the number of trees to be pruned, the operating terrain, and the type of equipment. When new types of equipment are introduced in a region it is important to know what kind of equipment service facilities are available in the area and how long it will take to obtain replacement parts. Finally, quality control of the pruning job is more critical than how fast the job can be done. The condition of branch stubs and stems after pruning will affect wound occlusion and wood quality. Early attempts at pruning using axes and clubs proved unsatisfactory because the jagged branch stubs left by those methods created pitch pockets beyond the stubs and delayed occlusion. The pitch pockets may have different impacts on appearance grade products than on structural products. A clean, smooth cut results in faster occlusion with the least amount of grain distortion and discoloration beyond the stub.

Western Hemlock and Sitka Spruce Branch Characteristics

Branch characteristics may affect natural and artificial pruning, branch stub occlusion rates, and wood quality. The amount of time required to prune trees to different heights may be affected by size, number, and arrangement of branches. Leaves are arranged on stems in specific patterns (phyllotaxy) that are determined in the apical meristem (Esau 1953; Romberger 1963; Fahn 1982; Wilson 1984; Oliver 1990). Buds produced by the apical meristem consist of shoot and leaf primordia and cataphylls (scales). Most, but not all, woody species form terminal buds at stem tips. Lateral buds (axillary buds) develop in the axils of leaves; in many species, lateral buds are initiated in the axils of leaf primordia within the terminal bud. More than one bud may form in a single leaf axil; many species may have lateral buds that are subtended by smaller "supplemental buds" (Romberger 1963). The larger lateral bud may form a branch while the supplemental buds remain suppressed.

Terminal buds and some lateral buds exhibit annual growth cycles;

however, most lateral buds remain suppressed as a result of apical dominance (Romberger 1963; Wilson 1984). These suppressed lateral buds have also been referred to as dormant buds, trace buds, and latent buds. Suppressed buds are connected to the pith by bud strands; as radial growth of the stem occurs, the bud strands may grow just enough to remain under or at the surface of the bark. In some cases, the buds may remain permanently suppressed and become grown over by wood or the bud strand may branch repeatedly, giving rise to more lateral buds. Suppressed buds may be stimulated by light to produce epicormic branches on stems and branches of some species after a disturbance such as fire, insect defoliation, thinning, pruning, or road construction (Daniel *et al.* 1979; Spurr and Barnes 1980; Smith 1986; Oliver 1990). Among the conifers, Douglas-firs, Sitka spruces, and true firs (*Abies* spp.) produce epicormic branches which may decrease the quality and value of wood (Isaac 1943; Stein 1955; Herman 1964; Cosens 1952). European foresters have been able to reduce sprouting of suppressed buds on such species as oak (*Quercus* spp.) by keeping the lower boles shaded with foliage of understory trees (Spurr and Barnes 1980).

Hemlock has a sustained (indeterminate or neoformed) growth pattern in which some shoot and leaf primordia are formed prior to budbreak. After spring budbreak, development and elongation of new primordia continues into summer as long as environmental conditions remain favorable. Hemlock phyllotaxy is spiral (Harlow *et al.* 1979); distinct annual branch whorls are lacking. Sitka spruce has a preformed (determinate) growth pattern in which most or all shoot and leaf primordia are formed prior to budbreak. Preformed primordia rapidly elongate at the beginning of the growing season and a new bud is set by early summer. Spruce phyllotaxy is also spiral (Harlow *et al.* 1979) but shoot elongation is minimal at first, and consequently, the first 4 to 6 lateral branches form a whorl where the terminal bud was located at the end of the previous growing season; shoot elongation continues above the whorl, forming a leader. New whorls are formed annually; and some smaller branches (interwhorl branches) and epicormic shoots develop between the annual whorls. Whorl branches are typically longer, larger in basal diameter, have more foliage than interwhorl branches, and thereby produce more photosynthate for tree growth. Epicormic branching on spruce is stimulated when stems are exposed to increased light levels by thinning or other disturbances that create openings in a stand (Herman 1964). Development of epicormic branches on Douglas-firs after pruning to different heights was reported by Isaac (1945) and Stein (1955). Epicormic branches formed within two years after pruning and were most prevalent on trees that had 75 percent live crown length removed.

Pruned Branch Stub Occlusion

Economic analyses of pruning take into account many variables, but perhaps the least understood is the length of time required from the time of pruning until clear, high-value wood is produced beyond the pruned branch stub. The time delay is important because pruning costs are carried as an investment; any delay of occlusion reduces the size of the clear shell and, hence, the return on the investment.

Branch collars are rings of wood and bark at the bases of branches. The collars are made up of branch and bole tissues (Shigo 1989). When a branch is pruned close to the branch collar, callus first forms at the margins of the branch stub. Callus is undifferentiated, homogenous tissue with little or no lignin (Küster 1903) and may be produced by cells of the vascular cambium or parenchyma of xylem and phloem rays (Esau 1962). By cell enlargement (hypertrophy) and division (hyperplasia), callus spreads inward from the margins of the branch stub, eventually covering the stub. Callus cells differentiate into cambial cells beginning first at the margins of the stub, where contact occurs with the intact vascular cambium of the bole; and a new cambium forms across the surface of the stub. When the new callus cambium divides, it forms xylem and phloem in continuity with the same vascular tissues of the bole. A cork cambium also develops in the outer portion of the callus and forms a periderm (bark) which is pushed outward as radial growth continues. A scar in the bark, referred to as a "branch indicator," remains visible for many years after occlusion. Branch indicators are used by log scalers as evidence of defects below the bark when natural pruning has occurred.

Küster (1903) reserved the terms "callus" for undifferentiated, thin-walled cells that form over wounds; "woundwood" for thick-walled, lignified cells that differentiate from the callus; and "corkwood" for cells in the outer portion of the callus that differentiate into an epidermis, which is continuous with the epidermis of the bole. The entire process whereby the branch stub is covered over by new growth has been referred to as "branch stub occlusion," "compartmentalization," "wound occlusion," "wound healing," "heal-over," and "sealing." As marketing of artificially pruned logs becomes more common, scalers should be aware that the branch indicators may remain visible for many decades after a shell of clear wood has grown over the pruned branch stub.

Importance of the Branch Collar

In 1756, Büchting recommended that branches be cut just to the outside of the branch collar, and advised against removing or injuring the branch collar (Mayer-Wegelin 1936). In 1878, Hartig described a "branch protection zone" at the base of branches. The branch protection zone is made up of chemicals derived from stored energy reserves, such as starch and oil, in living cells. The chemicals are terpene-based in conifers and resist spread of organisms from the branch into the bole (Shigo 1989, 1991).

In conifers, the protection zone is formed by resin, which begins to accumulate at the branch base shortly before death (Mayer-Wegelin 1936). Compression wood typically develops in conifer branch bases; the increased density and lignin content of compression wood impedes decay and is a cause of persistence long after the branch has died.

The branch collar, which consists of branch and bole tissue, varies in size with age and position on the bole. Large branches typically have large branch collars. Severing the branch collar results in a discontinuous protection zone at the base of the branch. When the protection zone is compromised, pathogens may enter the exposed bole wood and spread up and down the stem. Despite the discovery of the protection zone, many pruners favored cutting through the branch collar to promote rapid occlusion. Wounds created by cutting through the branch collar were observed to occlude more rapidly even though the wounds were larger than those created by cutting to the outside of the collar (Mayer-Wegelin 1936). Even though removal of the collar stimulates callus and woundwood formation, pathogens are able to enter the exposed bole wood and spread before the wound closes.

In 1942, an experimental pruning plot was established in a twelve-year-old Douglas-fir plantation to investigate wound occlusion rates and tool efficiency (British Columbia 1943). Four years after pruning it was reported that branch stub occlusion rates were enhanced when part of the living tissue forming the branch collar was removed (British Columbia 1947). In a follow-up report six years after pruning, the practice of cutting through the collar was reported to be detrimental and unnecessary (British Columbia 1949).

Empirical Research on Branch Stub Occlusion

Relatively little detailed research has been conducted on occlusion of branch stubs after pruning of Pacific Northwest conifers (Cahill *et al.* 1986). In general, the rate of branch stub occlusion is dependent on the radial growth rate of the bole, however, there appears to be a lot of variability in the quality of the wood immediately to the outside of the branch stub. Occlusion rate determines the amount of time required after pruning before clear wood is produced. Anderson (1951) found branch stub length and radial growth rate influenced the time for pruned-branch stubs of Douglas-fir to occlude. A short stub length, related to bark thickness and pruning technique, resulted in shorter occlusion time. Reports by the British Columbia Forest Branch (British Columbia 1948) and Finnis (1953) showed that pruning young stands of Douglas-fir in winter resulted in rapid occlusion, and no infections of the wounds were observed. Sectioning of pruned trees revealed faster occlusion of live-pruned stubs than dead-pruned stubs. Occlusion after live-pruning took one to five years, but after dead-branch pruning, occlusion took four to six years, and sometimes more than ten years, before production of clear wood over the stubs. Pitch pockets were also reported to form over jagged cuts but not over smooth cuts.

Dimock and Haskell (1962) reported an average of 3.9 inches (10 cm) of growth was needed after pruning Douglas-fir before grade A veneer could be recovered. Defects that degraded veneer included knots in the core, occluded pitch and bark pockets, and dimples resulting from irregular grain near the occluded knots.

A small pilot study was conducted by Briggs (1990) for ponderosa pine pruned on one site when about 50 years old. The study divided the occlusion phenomenon into two zones:

1. Number of years to grow wood to the end of the branch stub; and
2. Number of years from the end of the branch stub until clear, straight-grained wood was produced.

The number of years for the cambium to reach the end of the stub is mainly dependent on bark thickness and pruning method. The number of years is a function of the distance from the cambium at the time of pruning to the end of the stub outside the bark and the radial growth rate of the tree after pruning. The model developed argues for early pruning when bark is thin and branch collars are small so pruning can be flush with the bark. The model also argues for selecting trees with good growth rates and performing thinning and fertilization to maintain uniform growth rates.

Time to produce clear, straight-grained wood beyond the stub is more variable and is related to the number of years to cover the knot surface, as well as to embed pitch, bark, and stain pockets. The measurements were based on visually estimating when the transition to clear, straight grain occurred on radial sections that exposed the pruned branch stub and subsequent growth. This estimate did not consider whether there was an earlier, effective transition based on allowances in grading rules for lumber or veneer. The model developed indicated the number of years for this part of occlusion was dependent on the stub diameter and the radial growth rate of the tree.

If pruning is to be done, the forest manager must decide where, when, and how high to prune. Results of the branch stub occlusion studies indicate relatively fast growing trees with small limbs would be the best candidates for pruning. Performing the pruning in conjunction with thinning would minimize the number of stand entries and may significantly reduce administrative and operational costs. Pruning height determination is a function of wood utilization standards and tree physiology. If the objective is to produce a clear 16-foot (4.9 m) log for lumber manufacture, for example, then a conservative minimum height to prune is 18 feet (5.5 m), to allow for height of the stump and trimming at the mill. The physiological aspects of pruning are more complicated. Green pruning (*i.e.*, removing live branches) reduces crown size and may result in changes in photosynthate allocation. The general priorities of photosynthate allocation within trees are respiration; fine root and foliage production; flowering and seed production; height growth; diameter growth; and resistance to insects and diseases (Waring and Pitman 1985; Waring and Schlesinger 1985; Oliver 1990). In this order of allocation to metabolic pathways it would be expected that any appreciable changes in photosynthate production would be reflected first in pest resistance and diameter growth.

Effects of Pruning on Diameter Growth

Nordlinger (1864) and Vogl (1887) reported that one-third of the lower green branches of pine (*Pinus* spp.) and spruce (*Picea* spp.) could be removed without affecting stem increment. Stein (1955), working with Douglas-fir in Washington, pruned young trees to different heights and also concluded that one-third of the live crown length could be removed without harmful affect. Stein also reported that more diameter and height growth occurred on trees that had 25 percent of the live crown removed than on trees where only dead limbs were pruned. The reported increase in growth following pruning was, however, statistically nonsignificant. Möller (1960) theorized that almost any degree of pruning should result in a depressing effect on growth.

Gallagher (1975, 1984) reported the effects of green pruning on the growth of planted Sitka spruce in Ireland. Four levels of pruning intensity were applied: no pruning, 20 percent, 40 percent, and 60 percent removal of live crown. The results indicated that up to 40 percent of the live crown could be removed in one operation without significantly reducing diameter growth. Smith (1986) reported that diameter growth may be significantly reduced if the live crown ratio is reduced to 40 percent or less.

Effect of Pruning on Stem Form

Pressler (1865) discovered that, in some cases, pruning produced more cylindrically shaped boles than unpruned trees. Diameter growth at any point on the stem was found to be proportional to the amount of foliage above it, and the annual rings were widest directly beneath the crown. Similar findings were reported by Nordlinger (1864) and Hartig (1898). Staebler (1963) pruned Douglas-fir trees to breast height and to one-third, one-half, and two-thirds of their total height. Diameters were measured at breast height, at one-third, one-half, and two-thirds tree height, and at 0.5, 8.5, and 16.5 feet (0.15, 2.6, and 5.0 m) to compute log volume and taper. Analysis after two years indicated that pruning to more than one-third tree height resulted in a significant decrease in diameter growth at breast height but not at two-thirds height. The differential effects of pruning on diameter growth at different heights resulted in decreased taper along the stem. These results are consistent with Smith's (1986) explanation that growth along the stem is generally controlled by relative proximity to the photosynthate source.

Effects of Pruning on Height Growth

Height growth is generally reported to be less affected by pruning (Möller 1960; Staebler 1963; Smith 1986); however, Stein (1955) claimed that the intensity of pruning had a more critical effect on Douglas-fir height growth than on diameter growth. In Ireland, removing 60 percent of the live crown of Sitka spruce caused a 20 percent reduction in height growth in the first year after pruning; but thereafter there was no reduction (Gallagher 1975). Smith (1986) reported that height growth usually remains unaffected unless the live crown ratio is reduced to less than 30 percent. Excessive pruning, however, may result in tree mortality; pine (*Pinus* spp.), larch (*Larix* spp.), and spruce (*Picea* spp.) trees died when more than two-thirds to three-fourths of the crowns were removed (Hartig 1856; Fink 1863; Vogl 1887).

Sunscald Injury on Conifers

Sunscald is a stem lesion that appears after the phloem and cambium have died, usually in a long narrow strip. Sunscald is a winter phenomena and may occur on the south or southwest sides of trees with smooth, thin bark (Kramer and Kozlowski 1979; Smith 1986). The injury may occur on stems that were previously shaded and suddenly exposed to direct sunlight by thinning, pruning, or road construction (Smith 1986; Oliver 1990). Death of the cambium and phloem tissue may be caused by large temperature fluctuations during the dormant season; sunscald is primarily a result of the rapidity of temperature change rather than the intensity of heat (Kozlowski 1971; Daubenmire 1974). The injury may reduce diameter growth and provide an entrance for insects and decay-causing fungi.

Isaac (1945) and Stein (1955) reported on the occurrence of sunscald three, six, and 13 years after pruning 28-year-old Douglas-firs to different heights. Pruning treatments included removal of 25, 50, and 75 percent of live crown length and a control in which only lower dead branches were cut. Sunscald was more noticeable six years after pruning than it was three years after pruning; also, sunscald was more prevalent on trees that had 50 percent or more of the live crown length removed. Sunscald did not occur on any of the control trees. Three years after pruning, sunscald was present on two percent of the trees that had 25 and 50 percent crown removed and on 24 percent of the trees that had 75 percent crown removed. Six years after pruning, sunscald was present on two percent of the trees that had 25 percent crown removed, on 12 percent of the trees that had 50 percent crown removed, and on 33 percent of the trees that had 75 percent crown removed. Additional sunscald injury was not observed 13 years after pruning.

Potential Pathogens of Pruned Trees

Young trees with small branch diameters are better candidates for operational pruning than are trees with large branches because pruning time and effort increases as branch diameter increases. Furthermore, the amount of branch heartwood increases as branch diameter increases. Pruning wounds that expose heartwood are more likely to become infected with decay-causing fungi (Boyce 1961). Sleeth (1938) conducted an investigation of eastern white pine (*Pinus strobus* L.) and showed pruned branch stubs greater than two inches (5 cm) in diameter became infected with red heartrot (*Haematosterum sanguinolentum* (Alb. & Schw. ex Fr.) Pouzar[3]).

Branch protection zones develop within branch collars before branches die (Mayer-Wegelin 1936; Shigo 1989, 1991). In conifers, the protection zones are composed of fungi-inhibiting terpene-based substances. Decay-causing fungi colonize dead branches but are usually prevented from entering the main stem by the chemical barrier. The corewood of the branch may become infected, however, if the dead branch persists or if the fungi are aggressive. If the dead branch remains on the stem for a long time and aggressive fungi are present, the decay may enter the stem. Boyce (1923) described internal decay of Douglas-firs that entered through dead branches. Haddow (1938) studied white pocket rot in eastern white pines caused by *Phellinus pini* (Thore.:Fr.) A. Ames and

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[3] Fungi nomenclature conforms to that of Gilbertson and Ryvarden (1987) and Foster and Wallis (1974).

found the infections were associated with dead branches. Etheridge and Craig (1976) also found dead branches were vectors for heartrot in western hemlocks caused by Indian paint fungus (*Echinodontium tinctorium* Ell.& Ev.) Ell. Ev.

Childs and Wright (1956) dissected 253 pruned Douglas-fir trees. Infections by red heartrot (*Haematosterum sanguinolentum* (Alb.& Schw. ex Fr.) Pouzar) and brown top rot (*Fomitopsis cajanderi* (Karst.) Kotl. et Pouz.) were found to have entered both live- and dead-pruned branch stubs. Fifteen trees (6%) yielded heart-rotting fungi in cultures from discolored heartwood and 30 trees (12%) had some discolored heartwood but did not yield any heart-rotting fungi in culture. The average extent of the infections, however, was slight. In most cases, the infections were so limited in development that culturing was necessary for identification. Fungi usually die soon after compartmentalization of the pruning wounds; possibly early pruning with rapid wound occlusion would eliminate much of the internal defects caused by fungi that enter through dead branches.

Insects Attracted to Pruning Wounds

Pruned branch stubs are considered unsuitable habitats for most insects because resin begins to flow from the ends of live-pruned branch stubs. Resin flow is an effective determent against most insect attacks. Pitch moths, however, are an exception; the sequoia pitch moth (*Synanthedon sequoiae* Hy. Edwards[4]) and Douglas-fir pitch moth (*Synanthedon novaroensis* Hy. Edwards) are two clearwing moth species known to

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[4] Pitch moth nomenclature conforms to that of Eichlin and Duckworth (1988).

attack conifers in western North America. Adult female pitch moths are attracted to resin exudations and lay eggs at the edges of wounds on host trees. Larvae bore into the cambial region, severe resin canals in the sapwood, and cause pitch masses to form over the wounds. Pitch moth larvae may feed for one to three years before pupating. Presence of pitch masses may delay wound occlusion for many years and cause economic losses, especially if repeated attacks occur over a number of years. Occlusion of the pruned branch stub, plus any accumulated pitch and bark, must occur before clear wood is produced.

Johnson (1993) reported on the activity of Douglas-fir pitch moths in two pruned Douglas-fir stands in western Washington. Within two years, pitch moth attacks were observed on 14.8 percent of pruned trees in one stand, and 27.5 percent of pruned trees in the other stand. Johnson (1993) recommended pruning early in the rotation as part of a strategy to minimize economic losses caused by pitch moth damage. Early pruning results in rapid occlusion and thereby reduces the amount of time during which oviposition could occur. If pitch moth attacks occur on small pruned trees, the damage becomes compartmentalized within a smaller defect core than if a larger tree were pruned and subsequently attacked.

Economic Analyses of Pruning

An increase in value from pruning results from increased recovery of clear wood products from pruned logs compared to unpruned logs. Financial returns from pruning primarily depend on pruning costs and price differentials between clear grades and lower product grades of lumber and veneer. Pruning costs include labor wages, equipment overhead, operating costs, administrative costs, and the number of investment years (reflected in the compound interest rate). Return to the landowner is the price received for stumpage. Projecting stumpage prices for pruned trees is difficult because current log grading rules do not take into account increase in quality resulting from pruning. An alternative to trying to project stumpage prices is to utilize information from product recovery studies of pruned and unpruned logs. The value differential for products recovered from pruned and unpruned logs can be compared to the cost of pruning.

Expected financial returns from pruning Douglas-fir and ponderosa pine were estimated using DF PRUNE and PP PRUNE software programs (Fight *et al.* 1992, 1993; Bolon *et al.* (1992). DF PRUNE incorporates product recovery results from intensively managed Douglas-fir (Fahey *et al.* 1991). The DF PRUNE program requires the user to input data on tree age, diameter, height, and limb diameter at the time of pruning and at the time of harvest. Additional input used in the program includes diameter at breast-height-age 20 years, tree survival, pruning cost, projected product prices, and interest rates. The output includes lumber and veneer grade recovery from pruned and unpruned 16.5-foot (5 m) logs, future log values, and the present net worth of the increase in value from pruning.

Sensitivity analyses of pruning were performed using site index, fertilization, pruning age, rotation length, and interest rate as the variable factors (Fight *et al.* 1987; Fight 1993). The analyses indicate forest pruning is an economically feasible and viable silvicultural practice under a range of stand management regimes. Regimes promoting faster growth of crop trees showed greatest expected financial returns. Many regimes showed internal rates of return greater than four percent real rate -- up to seven percent in ponderosa pine and greater than nine percent in Douglas-fir.

Following are descriptions of additional biological and economic factors that may affect the outcomes of financial analyses:

Across sites there will be differences in interwhorl lengths (distances between branch whorls) which will determine the number of branches to be removed in a fixed-lift pruning. Trees growing on low sites may have shorter interwhorls and thus a greater number of branches to be pruned. Trees growing on high sites may have fewer branches within a given height but the branch diameters may be greater. Both of these factors, branch number and diameter, will most likely influence pruning time and, consequently, operation costs.

Pruning costs may vary with the age of the trees to be pruned. Operation costs may increase if pruning is done later in the rotation because of larger branch diameters, especially when trees are grown at wide spacing.

Rate of occlusion of pruned branch stubs may also vary with the age of the trees when pruned. Occlusion usually occurs faster when trees are pruned early in the rotation when branch collars are small and bark is thin. Branch stubs occlude faster when live branches are pruned compared to pruning dead branches (Finnis 1953). If pruning is done later in the rotation and branch stub occlusion is slower, then recovery of clears from the pruned logs will decrease.

The DF PRUNE program has a conservative bias because the lumber recovery for pruned logs is based on production-oriented rather than grade-oriented processing. A grade-oriented sawmill would probably get higher grade recovery from pruned logs than predicted by the model (Fight *et al.* 1992).

The estimated financial returns from pruning are based primarily on price differentials between clear grades and lower lumber and veneer grades. In actuality, all of the increase in product value from pruning will not be bid into the stumpage prices and thus, the landowner will not receive the full return predicted by DF PRUNE or PP PRUNE. In a competitive stumpage market, however, sellers should receive premiums for pruned trees that reflect the increase in value resulting from a higher proportion of clear wood.

Pruning in Northwestern North America

Implementation of proper pruning techniques in young stands of Douglas-fir, western hemlock, and Sitka spruce has the following potential benefits:

- production of a clear shell of high-quality wood outside a defect core on pruned trees;
- acceleration of the transition from juvenile to mature wood;
- decreased taper of pruned trees;
- reduction of fluting of western hemlock;
- improvement in the quantity and quality of understory vegetation;
- reduced fuels ladders;
- improved stand appearance (aesthetics); and
- employment opportunities that may help to maintain community

stability.

Undesirable effects of pruning may include:

- increased epicormic branching on pruned stems of Douglas-fir and Sitka spruce;
- sunscald;
- creation of infection courts for stem rotting fungi; and
- decreased diameter or height growth if too much of the live crown is removed.

Although the potential benefits of pruning appear to outweigh the adverse effects, the overall effects are poorly understood in the case of Douglas-fir, western hemlock, and Sitka spruce. For example, little is known about the effects of pruning to different live crown ratios on subsequent height and diameter growth. Operational pruning cost information is also needed for an adequate economic assessment. Separate studies of variable-lift pruning and pruned branch stub occlusion in Douglas-fir in Oregon, Washington, and British Columbia are being conducted through the Stand Management Cooperative, a university-industry-government agency research cooperative based at the University of Washington.

Part III. Experimental Design and Procedures

Permanent study plots were installed on the Tongass National Forest in 1990, 1991, and 1992 to monitor and quantify the biological response of western hemlock and Sitka spruce to thinning and pruning. A randomized complete block design with four blocks and four treatments was used for the experiment. Young trees in mixed stands were thinned to 170 trees per acre (420 trees/ha) and pruned to three different heights, 8, 12, and 17.4 feet (2.4, 3.7, and 5.3 m), to determine how much of the live crown can be removed before diameter and/or height growth are significantly affected. The 8- and 12-foot (3.7 and 5.3 m) heights were selected based on their practicality for operational pruning using handsaws and polesaws. Pruning to a height of at least 17.4 feet (5.3 m) is recommended to produce a clear 16-foot (4.9 m) log with allowance for stump height and mill trim; some contracts specify pruning to 18 or 20 feet (5.5 or 6.1 m). A pruner can easily reach to 8-feet (2.4 m) with a handsaw, and then to 12-feet (3.7 m) using a polesaw with a 6-foot (1.8 m) pole section. With two 6-foot (1.8 m) sections, a pruner can reach to 18-feet (5.5 m). If pruning young trees to 18 feet (5.5 m) in one operation proves to be too severe, and significantly reduces growth, then pruning could possibly be done in two or three stages, or lifts. For example, in a two-lift operation the trees could be pruned to 9 feet (2.7 m) in the first lift, and then several years later, after the trees have increased in height, the trees could be pruned to 18 feet (5.5 m) in the second lift.

Site Characteristics

Permanent study plots were established in four stands with uniform topography and species composition within the western hemlock-Sitka spruce forest type. The plots were established in three stands near Hollis, Thorne Bay, and Coffman Cove on Prince of Wales Island and in a fourth stand near Juneau (Figures 2 and 3); the respective stands are referred to as Cave Creek, Salamander Lake, Coffman Cove, and Lemon Creek. Stand characteristics are summarized in Table 1 and detailed site descriptions are given in Appendix A.

Table 1. Summary stand characteristics of four western hemlock-Sitka spruce pruning installations on the Tongass National Forest.

Features	Stands			
	Lemon Creek	Cave Creek	Salamander Lake	Coffman Cove
Elevation (ft)	140	600	340	300
Aspect	Southeast	North	South	Southwest
Slope (%)	7-12	5-40	10-35	25-35
Precipitation (in)	90	160	160	90
Clearcut	1967-68	1965	1962	1967
Thinned	1990	1984 1990	1980 1991	1982 1992
Pruned	1990	1990	1991	1992

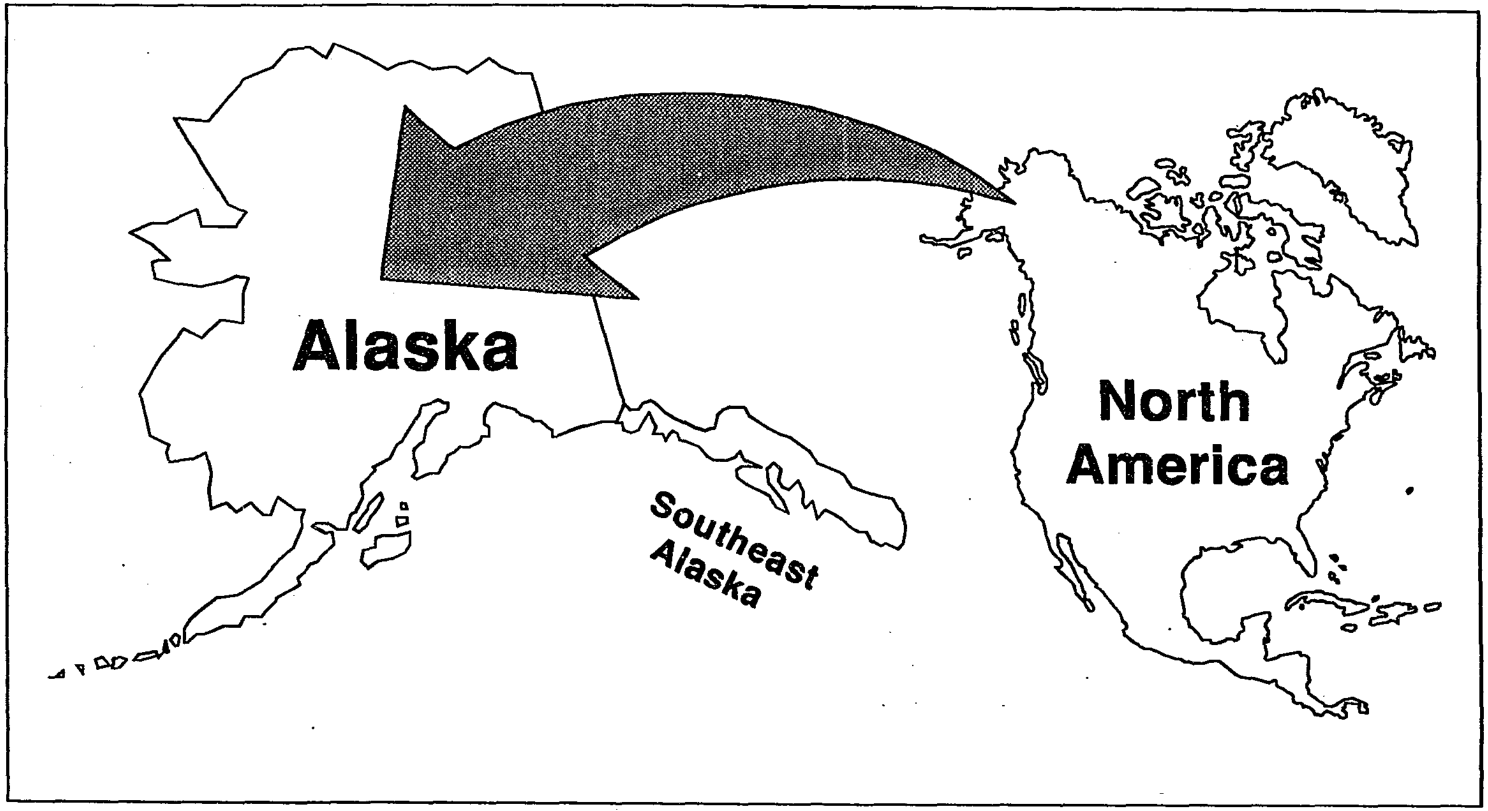


Figure 2. Location of Southeast Alaska in relation to North America.

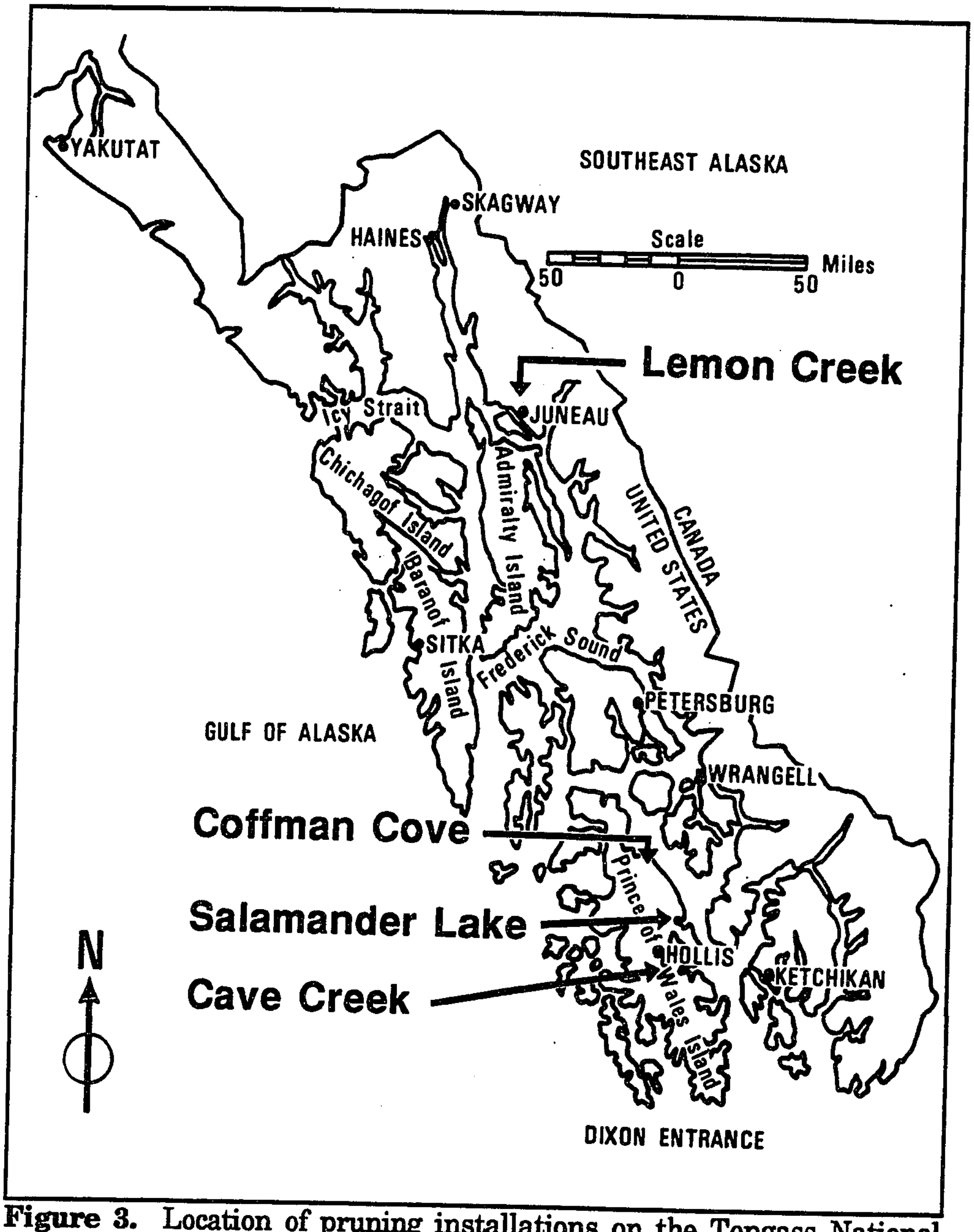


Figure 3. Location of pruning installations on the Tongass National Forest, Southeast Alaska.

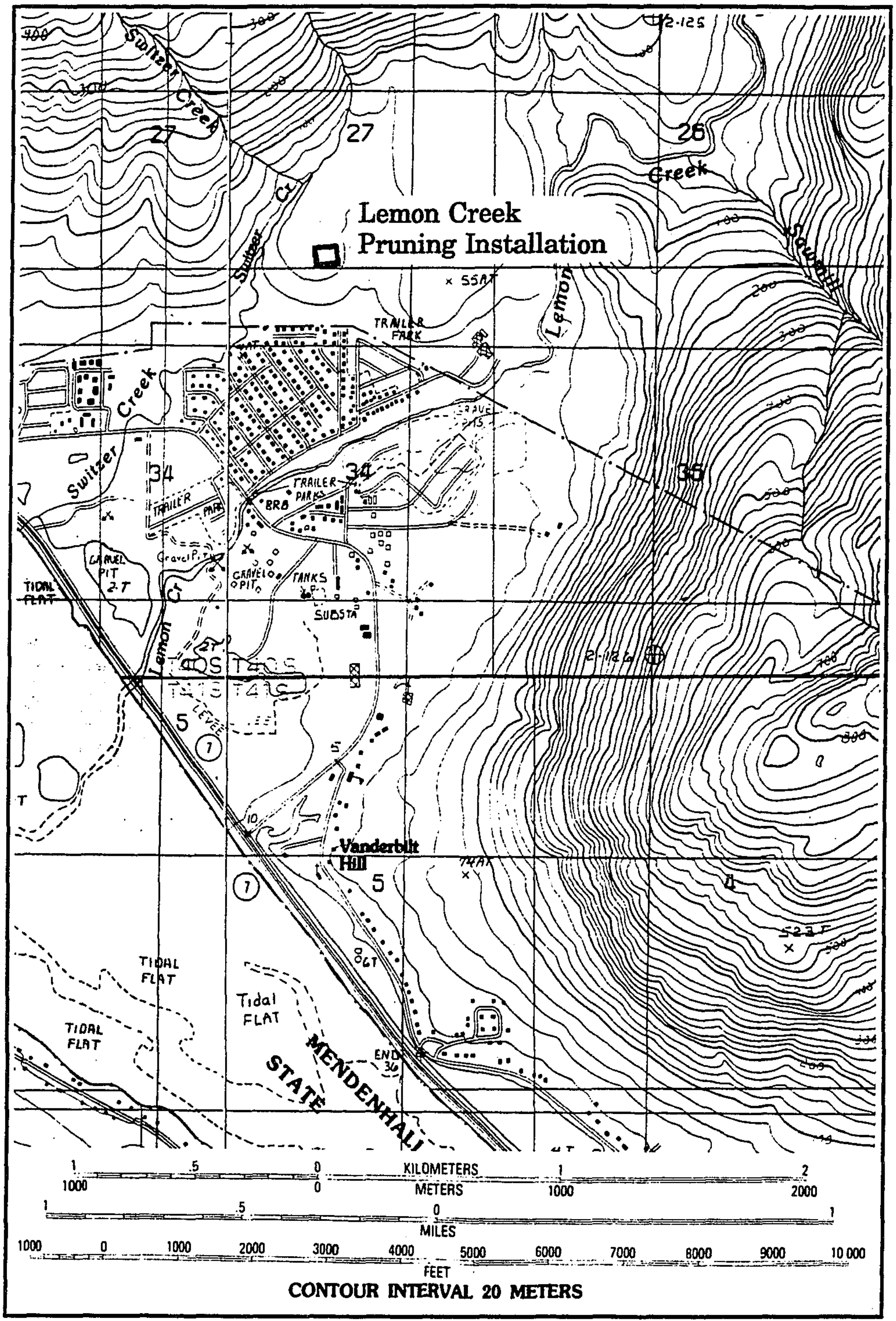


Figure 4. Location of Lemon Creek pruning installation: Section 27, T40S, R66E.

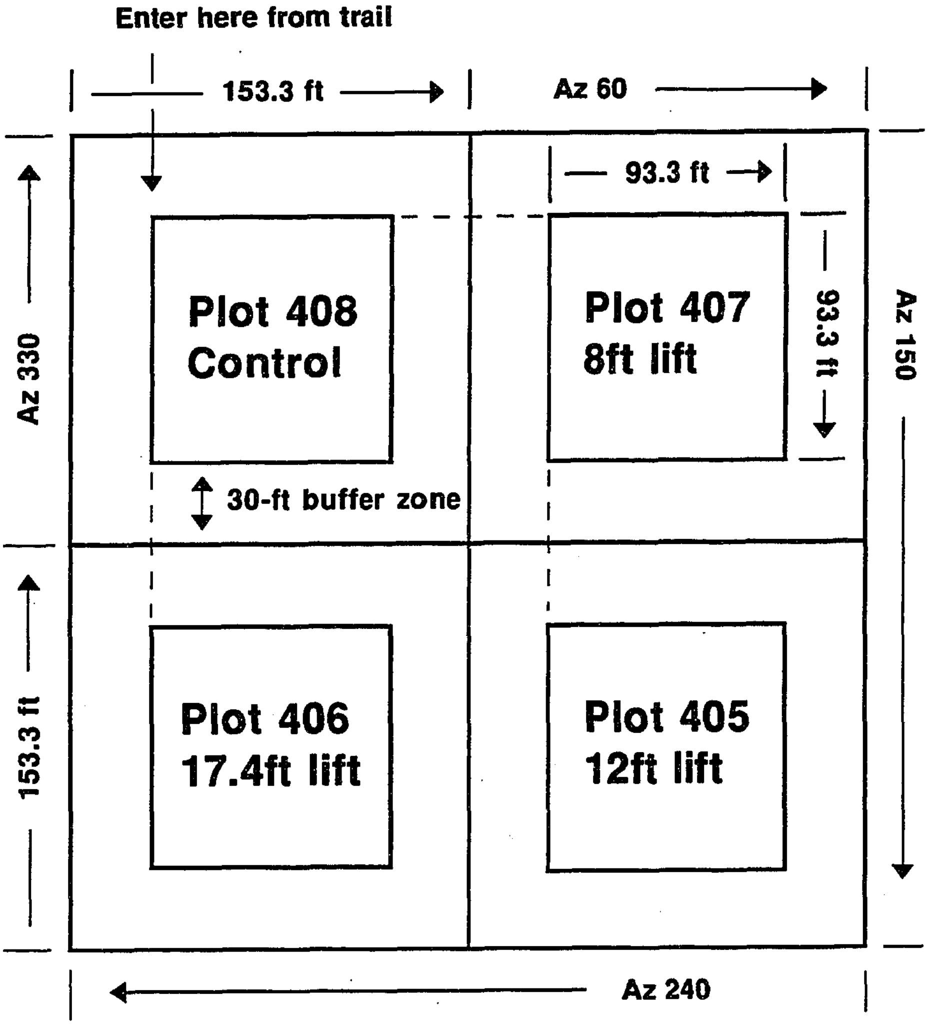


Figure 5. Layout of Lemon Creek pruning installation. Treatment plot dimensions are 153.3 x 153.3 feet (0.54 acre); each treatment plot contains a 0.2-acre measurement plot (93.3 x 93.3 feet) with a 30-feet buffer zone on all sides.

Plot Layout

At each location, four 0.54-acre (0.22 ha) treatment plots were established (Figures 5, A-4, A-5, and A-6); dimensions of a single treatment plot are 153.3 x 153.3 feet (46.7 x 46.7 m). Each treatment plot contains a 0.2-acre (0.08 ha) measurement plot with a 30-foot (9.1 m) buffer zone on all sides (Figure 6); dimensions of a single measurement plot are 93.3 x 93.3 feet (28.4 x 28.4 m). Total area for each installation is 2.15 acres (0.87 ha).

Treatment and measurement plots were established using compass and tape. Corners were marked with aluminum posts and aluminum tags indicating plot number and corner number (e.g., Plot 401, Corner 1). To facilitate inventory and stem mapping, each measurement plot was divided into 4 strips, each 23.3 feet (7.1 m) wide and 93.3 feet (28.4 m) long. Beginning at corner #1 and moving towards corner #2, temporary stakes were placed in the ground at 23.3-foot (7.1 m) intervals. Stakes were also placed in the ground at 23.3-foot (7.1 m) intervals between corner #3 and corner #4. Ropes were laid out across the plots (between the stakes) to delineate the 4 strips. Nine interior points were established with aluminum posts placed 23.3 feet (7.1 m) apart along the ropes. The interior points were numbered 1 through 9, as shown in Figure 6. Stem maps were prepared for each of the installations.

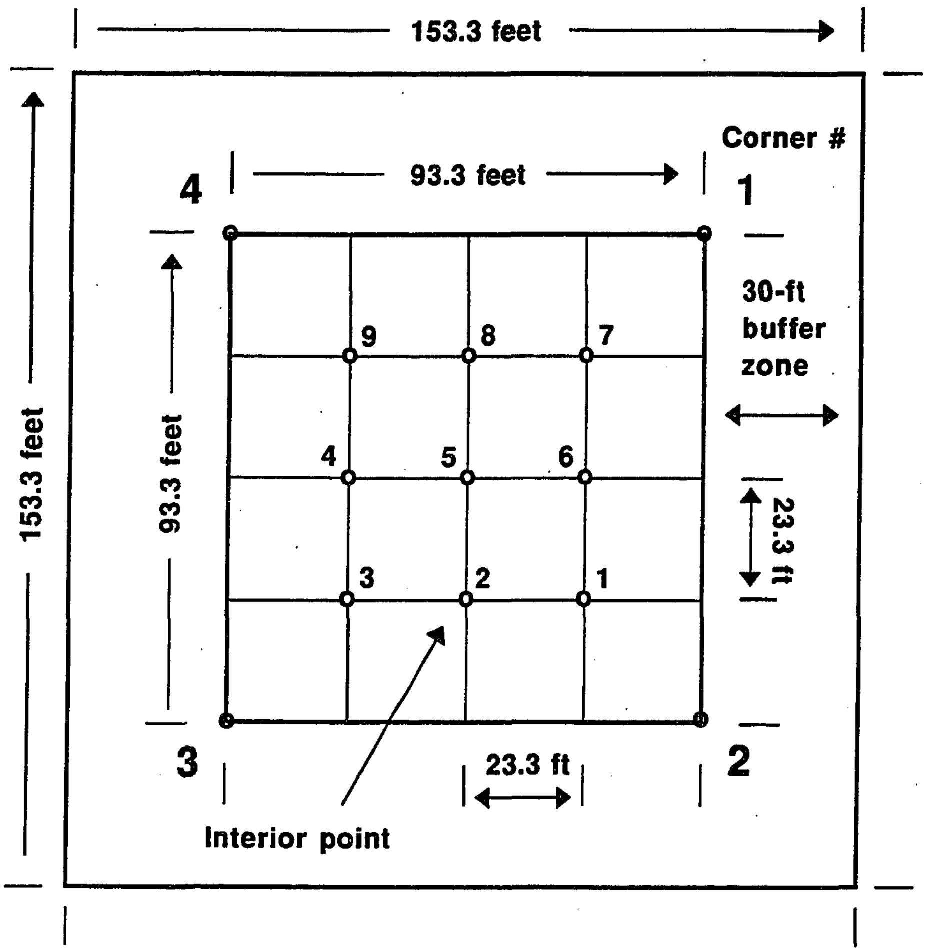


Figure 6. Layout of a treatment and measurement plot. Each treatment plot is 153.3 x 153.3 feet (0.54 acre) and contains a 0.2-acre measurement plot (93.3 x 93.3 feet) with a 30-feet buffer zone on all sides.

Selection of Leave Trees

Dominant and codominant hemlocks and spruces were selected and marked with flagging at an average spacing of 16 x 16 feet (5 x 5 m) to reduce the average stand density to 170 trees per acre (420 trees/ha). Some western redcedars were selected to maintain uniform spacing.

Thinning Operation

Stand density at Lemon Creek was reduced to 170 trees per acre (420 trees/ha) in 1990 using chainsaws. The stand at Cave Creek had been precommercially thinned in 1984 to an average spacing of 13 x 13 feet (4 x 4 m), which reduced stand density to 244 trees per acre (603 trees/ha). Additional trees were felled in 1990 to obtain a uniform density of 170 trees per acre (420 trees/ha). The stands at Thorne Bay and Coffman Cove were also precommercially thinned prior to selection (Table 1) and then respaced to 170 trees per acre (420 trees/ha) at the time of pruning.

Treatments

All experimental units were thinned to 170 trees per acre (420 trees/ha). Treatments also included pruning to three different heights (fixed lifts) and a control in which no pruning was done (Figure 7). The following treatments were randomly assigned to each of the four treatment plots in each block:

- Control - thin with no pruning;
- Thin and prune to 8 feet (2.4 m);
- Thin and prune to 12 feet (3.7 m); and
- Thin and prune to 17.4 feet (5.3 m).

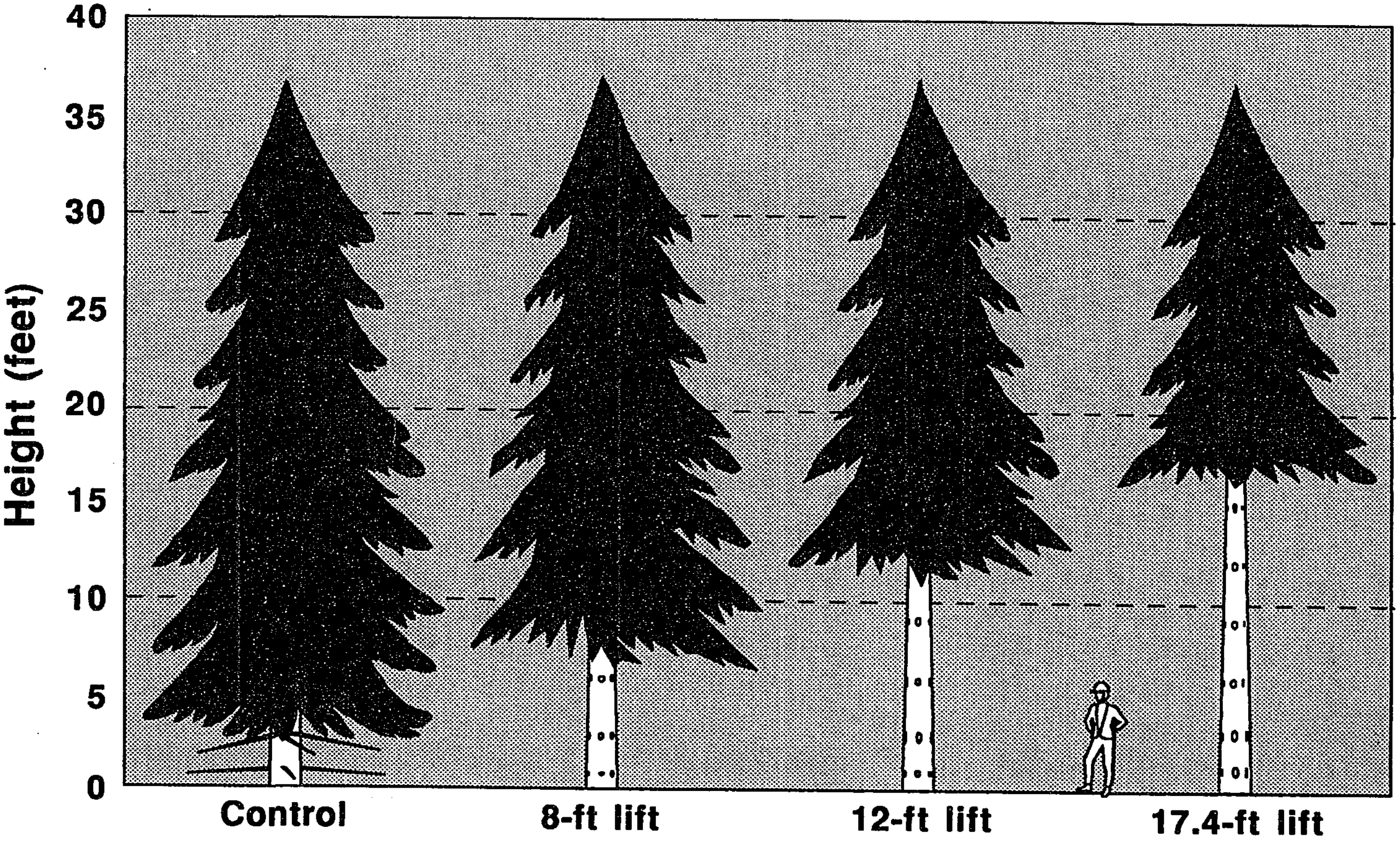


Figure 7. Treatments included three pruning heights (fixed lifts of 8, 12, and 17.4 feet) and a control in which no pruning was done. All experimental units were thinned to 170 trees per acre.

Trees were pruned to 8 feet (2.4 m) above the ground using a 24-inch (61 cm) D-handle pruning saw. The saw had a removable handle which allowed the same saw blade to be mounted on a 6-foot (1.8 m) pole. Trees were pruned from 8 to 12 feet (2.4 to 3.7 m) using one 6-foot (1.8 m) pole section; and from 12 to 17.4 feet (3.7 to 5.3 m) using two interconnecting pole sections.

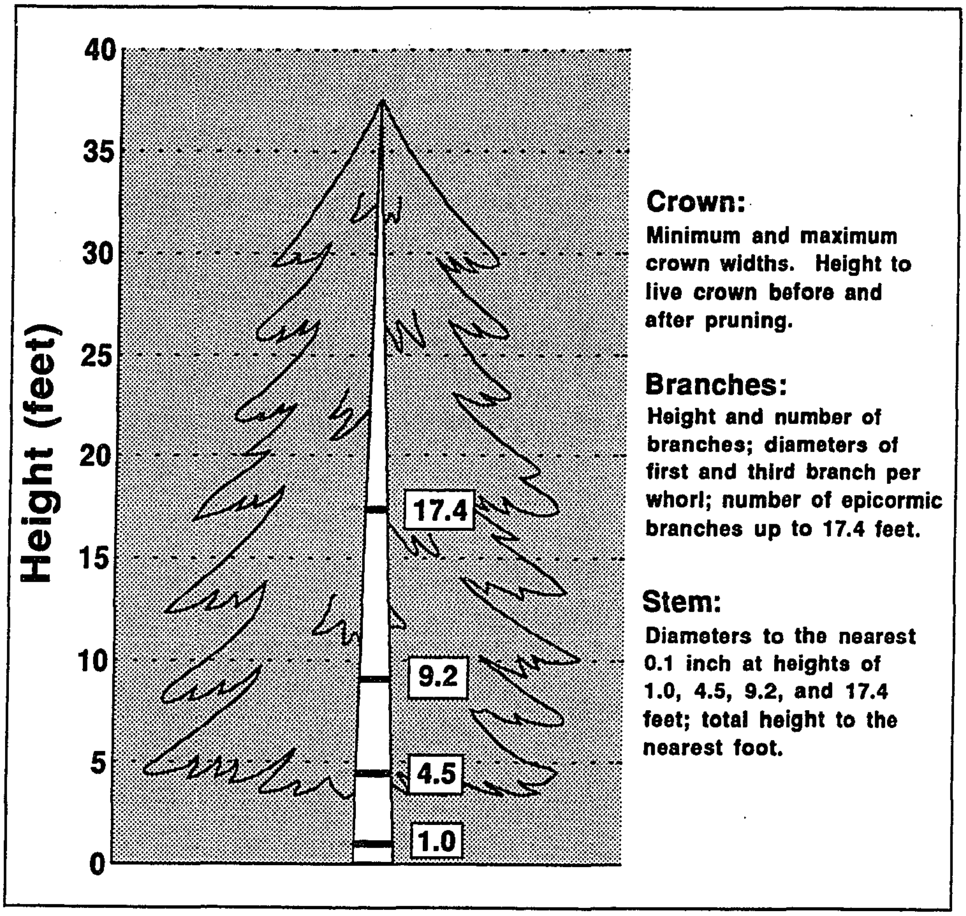
Measurements

All trees within measurement plots were numbered and plotted on stem maps; the following measurements were recorded for each tree:

- species code (spruce=98; hemlock=263; redcedar=242);
- diameter at 4.5 feet (1.4 m) to the nearest 0.1 inch (0.25 cm);
- height to live crown before pruning to the nearest 0.1 foot (0.03 m);
- height to live crown after pruning to the nearest 0.1 foot (0.03 m);
- total height to the nearest 1.0 foot (0.03 m).

At Lemon Creek and Cave Creek, five hemlocks and five spruces were randomly selected within each measurement plot for detailed stem, branch, and crown measurements before pruning (Figure 8). Additional measurements on these 80 trees included:

- Stem: Diameters to the nearest 0.1 inch (0.25 cm) at heights of 1.0, 9.2, and 17.4 feet (0.3, 2.8, and 5.3 m).
- Branches: Total number of branches up to 17.4 feet (5.3 m); separate record of epicormic branches; branch diameters of first and third branch per whorl on spruce, and diameter of upper branch at 2-foot (0.6 m) intervals up the stem on hemlock.



Crown:
Minimum and maximum crown widths. Height to live crown before and after pruning.

Branches:
Height and number of branches; diameters of first and third branch per whorl; number of epicormic branches up to 17.4 feet.

Stem:
Diameters to the nearest 0.1 inch at heights of 1.0, 4.5, 9.2, and 17.4 feet; total height to the nearest foot.

Figure 8. Sitka spruce crown, branch, and stem measurements recorded at Cave Creek and Lemon Creek pruning installations.

▸ Crown: Minimum and maximum crown radii to the nearest 1.0 foot (0.3 m); height to live crown before and after pruning to the nearest 0.1 foot (0.03 m).

Time-and-Motion Data

Times were recorded to the nearest second for each of the following motions:

- Walk between trees;
- Prune to 8 feet (2.4 m);
- Prune from 8 to 12 feet (2.4 to 3.7 m); and
- Prune from 12 to 17.4 feet (3.7 to 5.3 m).

Data Analysis

The general linear models procedure in the Strategic Applications Software (SAS®) system was used to perform analysis of variance for the randomized complete block design. Block, treatment, and species means were compared using Duncan's multiple-range test. Multiple regression analysis was also used to model the time required for pruning and the growth responses of western hemlock and Sitka spruce after pruning.

It was hypothesized that the time required for pruning would be a function of number of branches, branch basal area, stem diameter, and pruned height. The null hypotheses were there are no functional relationships between the time required for pruning and branch number, branch basal area, stem diameter, or pruned height.

It was also hypothesized that stem quality and growth responses of hemlock and spruce would be a function of pruned height, percent live crown length removed, live crown ratio after pruning, and stem diameter at the time of pruning. The null hypotheses were there are no functional relationships between stem quality or growth and pruning. Epicormic branching and incidence of sun scald were evaluated to assess pruning affects on stem quality. Parameters used to quantify the growth responses included survival, changes in tree height, stem diameter, taper of the first 16-foot (4.9 m) log, tree basal area, and volume of the first

16-foot (4.9 m) log. These parameters were evaluated individually and in combinations to determine the functional relationships between tree growth and pruning.

Part IV. Experimental Results and Discussion

The randomized complete block design included four blocks with four treatment plots per block. The blocks are also referred to as installations or stands. Each treatment plot, consisting of a measurement plot and a buffer zone, was thinned to a stand density of 170 trees per acre (420 trees/ha). After thinning there were approximately 1500 trees within the boundaries of the four installations (including measurement plots and buffer zones). A total of 537 trees included within the 16 measurement plots were measured prior to pruning and were monitored for responses after treatment.

Species Composition

Numbers of trees by species and stands are shown in Table 2. The low-elevation commercial forests of Southeast Alaska range in species composition from pure stands of either western hemlock or Sitka spruce to mixed proportions of hemlock, spruce, western redcedar (*Thuja plicata* Donn ex D. Don), and Alaska cedar (*Chamaecyparis nootkatensis* (D. Don) Spach.). Spruce is usually favored in thinning operations. Equal numbers of hemlock and spruce were selected when possible during thinning of the installations; occasional redcedars were retained to maintain a uniform stand density. The total number of trees in all measurement plots in the four stands included 268 (49.9%) western hemlock; 251 (46.7%) Sitka spruce; and 18 (3.4%) western redcedar.

Diagnostic Stand Variables

Diagnostic stand variables measured after thinning and before and after pruning included stem diameter at breast height (DBH), total tree height, height to live crown, and live crown ratio. Distributions of the stand variables for all species and all stands combined are shown in Figure 9.

Table 2. Frequency by species within 16 measurement plots in four stands on the Tongass National Forest.

Species	Stands Cave Creek #	 %	 Lemon Creek #	 %	 Salamander Lake #	 %	 Coffman Cove #	 %
Hemlock	76	58.5	56	41.2	67	48.6	69	51.9
Spruce	51	39.2	80	58.8	65	47.1	55	41.3
Redcedar	3	2.3	0	0	6	4.3	9	6.8
Total #	130		136		138		133	

Means, standard deviations, and ranges of the variables by stands are shown in Table A-1. The general linear models procedure in the Strategic Applications Software (SAS®) system was used to perform analysis of variance for the stand variables. Variable means were compared using Duncan's multiple-range test and significant differences between stands, treatments, and species are reported at the 0.05 level of significance unless noted otherwise.

Targets for stand selection were mean diameter (DBH) of 6 inches (15 cm) and mean height of 35 feet (10.7 m). Mean diameter (DBH) for the four selected stands combined was 7.1 inches (18 cm); approximately two-thirds (68%) of the diameters were between 4.6 and 9.6 inches (11.7 and 24.4 cm). Mean diameter was highest at Coffman Cove (9.1 inches, 23.1 cm), and lowest at Lemon Creek (5.3 inches, 13.5 cm). Mean height for all stands combined was 37.4 feet (11.4 m); approximately two-thirds (68%) of the heights were between 29.3 and 45.5 feet (8.9 and 13.9 m). Mean height was highest at Coffman Cove (43.6 feet, 13.3 m), and lowest at Cave Creek (33.3 feet, 10.1 m). The wide range of diameters (1.8 to 16 inches, 4.6 to 40.6 cm) and heights (13 to 62 feet, 4 to 19 m) reflected the high degree of microsite variability within each of the stands. Nonuniform site conditions are typical for the western hemlock-Sitka spruce forest type on the Tongass National Forest.

Height to live crown (HLC) is a measure of crown recession and is affected by stand density. Live crown length (CL) is calculated by subtracting height to live crown from total tree height (HT) (*i.e.*, CL = HT - HLC). Live crown ratio (LCR) is a ratio of crown length to total tree height; it is a relative measure of the photosynthate production potential of a tree and is calculated by dividing crown length by height and multiplying by 100 (*i.e.*, LCR = CL/HT x 100). As stand density increases, height to live crown increases, crown length decreases, and live crown ratio decreases. Height to live crown and live crown ratio distributions (Figure 9) were representative of trees within the sampled height and diameter ranges. Mean height to live crown for all species and stands combined was 5.5 feet (1.7 m). Mean height to live crown was highest at Lemon Creek (10.1 feet, 3.1 m) and lowest at Cave Creek (3.3 feet, 1.0 m). Mean live crown ratio for all species and stands combined was 85 percent. Mean live crown ratio was highest at Coffman Cove (90%) and lowest at Lemon Creek (71%).

Figure 10 shows the means of the stand variables after thinning, but before pruning, for all species combined by stands. Lemon Creek differs from the other three stands in that it was precommercially thinned for the first time at stand age 22, in the same year it was pruned. Cave Creek was precommercially thinned at stand age 19; it was respaced and pruned six years later, at age 25. Salamander Lake was precommercially thinned at age 17 and then respaced and pruned 11 years later, at age 28. Precommercial thinning at Coffman Cove was done at age 14; respacing and pruning was done 10 years later, at age 24. Mean height to live crown at Lemon Creek (10.1 feet, 3.1 m) was significantly higher than the other stands as a result of the delayed thinning; and mean live crown ratio (71%) was significantly lower than the other stands.

Mean height-to-diameter ratios by stands are shown in Figure 11. The height-to-diameter ratio (tree height and diameter in the same units, *e.g.*, feet or meters) is an indicator of tree stability, the higher the value the less stable the trees are. Trees with high height-to-diameter ratios are susceptible to wind breakage or blowdown. Height-to-diameter ratios were significantly higher for both hemlock and spruce at Lemon Creek. Storms with high winds are common during Autumn in Southeast Alaska. In October 1990, several hemlocks and spruces at Lemon Creek were blown down or broken during a storm with high winds. Low height-to-diameter ratios can be maintained by thinning stands early in the rotation, delayed thinning or no thinning at all results in high height-to-diameter ratios.

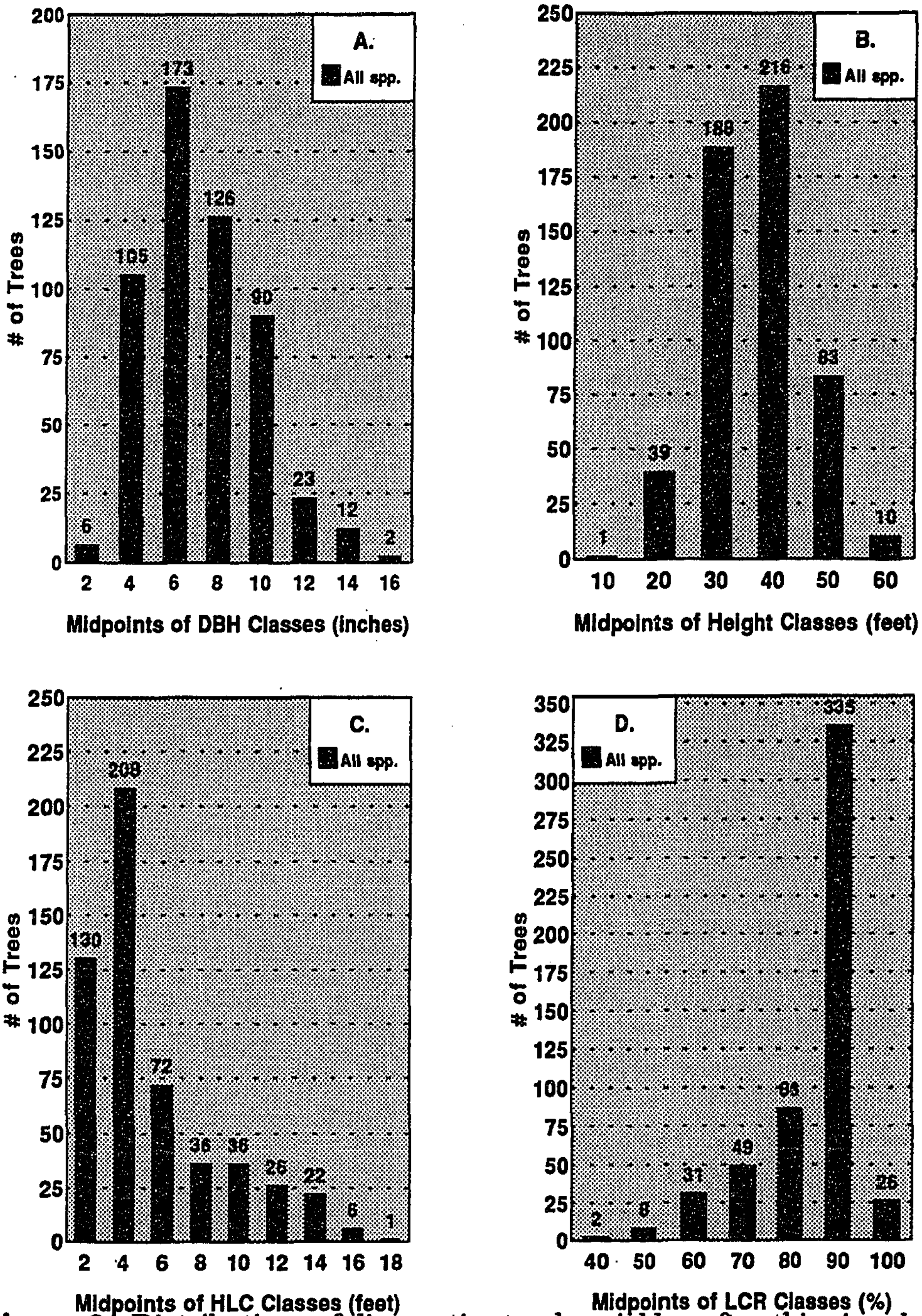


Figure 9. Distributions of diagnostic stand variables after thinning, but before pruning, for all species and all stands combined: A. diameter at breast height (DBH); B. total height; C. height to live crown (HLC); and D. live crown ratio (LCR).

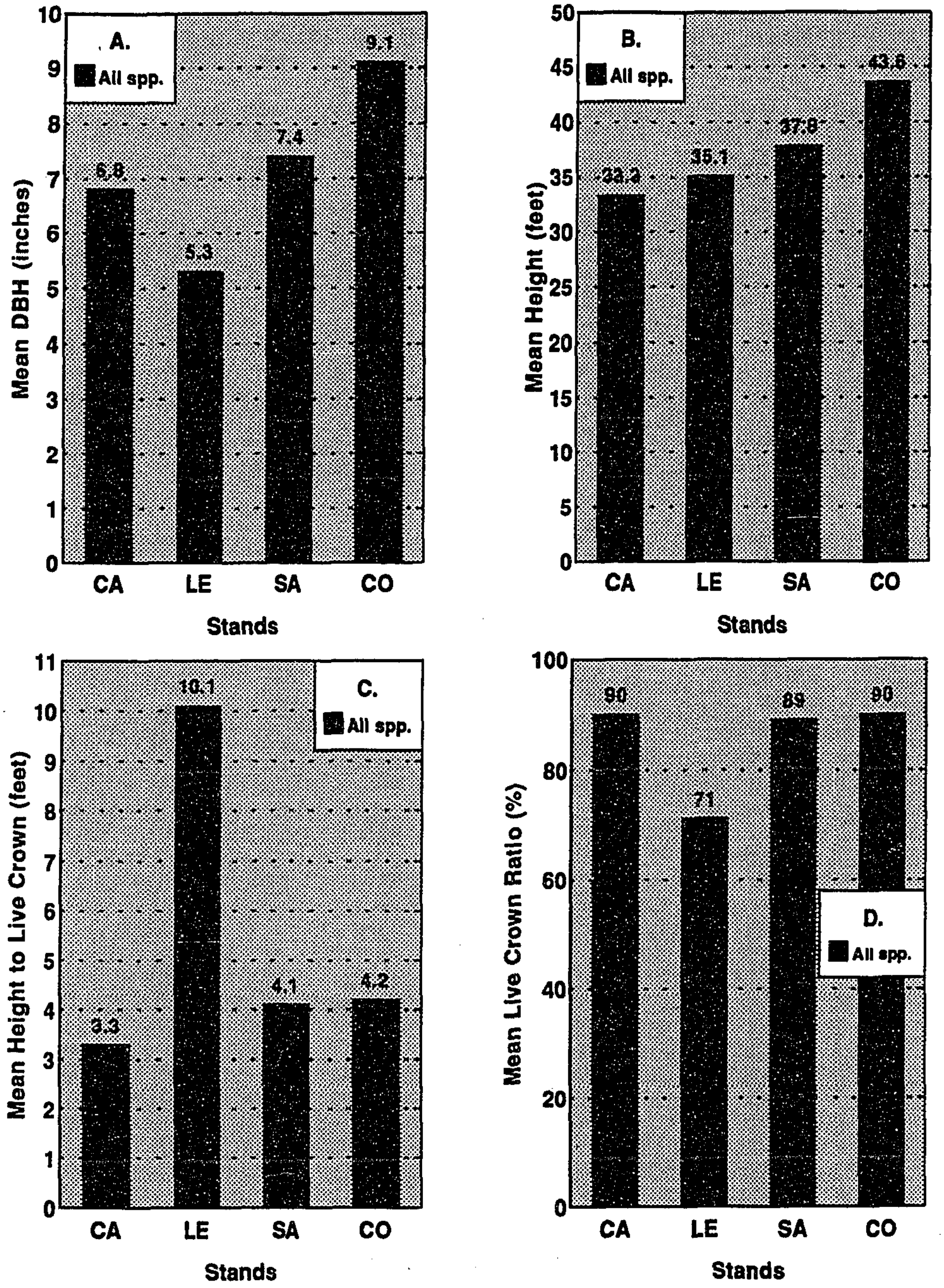


Figure 10. Means of diagnostic stand variables after thinning (before pruning) for all species combined by stands: A. diameter at breast height (DBH); B. height; C. height to live crown; and D. live crown ratio. CA=Cave Creek; LE=Lemon Creek; SA=Salamander Lake; and CO=Coffman Cove.

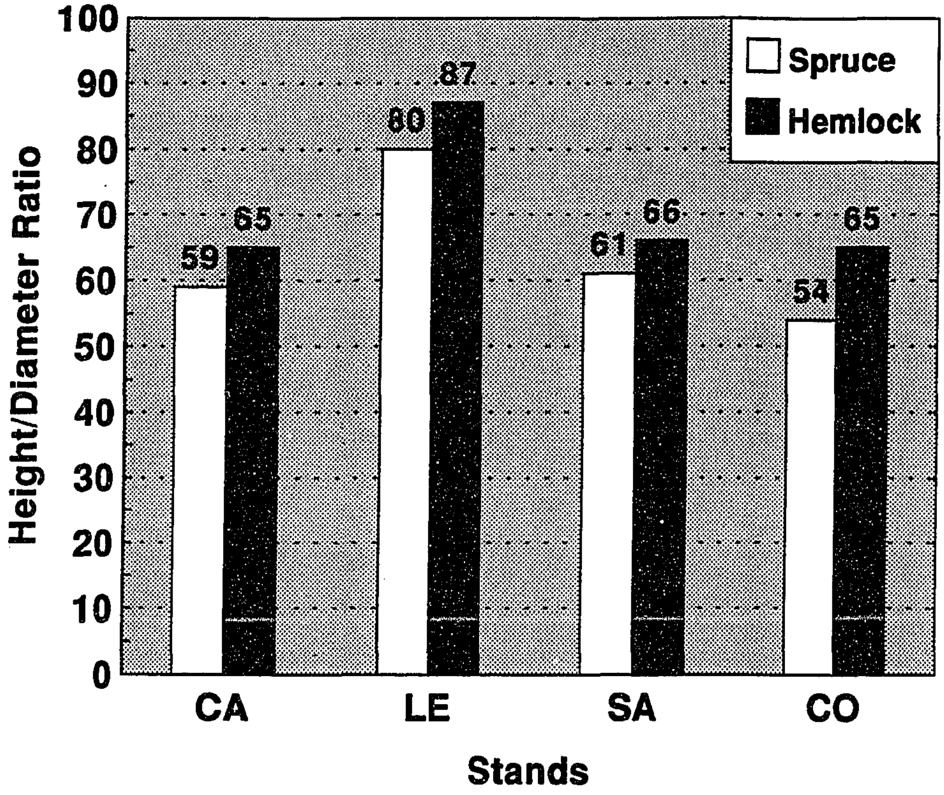


Figure 11. Height/diameter ratios for hemlock and spruce by stands: CA=Cave Creek; LE=Lemon Creek; SA=Salamander Lake; and CO=Coffman Cove.

Hemlock and spruce diameter distributions by stands are shown in Figure 12 and Table A-2. There were more hemlocks than spruces at Cave Creek (see also Table 2), especially in the 6-inch diameter class, and more spruces than hemlocks at Lemon Creek, also most noticeable in the 6-inch diameter class. Lemon Creek had a narrower range of diameters because of the delayed thinning. Salamander Lake and Coffman Cove had approximately equal numbers of hemlocks and spruces. Mean hemlock diameter (DBH), for all stands combined was 6.7 inches (17.0 cm) with a standard deviation (s) of 2.1 inches; and mean spruce diameter was 7.7 inches (19.5 cm, s=2.9 inches).

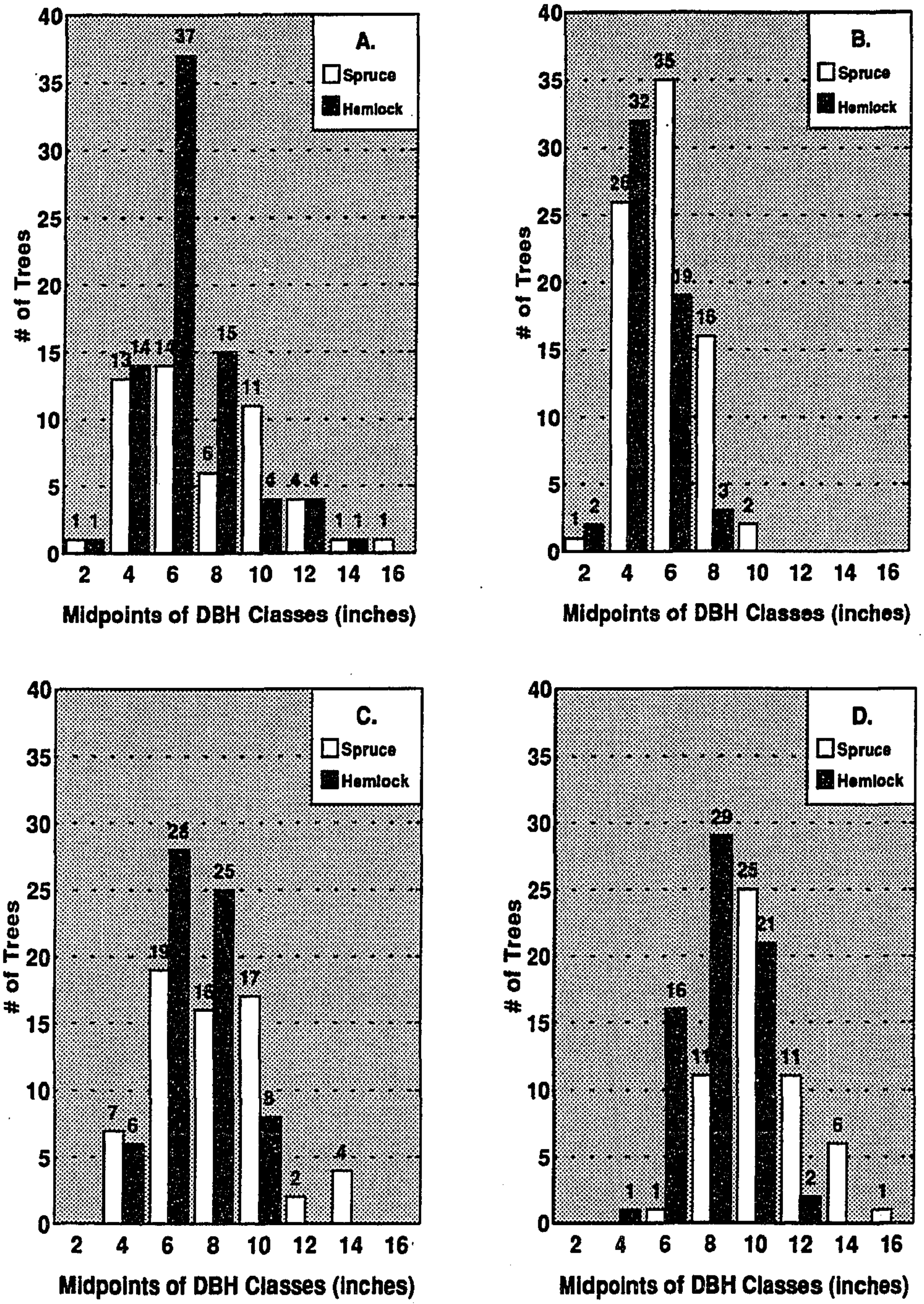


Figure 12. Hemlock and spruce diameter distributions by stands: A. Cave Creek; B. Lemon Creek; C. Salamander Lake; and D. Coffman Cove.

Hemlock and spruce height distributions by stands are shown in Figure 13 and Table A-3. Mean height of hemlock, for all stands combined, was 37 feet (11.3 m, s=7.2 feet); and mean spruce height was 39 feet (12 m, s=8.4 feet).

Figure 14 shows height to live crown distributions before pruning for all species combined by stands. Mean hemlock height to live crown was 5.5 feet (1.7 m, s=3.7 feet) and mean spruce height to live crown was 5.6 feet (1.7 m, s=3.3 feet). Differences between species were not as great as differences between stands so species were grouped together by height to live crown classes in Figure 14. Lemon Creek had a higher mean height to live crown as well as a wider range of height to live crown values because of the delayed thinning. Live crown ratio distributions before pruning are shown in Figure 15; mean hemlock live crown ratio was 85 percent (s=11.2) and mean spruce LCR was also 85 percent (s=9.4). Live crown ratio differences between species were not as great as differences between stands so species were grouped together for graphical display. Lemon Creek had the lowest mean live crown ratio and the widest range of live crown ratio values because of the high stand density prior to thinning.

Figure 16 shows the mean diameters (DBH) and heights by plots prior to treatment. Differences in mean diameters and heights between plots within stands (blocks) were statistically nonsignificant.

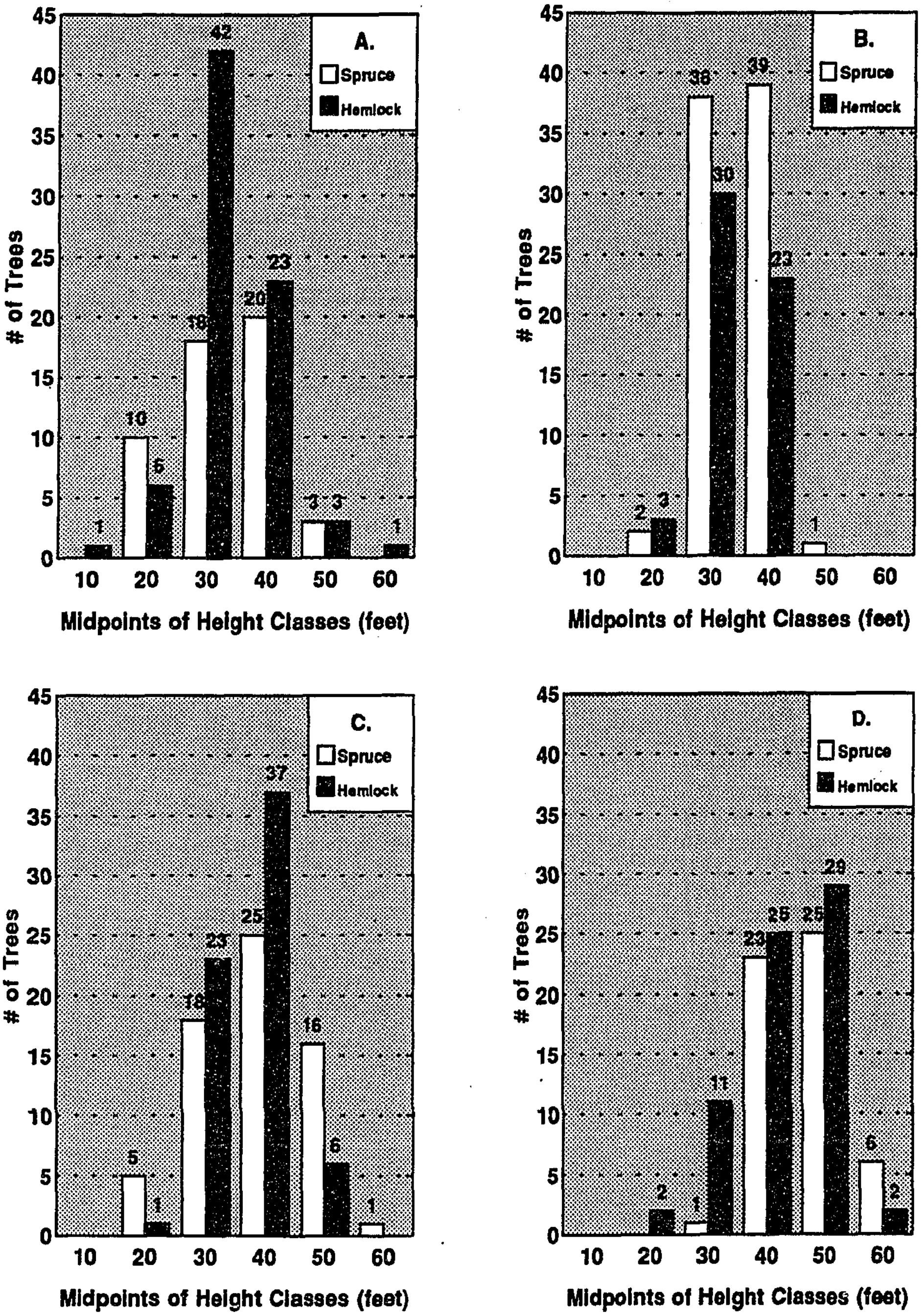


Figure 13. Hemlock and spruce height distributions by stands: A. Cave Creek; B. Lemon Creek; C. Salamander Lake; and D. Coffman Cove.

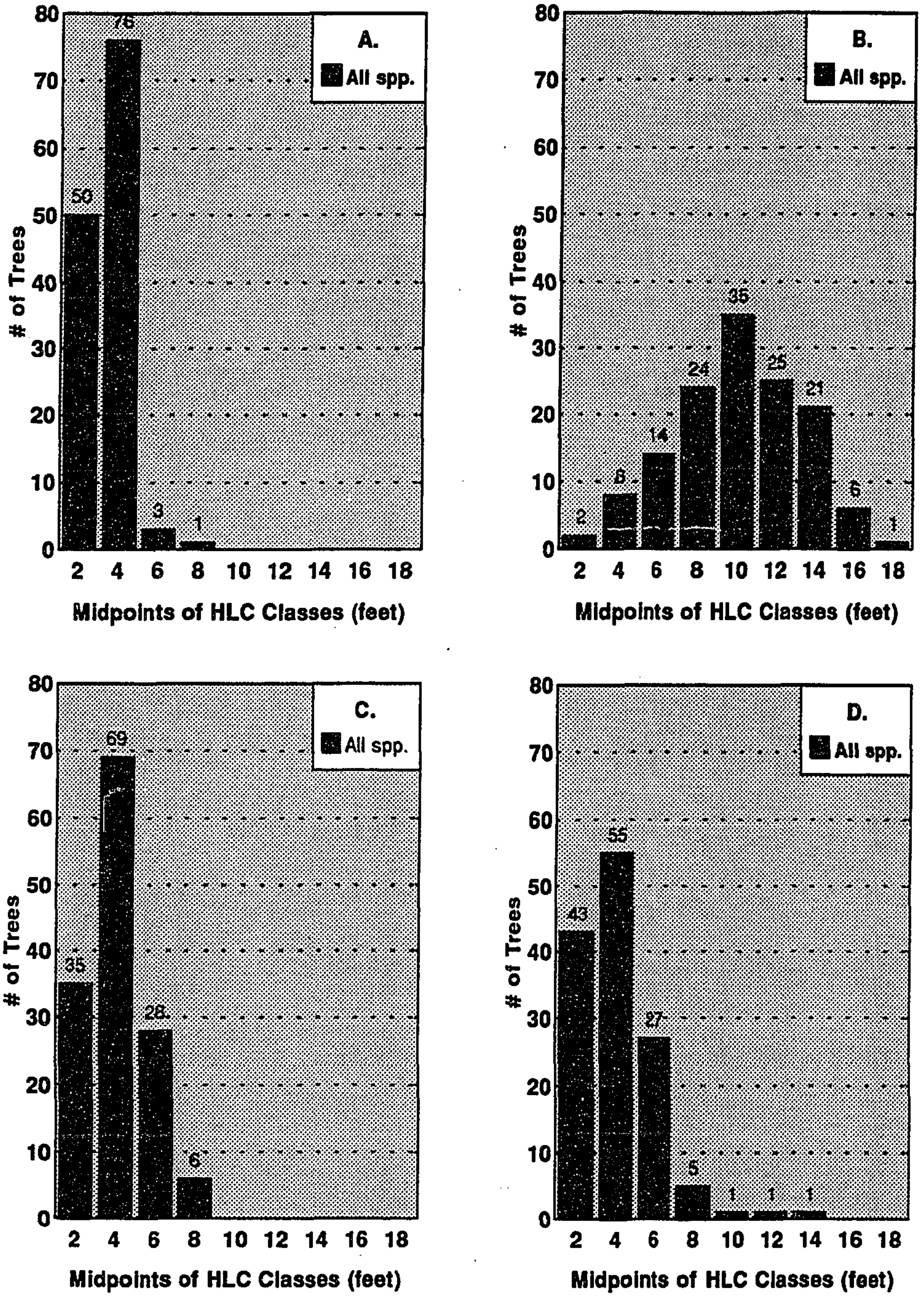


Figure 14. Distributions of height to live crown (HLC) before pruning for all species combined by stands: A. Cave Creek; B. Lemon Creek; C. Salamander Lake; and D. Coffman Cove.

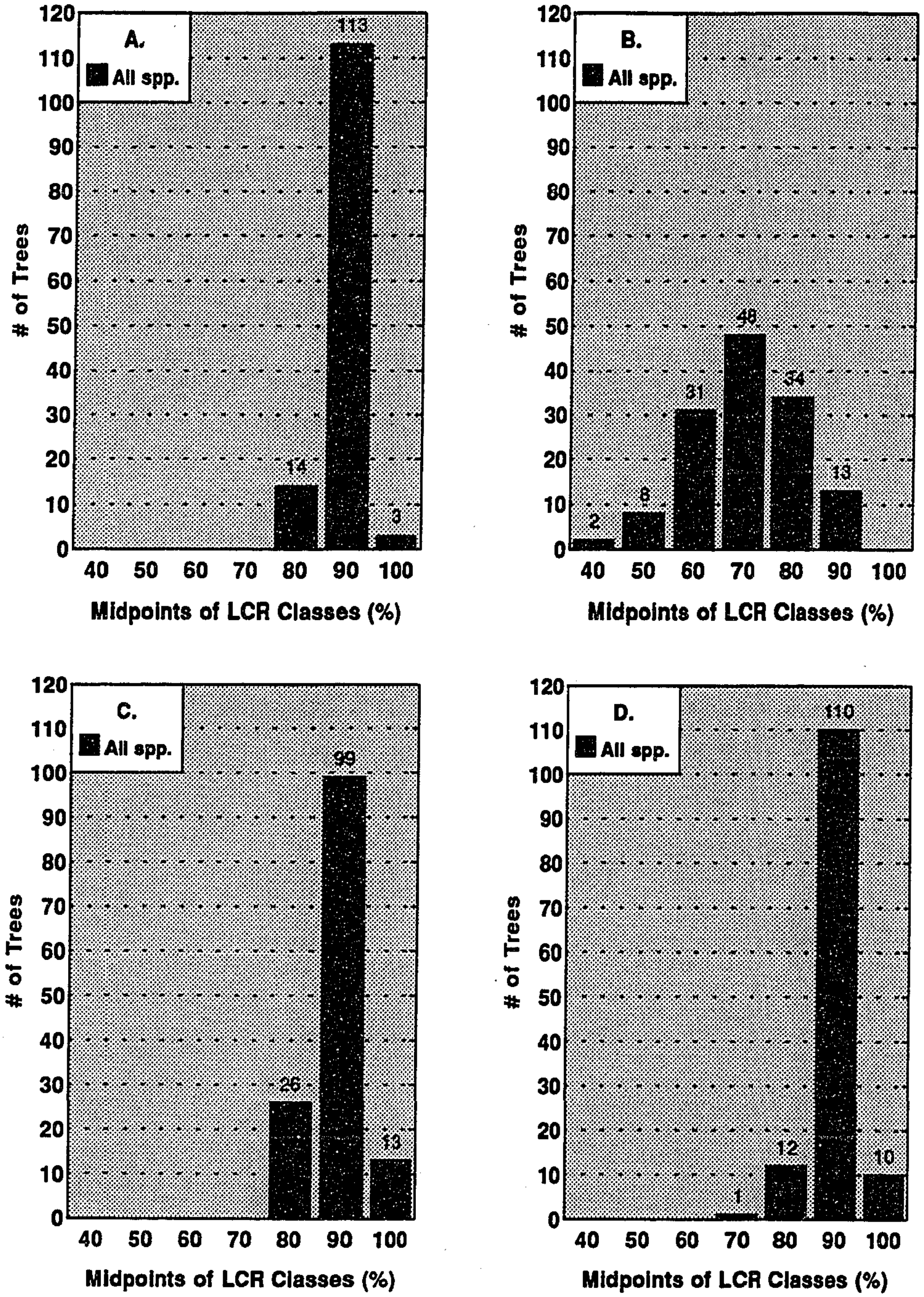


Figure 15. Distributions of live crown ratios (LCR) before pruning for all species combined by stands: A. Cave Creek; B. Lemon Creek; C. Salamander Lake; and D. Coffman Cove.

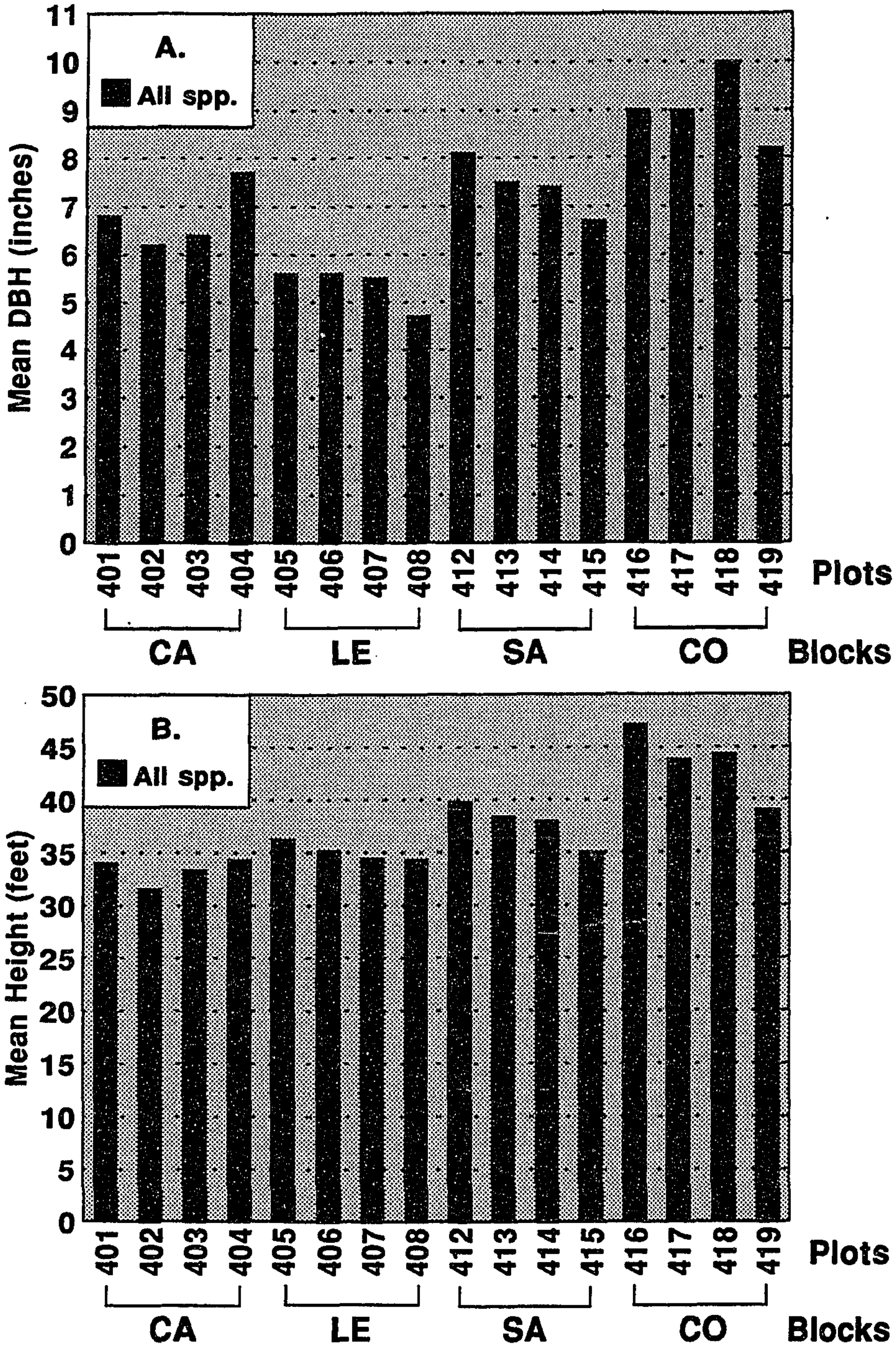


Figure 16. Mean DBH (A) and height (B) by plots prior to treatment. Differences between plots within stands (blocks) were statistically nonsignificant. CA=Cave Creek; LE=Lemon Creek; SA=Salamander Lake; and CO=Coffman Cove.

Branch Characteristics

Prior to pruning, branches were measured on 40 western hemlocks and 40 Sitka spruces at Cave Creek and Lemon Creek (20 trees per species per block). Mean crown width for hemlock and spruce at Cave Creek and Lemon Creek was 14.2 feet (4.3 m).

Hemlock branch characteristics by 2-foot stem height classes are shown in Figure 17 and Table 3. The number of live branches relative to dead branches increased with height up to 17.4 feet (5.3 m). "Branch basal areas" are the cross-sectional areas of branches and were calculated from the branch diameter measurements; branch diameters were measured at the branch bases just to the outside of the branch collar. Mean branch diameter and mean branch basal area increased with height up to 6 feet (1.8 m) and then remained approximately constant up to 17.4 feet (5.3 m).

Sitka spruce branch characteristics by 2-foot height classes are shown in Figure 18 and Table 4. The number of whorl branches per 2-foot height class decreased as interwhorl distances increased with height. The number of branches per whorl was usually between 4 and 6 and did not vary much with height up to 17.4 feet (5.3 m). Frequency of interwhorl branches increased with height up to 17.4 feet (5.3 m) while the total number of whorl and interwhorl branches remained approximately constant. Frequency of epicormic shoots on spruce did not vary significantly with height up to 17.4 feet (5.3 m) and averaged 34 epicormics per tree before treatment. Frequency of live branches relative to dead branches increased with height. Only whorl branch diameters were measured on spruce; mean whorl branch diameter and mean whorl

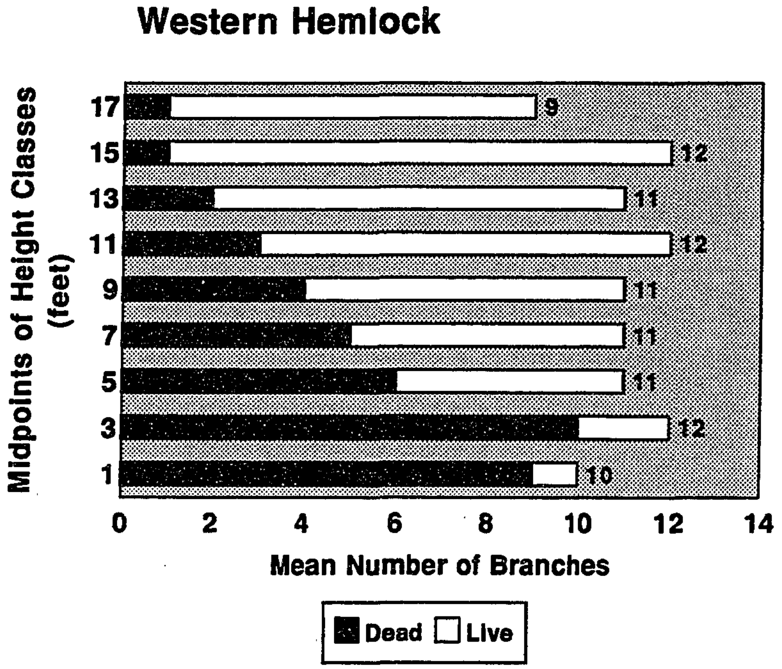


Figure 17. Western hemlock live and dead branch distribution by two-foot stem height classes. Mean values from 40 trees measured at Cave Creek and Lemon Creek.

branch basal area increased with height up to 6 feet (1.8 m) and then stayed nearly constant up to 17.4 feet (5.3 m).

Branch characteristics by pruning heights and species are shown in Table 5. Spruce had a significantly greater number of branches than hemlock; however, branch basal area differences between species were statistically nonsignificant. Differences in branch basal area between stands were significant; mean branch basal area of hemlock and spruce was significantly higher at Cave Creek (37.63 in^2, 242.8 cm^2) than at Lemon Creek (23.91 in^2, 154.3 cm^2). Stand density and, consequently, height to live crown were higher at Lemon Creek prior to treatment;

Table 3. Western hemlock branch characteristics by 2-foot stem height classes up to 17.4 feet above the ground (mean values, n=40).

Midpoints of Stem Height Classes (feet)	Live Branches #	Dead Branches #	Total Branches #	Branch Diameter (inches)	Branch Basal Area (inches^2)
1	1	9	10	0.4	1.54
3	2	10	12	0.4	2.25
5	5	6	11	0.5	3.21
7	6	5	11	0.6	3.92
9	7	4	11	0.6	4.10
11	9	3	12	0.6	4.33
13	9	2	11	0.6	4.23
15	11	1	12	0.6	4.44
17	8	1	9	0.5	2.27
Total	58	41	99	0.5	30.29

however, differences in numbers of branches between stands were statistically nonsignificant.

Time Required for Pruning

It was hypothesized that the time required for pruning would be a function of number of branches, branch basal area, stem diameter, and pruned height.

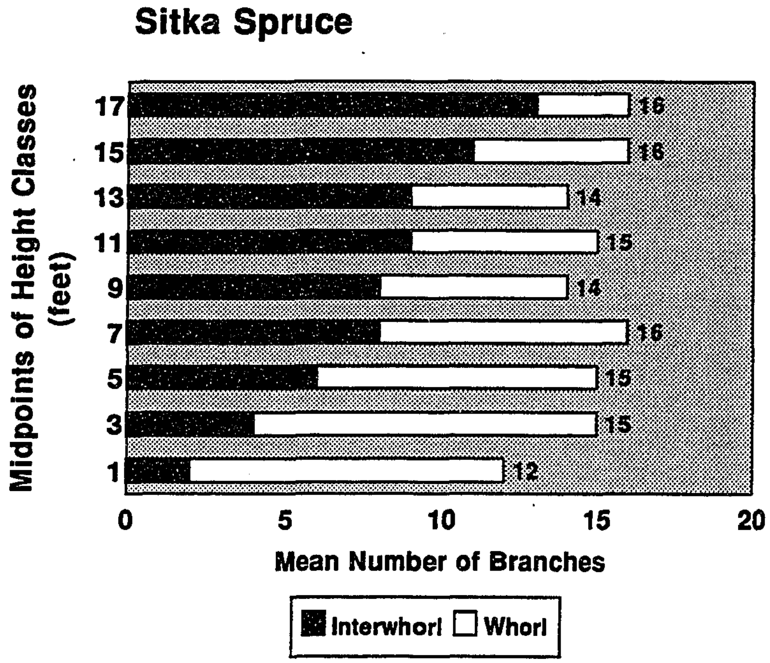


Figure 18. Sitka spruce whorl and interwhorl branch distribution by two-foot stem height classes. Mean values are from 40 trees measured at Cave Creek and Lemon Creek.

Hypothesis 1.0: Time required to prune (PT) may be a function of the number of cut branches.

Hypothesis 1.1: { PT ≠ f (BN) } -- was not rejected.

Hypothesis 1.2: { PT = f (BN) }.

Summaries of western hemlock and Sitka spruce branch characteristics by pruning heights are shown in Table 5. Mean number of branches up to 17.4 feet (5.3 m) above the ground was significantly greater for spruce (133) than hemlock (99). The general linear models procedure was used to perform an analysis of variance with time required to prune as the dependent variable and branch number as the independent variable; the

Table 4. Sitka spruce branch characteristics by 2-foot stem height classes up to 17.4 feet above the ground (mean values, n=40).

Midpoints of Stem Height Classes (feet)	Whorl Branches #	Whorl Branch Diameter (inches)	Interwhorl Branches #	Whorl + Interwhorl Branches #	Epicormic Shoots	Whorl Branch Basal Area (inches^2)
1	10	0.3	2	12	3	1.25
3	11	0.5	4	15	4	2.99
5	9	0.7	6	15	5	4.78
7	8	0.9	8	16	6	5.27
9	6	0.9	8	14	4	4.47
11	6	0.9	9	15	3	4.08
13	5	1.0	9	14	4	3.9
15	5	1.0	11	16	3	3.73
17	3	1.0	13	16	4	3.5
Total	63	0.7	70	133	36	33.97

Table 5. Summaries of western hemlock and Sitka spruce branch characteristics by pruning heights (mean values, n=40 for each species).

Pruning Heights	Western Hemlock Total Branches #	Western Hemlock Branch Basal Area (inches^2)	Sitka Spruce Total Branches #	Sitka Spruce Branch Basal Area (inches^2)
0-8 ft	44	10.92	58	14.29
8-12 ft	23	8.43	27	8.55
12-17.4 ft	32	10.94	43	11.13
Total	99	30.29	128*	33.97

* Statistically significant at alpha=0.05

results were statistically nonsignificant and hypothesis 1.1 was not rejected.

Hypothesis 2.0: Time required to prune may be a function of the sum of the basal areas of the cut branches.

Hypothesis 2.1: { PT ≠ f (BBA) } -- was rejected.

Hypothesis 2.2: { PT = f (BBA) }.

Regression models for predicting pruning time based on branch basal area are shown in Table 6. All of the models were significant at the 0.01 level of significance and hypothesis 2.1 was rejected. The coefficients of determination for the models were low, however, and did not account for more than 40 percent of the variation in time required to prune.

Table 6. Regression models of pruning time (minutes) and branch basal area (inches^2) for western hemlock and Sitka spruce. Pruning times (PT) and branch basal areas (BB) were measured from 0 to 8 feet (PT8, BB8), 8 to 12 feet (PT12, BB12), and 12 to 17.4 feet (PT17, BB17).

#	Regression Model	R^2
1.	0-8 feet: PT8 = 1.732 + 0.053*BB8	0.40
2.	8-12 feet: PT12 = 1.518 + 0.069*BB12	0.18
3.	12-17.4 feet: PT17 = 2.738 + 0.106*BB17	0.33

The following analyses of time-and-motion data were based on 195 trees (105 hemlock and 90 spruce) pruned to 8 feet (2.4 m), 134 trees (67 hemlock and 67 spruce) pruned to 12 feet (3.7 m), and 77 trees (39 hemlock and 38 spruce) pruned to 17.4 feet (5.3 m). Comparisons of mean time to prune western hemlock versus Sitka spruce are shown in Table 7. Comparisons of mean times to prune a western hemlock or Sitka spruce at Cave Creek versus Lemon Creek are shown in Table 8 and Figure 19. Differences in pruning times between species and between stands were statistically nonsignificant.

Hypothesis 3.0: Time required to prune (PT) may be a function of the diameter at breast height (DBH) of the pruned tree.

Hypothesis 3.1: { PT ≠ f (DBH) } -- was rejected.
Hypothesis 3.2: { PT = f (DBH) }.

Regression models of pruning time and stem diameter (DBH) are shown in Table 9. All of the models were significant at the 0.01 level of significance and hypothesis 3.1 was rejected. The coefficients of determination for the models were low, however, and did not account for more than 37 percent of the variation in pruning time.

Table 7. Comparisons of mean time to prune western hemlock versus Sitka spruce to three increasing heights at Cave Creek and Lemon Creek.

Pruning Height	Western Hemlock	Sitka Spruce	Average for both species		
	--- time (minutes) ---			min/ft	ft/min
0-8 ft	2.2	2.4	2.3	0.3	3.5
8-12 ft	1.9	2.2	2.0	0.5	2.0
12-17.4 ft	4.2	4.4	4.3	0.8	1.3
0-17.4 ft	8.3	9.0	8.6	0.5	2.0
walk to tree	0.3	0.3	0.3	0.02	53.3
Total	8.6	9.3	8.9		

Table 8. Comparisons of mean time to prune a western hemlock or Sitka spruce to three increasing heights at Cave Creek versus Lemon Creek.

Pruning Height	Cave Creek	Lemon Creek	Average for both stands
		--- time (minutes) ---	
0-8 ft	2.4	2.2	2.3
8-12 ft	2.1	2.0	2.0
12-17.4 ft	4.4	4.2	4.3
0-17.4 ft	8.9	8.4	8.6
walk to tree	0.3	0.3	0.3
Total	9.2	8.7	8.9

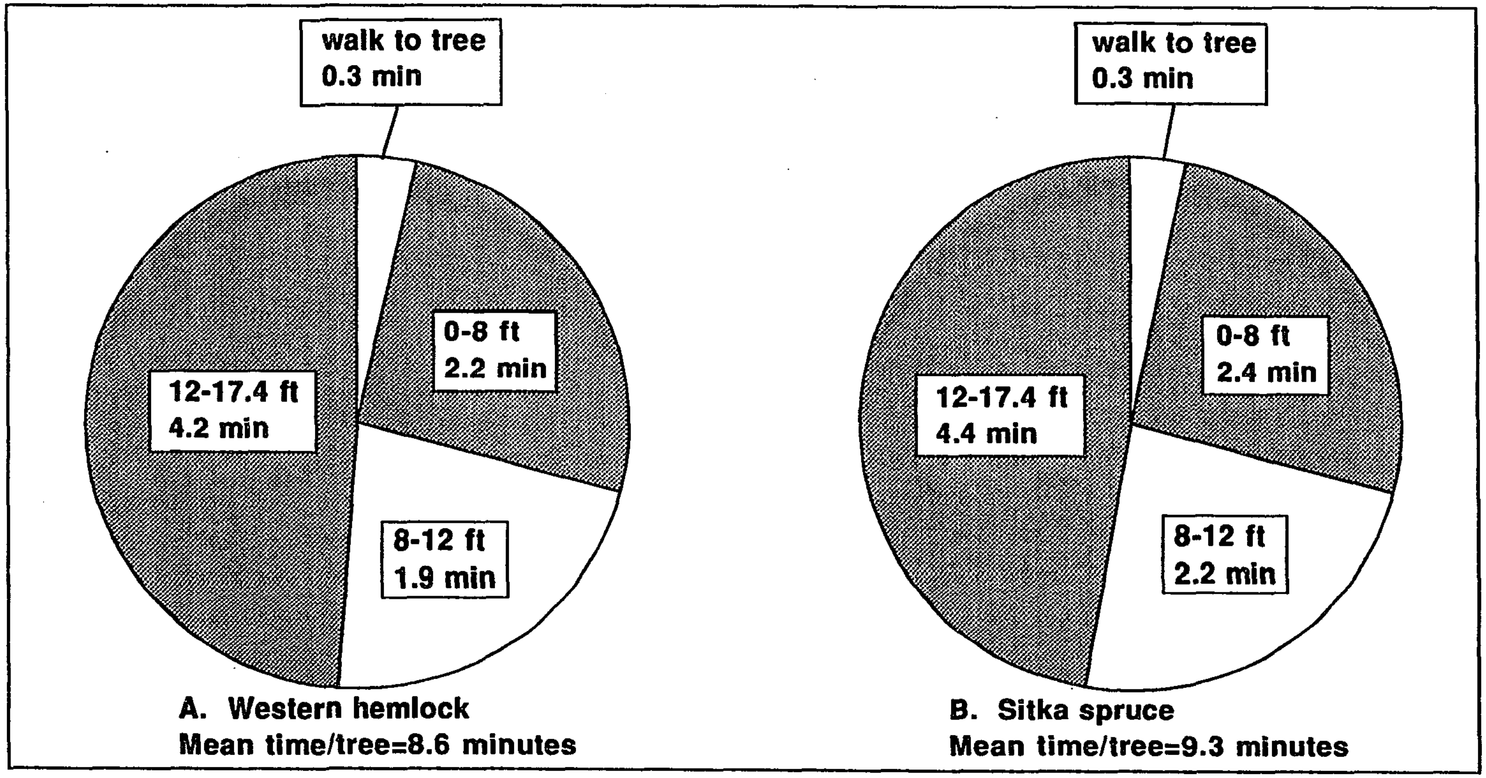


Figure 19. Mean time to prune (A) western hemlock and (B) Sitka spruce to three increasing heights at Cave Creek and Lemon Creek pruning installations on the Tongass National Forest.

Table 9. Regression models of pruning time (minutes) and stem diameter (DBH, inches) for western hemlock and Sitka spruce. Pruning times (PT) were measured from 0 to 8 feet (PT8), 8 to 12 feet (PT12), and 12 to 17.4 feet (PT17).

#	Regression Model	R^2
4.	0-8 feet: PT8 = 0.943 + 0.231*DBH	0.32
5.	8-12 feet: PT12 = 1.052 + 0.175*DBH	0.18
6.	12-17.4 feet: PT17 = 1.72 + 0.361*DBH	0.37

Hypothesis 4.0: Time required to prune (PT) may be a function of the pruned height (PH).

Hypothesis 4.1: { PT $\neq$ f (PH) } -- was rejected.

Hypothesis 4.2: { PT = f (PH) }.

Differences in pruning times between all pruning heights were significant at the 0.0001 level of significance and hypothesis 4.1 was rejected. The regression models in Table 10 were developed for predicting time (minutes) to prune western hemlock and Sitka spruce to any height up to 19 feet (5.8 m) using a handsaw and polesaw. Pruned height (PH) and stem diameter (DBH) were better predictors of pruning time-and-motion than number of branches and branch basal area.

Table 10. Regression models of pruning time (PT, in minutes), pruning height (PH, in feet), and stem diameter (DBH, in inches) for western hemlock and Sitka spruce.

#	Regression Model	R^2
7.	PT = -2.9354 + 0.6214*PH	0.83
8.	PT = -4.4942 + 0.6258*PH + 0.2535*DBH	0.86

Immediate Effects of Pruning Treatments

Figure 20 shows mean posttreatment height to live crown, percent live crown length removed, and posttreatment live crown ratio by treatment for four stands of western hemlock and Sitka spruce. Table 11 shows means, standard deviations, and ranges of stand variables immediately after thinning and pruning four stands. Mean height to live crown values indicated target pruning heights were achieved for approximately 84 percent of the trees in the 8- and 12-foot (2.4 and 3.7 m) pruning lifts. Approximately 84 percent of the trees in the 17.4-foot (5.3 m) lift were pruned to at least 16.7 feet (5.1 m); some were not pruned to the target heights because the trees were below average height and over-pruning would have risked killing the trees.

Tree height variations commonly result from nonuniform site conditions; tree age is another source of height variation in stands which have regenerated naturally after harvest of the previous stands. In the western hemlock-Sitka spruce forest type, trees may become established over many years during the stand initiation stage; regeneration sources often include hemlock advance reproduction and hemlock and spruce seeds from previous and adjacent stands. The wide range in tree heights and heights to live crown in the four treated stands resulted in varying proportions of live crown removal and, consequently, a wide range in live crown ratios in each of the fixed-lift pruning treatments. Trees in the control plots were thinned but not pruned so percent crown removed was zero. Trees in the 17.4-foot (5.3 m) lift had from 10 to 85 percent live crown removed, and 13 to 72 percent live crown ratios after pruning. Wide ranges in percent crown removal will, therefore, typically result if fixed-lift pruning is prescribed in the western hemlock-Sitka spruce

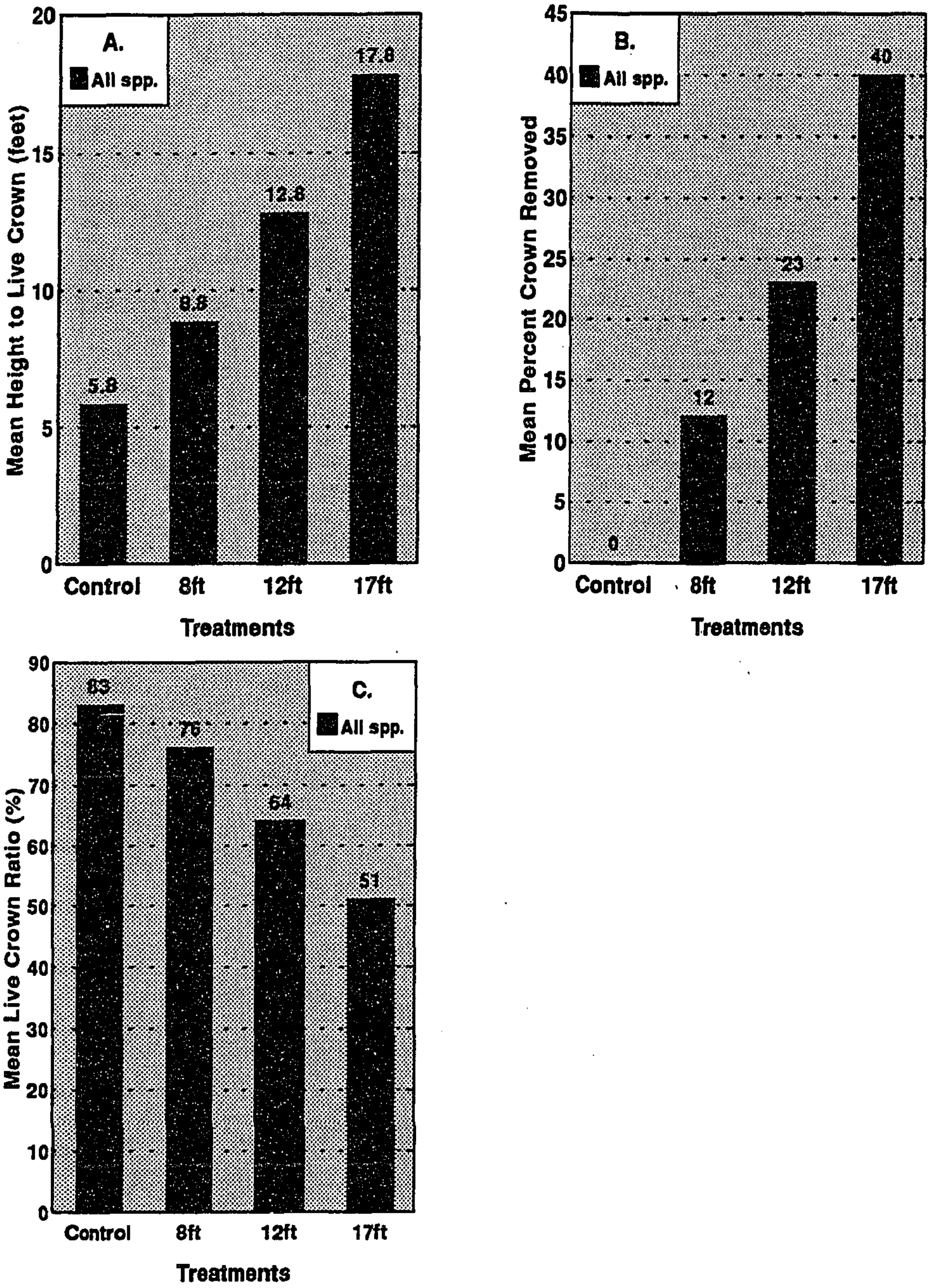


Figure 20. Effects of pruning treatments on stand structure: A. mean height to live crown; B. mean percent live crown length removed; C. mean posttreatment live crown ratio. Control plots were thinned but not pruned.

Table 11. Means, standard deviations (s.d.), and ranges of stand variables immediately after thinning and pruning western hemlock and Sitka spruce at Cave Creek, Lemon Creek, Salamander Lake, and Coffman Cove.

Pruning Treatments	Height to Live Crown (feet)			Percent Crown Removed			Live Crown Ratio (%)		
	Mean	s.d.	Range	Mean	s.d.	Range	Mean	s.d.	Range
Control	5.8	4.2	1.0-18.4	0	0	0	83.4	12.4	42.5-97.9
8-ft lift	8.8	0.8	7.4-11.9	11.7	7.9	0-36.5	76.2	5.9	50.0-85.5
12-ft lift	12.8	0.9	8.5-16.0	23.3	13.0	0-65.1	63.8	8.8	28.9-78.3
17.4-ft lift	17.8	1.1	12.4-19.7	40.2	12.8	10.1-85.3	50.6	11.4	12.5-71.8

forest type. For example, if a 20-foot tree (6.1 m) with a height to live crown of 9 feet (2.7 m) were pruned to 8 feet (2.4 m), only dead branches would be removed and percent live crown removal would be zero. If a 20-foot (6.1 m) tree with a height to live crown of 2 feet (0.6 m) were pruned to 8 feet (2.4 m) then 33 percent of the live crown length would be removed.

Sunscald and Mortality

Sunscald was not noticed on any trees in any of the stands -- possibly the short winter days and frequent cloud cover preclude sunscald injury after thinning and pruning in Southeast Alaska. In the first year after treatment, it was discovered that over-pruning could result in tree mortality. Seven trees died, including four spruces and two hemlocks at Cave Creek and one hemlock at Lemon Creek. Dead tree diameters (DBH) averaged 4.5 inches (11.4 cm) and ranged from 3.3 to 6.5 inches (8.4 to 16.5 cm); tree heights averaged 25 feet (7.6 m) and ranged from 18 to 32 feet (5.5 to 9.7 m). Pretreatment live crown ratios of trees that died ranged from 82 to 96 percent and pruning heights ranged from 12 to 18.5 feet (3.7 to 5.6 m). Those trees that died had 50 percent or more of the live crowns removed and live crown ratios were reduced to less than 50 percent after pruning. Crown removal averaged 66 percent and ranged from 50 to 86 percent; live crown ratios after pruning averaged 30 percent and ranged from 12 to 45 percent.

Epicormic Shoots on Spruce

Hypothesis 5.0: Frequency of epicormic shoots one year (EBF1) and two years after pruning (EBF2) may be a function of pruned height (PH).

Hypothesis 5.1: {EBF1 ≠ f(PH)} -- was not rejected.
Hypothesis 5.2: {EBF1 = f(PH)}
Hypothesis 5.3: {EBF2 ≠ f(PH)} -- was not rejected.
Hypothesis 5.4: {EBF2 = f(PH)}

Prior to treatment, epicormic buds and shoots averaged 34 per tree; the average number of epicormics one year after treatment remained 34 per tree and differences between treatments were statistically nonsignificant. Two years after treatment the average number of epicormics increased to 57 per tree but differences between treatments were statistically nonsignificant. Hypotheses 5.1 and 5.3 were not rejected; the data suggests thinning and pruning did not increase the number of epicormics compared to thinning alone. Epicormic branch lengths were not measured, however, and there may be differences in shoot development between treatments. Development of epicormic branches on pruned Sitka spruce may reduce expected returns on pruning investments. Additional analyses were performed to test for differences in height distribution of epicormics between treatments and the results were statistically nonsignificant.

Height Growth Responses

Mean height growth responses one and two years after thinning and pruning western hemlock and Sitka spruce are shown in Figure 21 and Table 12. It was hypothesized that height growth responses would be a function of pruned height, percent live crown length removed, live crown ratio after pruning, and stem diameter at the time of pruning. The null hypothesis were: there are no functional relationships between height growth and pruning.

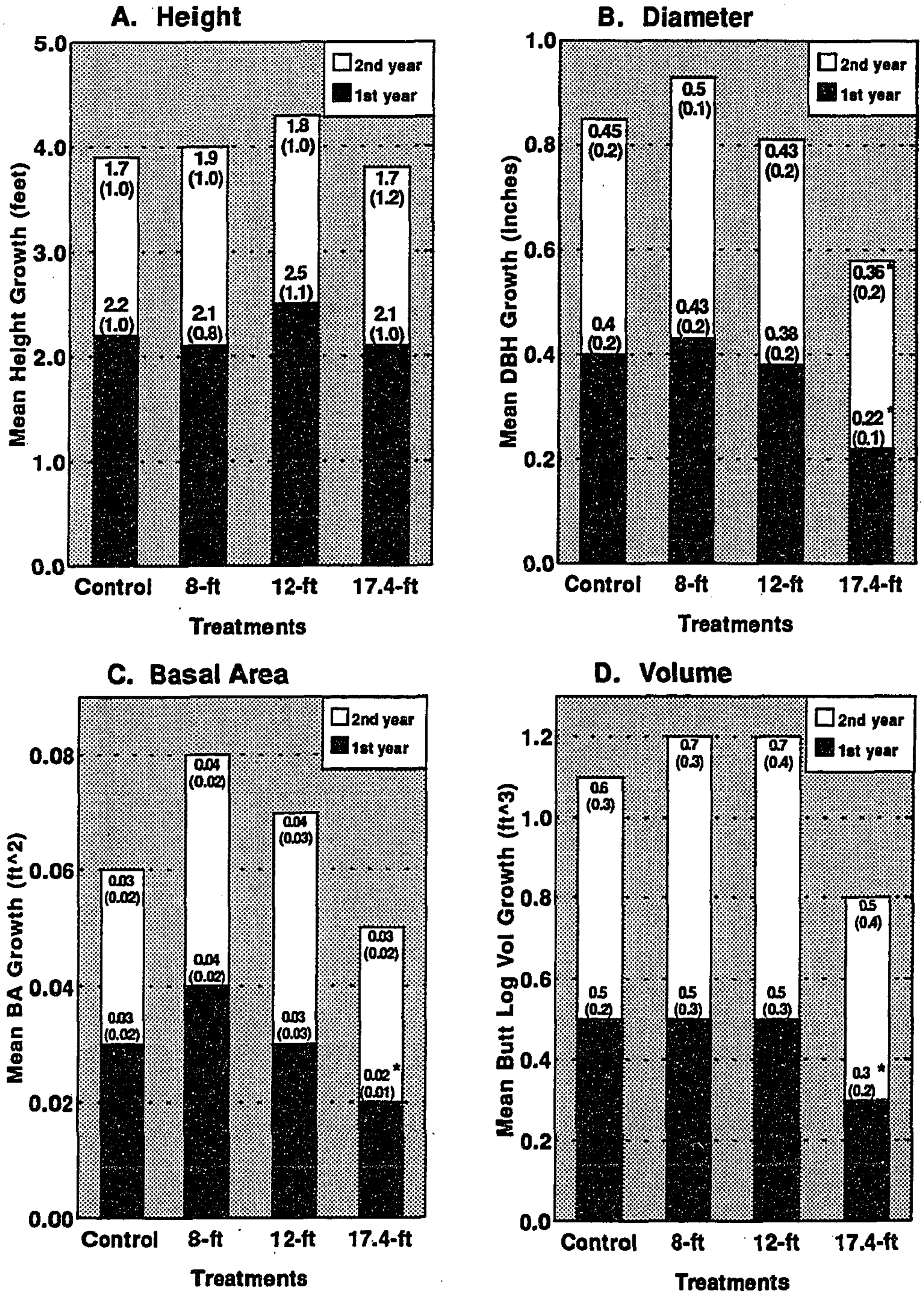


Figure 21. First and second year posttreatment growth responses of western hemlock and Sitka spruce at Cave Creek, Lemon Creek, and Salamander Lake: A. height; B. diameter; C. basal area; and D. volume. Standard deviations in ( ), * statistically significant at alpha = 0.05.

Table 12. Mean posttreatment height (HT) growth responses of western hemlock and Sitka spruce. Stands at Cave Creek, Lemon Creek, and Salamander Lake were included in the first year measurements (n=377) and stands at Cave Creek and Lemon Creek were included in the second year measurements (n=231).

Pruning Treatments	First Year HT Growth (n=377)		Second Year HT Growth (n=231)		Two-Year Cumulative Growth (n=231)	
	(ft)	s.d.	(ft)	s.d.	(ft)	s.d.
Control	2.2	1.0	1.7	1.0	4.0	1.7
8-ft lift	2.1	0.8	1.9	1.0	3.8	1.3
12-ft lift	2.5	1.1	1.8	1.1	4.4	2.0
17.4-ft lift	2.1	1.0	1.7	1.2	3.9	1.6

Hypothesis 6.0: First year (▲HT1), second year (▲HT2), and two-year cumulative height growth may be a function of pruned height (PH).

Hypothesis 6.1: {▲HT1 ≠ f(PH)} -- was not rejected.
Hypothesis 6.2: {▲HT1 = f(PH)}.
Hypothesis 6.3: {▲HT2 ≠ f(PH)} -- was not rejected.
Hypothesis 6.4: {▲HT2 = f(PH)}.
Hypothesis 6.5: {▲HT2C ≠ f(PH)} -- was not rejected.
Hypothesis 6.6: {▲HT2C = f(PH)}.

Pruned height was statistically nonsignificant in the analysis of variance of first, second, and two-year cumulative posttreatment height growth; null hypotheses 6.1, 6.3, and 6.5 were not rejected.

Hypothesis 7.0: First year (▲HT1), second year (▲HT2), and two-year cumulative height growth (▲HT2C) may be a function of percent live crown length removed (PCR) and stem diameter at the time of pruning (DBHp).

Hypothesis 7.1: {▲HT1 ≠ f(PCR, DBHp)} -- was not rejected.
Hypothesis 7.2: {▲HT1 = f(PCR, DBHp)}.
Hypothesis 7.3: {▲HT2 ≠ f(PCR, DBHp)} -- was not rejected.
Hypothesis 7.4: {▲HT2 = f(PCR, DBHp)}.
Hypothesis 7.5: {▲HT2C ≠ f(PCR, DBHp)} -- was not rejected.
Hypothesis 7.6: {▲HT2C = f(PCR, DBHp)}.

Percent live crown length removed was statistically nonsignificant in the analysis of variance of first, second, and two-year cumulative posttreatment height growth; null hypotheses 7.1, 7.3, and 7.5 were not rejected.

Hypothesis 8.0: First year (▲HT1), second year (▲HT2), and two-year cumulative height growth (▲HT2C) may be a function of live crown ratio after pruning (LCRa) and stem diameter at the time of pruning (DBHp).

Hypothesis 8.1: {▲HT1 ≠ f(LCRa, DBHp)} -- was not rejected.
Hypothesis 8.2: {▲HT1 = f(LCRa, DBHp)}.
Hypothesis 8.3: {▲HT2 ≠ f(LCRa, DBHp)} -- was not rejected.
Hypothesis 8.4: {▲HT2 = f(LCRa, DBHp)}.
Hypothesis 8.5: {▲HT2C ≠ f(LCRa, DBHp)} -- was not rejected.
Hypothesis 8.6: {▲HT2C = f(LCRa, DBHp)}.

Posttreatment live crown ratio was statistically nonsignificant in the analysis of variance of first, second, and two-year cumulative posttreatment height growth; null hypotheses 8.1, 8.3, and 8.5 were not rejected. Height growth was less affected by pruning than was diameter, possibly because height growth has a higher priority in the allocation of photosynthates. Height growth of all species averaged two feet per year in the first two years after treatment. Annual stem increment of pruned trees is expected to increase as live crown lengths continue to increase.

Diameter Growth Responses

Diameter growth responses one and two years after thinning and pruning western hemlock and Sitka spruce are shown in Figure 21 and Table 13. Growth responses were based on first year posttreatment measurements at Cave Creek, Lemon Creek, and Salamander Lake (n=377) and second year posttreatment measurements at Cave Creek and Lemon Creek (n=231). It was hypothesized that diameter (DBH) growth responses would be a function of pruned height, percent live crown length removed, live crown ratio after pruning, and stem diameter at the time of pruning (initial diameter). The null hypothesis were: there are no functional relationships between diameter growth and pruning.

Hypothesis 9.0: First year (▲DBH1), second year (▲DBH2), and two-year cumulative posttreatment diameter growth (▲DBH2C) may be a function of pruned height (PH).

Hypothesis 9.1: {▲DBH1 ≠ f(PH)} -- was rejected.
Hypothesis 9.2: {▲DBH1 = f(PH)}.
Hypothesis 9.3: {▲DBH2 ≠ f(PH)} -- was rejected.
Hypothesis 9.4: {▲DBH2 = f(PH)}.
Hypothesis 9.5: {▲DBH2C ≠ f(PH)} -- was rejected.
Hypothesis 9.6: {▲DBH2C = f(PH)}.

Table 13. Mean posttreatment diameter growth responses of western hemlock and Sitka spruce by treatment. Stands at Cave Creek, Lemon Creek, and Salamander Lake were included in the first year posttreatment measurements and stands at Cave Creek and Lemon Creek were included in the second year posttreatment measurements.

Pruning Treatments	First Year DBH Growth (n=377)		Second Year DBH Growth (n=231)		Two-Year Cumulative Growth (n=231)	
	(in)	s.d.	(in)	s.d.	(in)	s.d.
Control	0.40	0.19	0.45	0.17	0.95	0.28
8-ft lift	0.43	0.17	0.50	0.15	0.97	0.29
12-ft lift	0.38	0.18	0.43	0.19	0.84	0.33
17.4-ft lift	0.22*	0.15	0.36*	0.18	0.65*	0.30

* Statistically significant at alpha=0.05

The general linear models procedure was used to perform analysis of variance to assess the influence of pruned height on first year, second year, and two-year cumulative posttreatment diameter growth. Classification variables included blocks, pruned height classes, species, and diameter classes. Significant analysis of variance models are shown in Table 14.

Pruned height was a significant variable for predicting first year, second year, and two-year cumulative posttreatment diameter growth and hypotheses 9.1, 9.3, and 9.5 were rejected. The coefficient of determination (R^2) for the general linear model was 0.31 when only blocks and pruned height were assessed. The low R^2 value for the model may be explained by the wide range in percent crown removed within each of the pruning treatments (see Table 11) which resulted in overlapping values between the treatments for both percent crown removed and live crown ratio after pruning.

Table 14. The general linear models procedure was used to perform analysis of variance (ANOVA) to assess the influence of pruned height on first year (▴DBH1), second year (▴DBH2), and two-year cumulative (▴DBH2C) posttreatment diameter growth. Classification variables included blocks (BLK), pruned height classes (PHC), species (SPP), and stem diameter classes (DC).

#	ANOVA Model	Prob > F	R^2
9.	▴DBH1 = f(BLK, PHC)	0.0001	0.31
10.	▴DBH1 = f(BLK, PHC, SPP, DC)	0.0001	0.61
11.	▴DBH2 = f(PHC, SPP, DC)	0.0001	0.54
12.	▴DBH2C = f(BLK, PHC, SPP, DC)	0.0001	0.69

Pruned height and initial stem diameter were significant variables for predicting first year diameter growth; significant differences between species were also detected. Blocks were significant in the analysis of variance of first year and two-year cumulative diameter growth; blocks, however, were nonsignificant in the second year models. Models with blocks, pruned height classes, species, and initial stem diameter classes accounted for more variation in diameter growth than the model with only blocks and pruned height.

Significant block effects one year after treatment indicated the precision of the experiment was increased by use of the randomized complete block design relative to use of the completely random design. The scope of the experiment was also increased since treatments were tested over a wide range of site conditions. Significant treatment effects were evidence of real differences among treatment means. Multiple comparison tests were performed using Duncan's multiple-range test to determine which treatment means were significantly different; significant differences were reported at the 0.05 level of significance unless noted otherwise. Diameter growth in the 17.4-foot (5.3 m) lift was significantly reduced in the first two years after treatment; first year diameter growth was 50 percent less than the control, second year diameter growth was 20 percent less than the control, and two-year cumulative diameter growth was 32 percent less than the control. These results indicate that pruning to 17.4 feet (5.3 m) in one operation significantly decreased diameter growth of some trees in the first two years after treatment; however, it is possible that some of the taller trees were less affected by pruning to 17.4 feet (5.3 m) because the taller trees with larger crowns had less live crown removed and had higher live crown ratios after pruning than the shorter trees. Additional analyses were performed to determine if diameter growth responses were correlated with percent crown removed and live crown ratios after pruning.

Hypothesis 10.0: First year (▲DBH1), second year (▲DBH2), and two-year cumulative (▲DBH2C) posttreatment diameter growth may be a function of percent live crown length removed (PCR) and stem diameter at the time of pruning (DBHp).

Hypothesis 10.1: $\{\blacktriangle \mathrm{DBH1} \neq f(\mathrm{PCR}, \mathrm{DBHp})\}$ -- was rejected.

Hypothesis 10.2: $\{\blacktriangle \mathrm{DBH1} = f(\mathrm{PCR}, \mathrm{DBHp})\}$.

Hypothesis 10.3: $\{\blacktriangle \mathrm{DBH2} \neq f(\mathrm{PCR}, \mathrm{DBHp})\}$ -- was rejected.

Hypothesis 10.4: $\{\blacktriangle \mathrm{DBH2} = f(\mathrm{PCR}, \mathrm{DBHp})\}$.

Hypothesis 10.5: $\{\blacktriangle \mathrm{DBH2C} \neq f(\mathrm{PCR}, \mathrm{DBHp})\}$ -- was rejected.

Hypothesis 10.6: $\{\blacktriangle \mathrm{DBH2C} = f(\mathrm{PCR}, \mathrm{DBHp})\}$.

The general linear models procedure was used to perform analysis of variance to assess the influence of percent live crown removal on first year, second year, and two-year cumulative posttreatment diameter growth. Classification variables included blocks, crown removal classes, species, and diameter classes. Significant analysis of variance models are shown in Table 15. Percent crown removed was statistically significant in the analysis of variance of first year, second year, and two-year cumulative diameter growth and hypotheses 10.1, 10.3, and 10.5 were rejected. Significant differences in diameter growth responses between species and diameter classes were also detected.

Table 15. The general linear models procedure was used to perform analysis of variance (ANOVA) to assess the influence of percent crown removed on one year (▲DBH1), two year (▲DBH2), and two year cumulative (▲DBH2C) posttreatment diameter growth. Classification variables included blocks (BLK), crown removal classes (PCRC), species (SPP), and stem diameter classes (DC).

#	ANOVA Model	Prob > F	R^2
13.	▲DBH1 = f(BLK, PCRC)	0.0001	0.47
14.	▲DBH1 = f(BLK, PCRC, SPP, DC)	0.0001	0.64
15.	▲DBH2 = f(PCRC, SPP, DC)	0.0001	0.55
16.	▲DBH2C = f(BLK, PCRC, SPP, DC)	0.0001	0.73

Hypothesis 11.0: First year (▲DBH1), second year (▲DBH2), and two-year cumulative posttreatment diameter growth (▲DBH2C) may be a function of live crown ratio after pruning (LCRa) and stem diameter (▲DBH2C) at the time of pruning (DBHp).

Hypothesis 11.1: {▲DBH1 ≠ f(LCRa, DBHp)} -- was rejected.

Hypothesis 11.2: {▲DBH1 = f(LCRa, DBHp)}.

Hypothesis 11.3: {▲DBH2 ≠ f(LCRa, DBHp)} -- was rejected.
Hypothesis 11.4: {▲DBH2 = f(LCRa, DBHp)}.
Hypothesis 11.5: {▲DBH2C ≠ f(LCRa, DBHp)} -- was rejected.
Hypothesis 11.6: {▲DBH2C = f(LCRa, DBHp)}.

The general linear models procedure was used to perform analysis of variance to assess the influence of posttreatment live crown ratio on first year, second year, and two-year cumulative posttreatment diameter growth. Classification variables included blocks, live crown ratio classes, species, and diameter classes. Significant analysis of variance models are shown in Table 16. Live crown ratio after pruning was statistically significant in the analysis of variance of first year, second year, and two-year cumulative diameter growth and hypotheses 11.1, 11.3, and 11.5 were rejected. Significant differences in diameter growth responses between species and diameter classes were also detected.

Table 16. The general linear models procedure was used to perform analysis of variance (ANOVA) to assess the influence of live crown ratio after pruning on one year (▲DBH1), two year (▲DBH2), and two year cumulative (▲DBH2C) posttreatment diameter growth. Classification variables included blocks (BLK), live crown ratio classes (LCAC), species (SPP), and stem diameter classes (DC).

#	ANOVA Model	Prob > F	R^2
17.	▲DBH1 = f(BLK, LCAC)	0.0001	0.50
18.	▲DBH1 = f(BLK, LCAC, SPP, DC)	0.0001	0.64
19.	▲DBH2 = f(LCAC, SPP, DC)	0.0001	0.57
20.	▲DBH2C = f(BLK, LCAC, SPP, DC)	0.0001	0.72

Multiple regression models incorporating percent crown removed, live crown ratio after pruning, and initial stem diameter (DBH) for predicting first year posttreatment diameter growth are shown in Table 17.

Table 17. Multiple regression models incorporating percent crown removed (PCR), live crown ratio after pruning (LCRa), and stem diameter at the time of pruning (DBHp) for predicting first year posttreatment diameter growth (▲DBH1) of western hemlock and Sitka spruce.

#	Multiple Regression Model	R^2
	▲DBH1 = f(PCR, DBHp)	
21.	Hemlock ▲DBH1 = 0.1928 - 0.0001*PCR^2 + 0.0279*DBHp	0.28
22.	Spruce ▲DBH1 = 0.2834 - 0.0001*PCR^2 + 0.0254*DBHp	0.40
23.	Hemlock & Spruce ▲DBH1 = 0.2222 - 0.0001*PCR^2 + 0.0287*DBHp	0.35
	▲DBH1 = f(LCRa, DBHp)	
24.	Hemlock ▲DBH1 = -0.3718 + 0.0128*LCRa - 0.0001*LCRa^2 + 0.0177*DBHp	0.30
25.	Spruce ▲DBH1 = -0.4542 + 0.0166*LCRa - 0.0001*LCRa^2 + 0.0194*DBHp	0.40
26.	Hemlock & Spruce ▲DBH1 = -0.4324 + 0.0149*LCRa - 0.0001*LCRa^2 + 0.0215*DBHp	0.35

Analysis of variance models accounted for block effects, which may have reflected soil or precipitation differences, but soil and precipitation were not directly measured in the experiments so differences between blocks could not be accounted for in the multiple regression models. Models 21-23 included percent crown removed and diameter at the time of pruning as independent variables; models 24-26 included live crown ratio after pruning and stem diameter at the time of pruning as independent variables. Comparisons of the models showed percent live crown removed and live crown ratio after pruning were equally as useful for predicting first year posttreatment diameter growth.

Relationships between percent crown removed and first year posttreatment diameter growth of hemlock and spruce are shown in Figure 22; relationships between live crown ratio after pruning and first year posttreatment diameter growth are shown in Figure 23. Multiple comparison tests indicated significant decreases in diameter growth occurred when 40 percent or more of the live crown lengths were removed; significant decreases in diameter growth were also evident when live crown ratios were reduced below 50 percent.

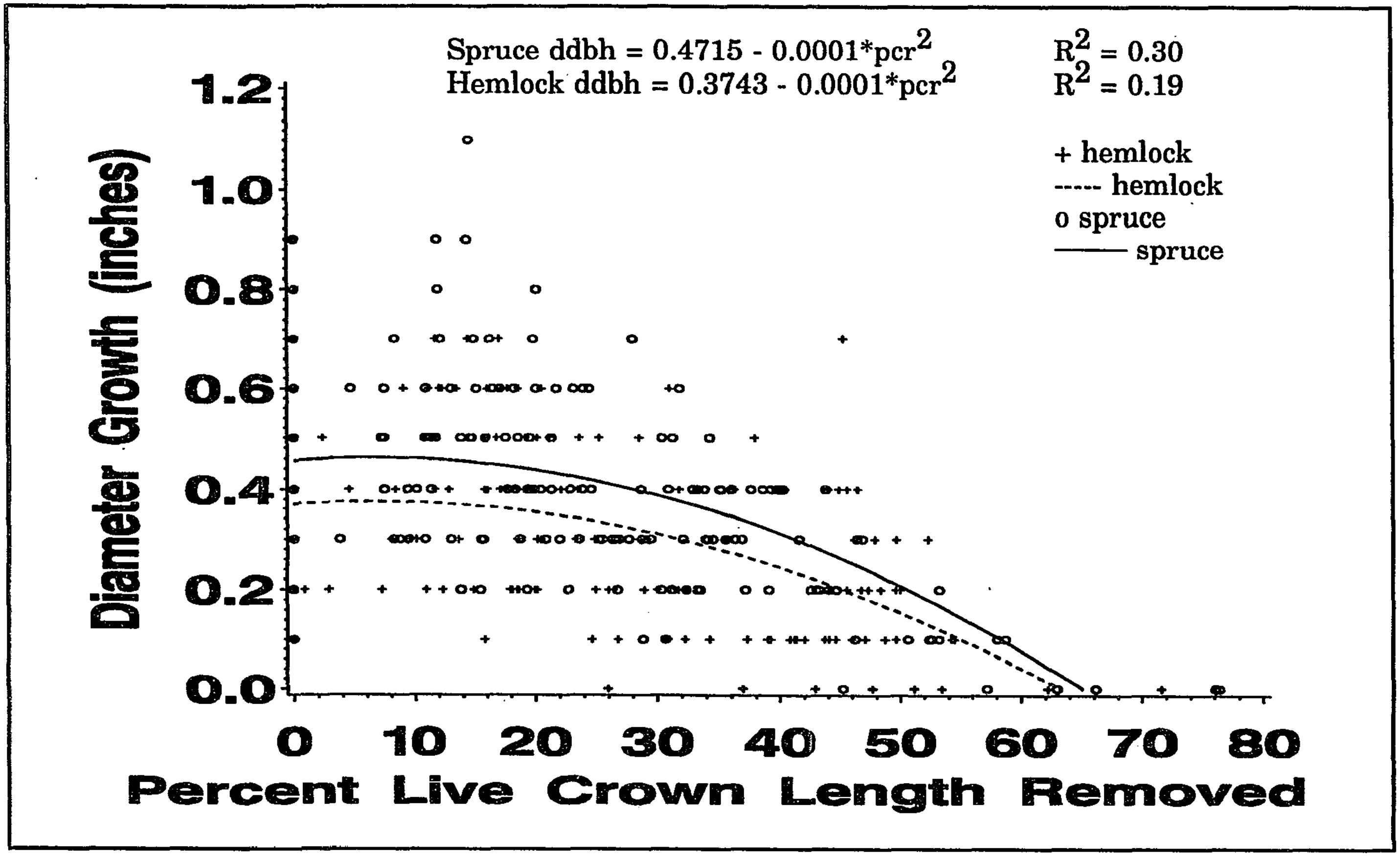


Figure 22. Relationship between percent live crown length removed and first year posttreatment diameter growth of western hemlock and Sitka spruce. Significant decreases in diameter growth occurred when 40 percent or more of the live crown lengths were removed.

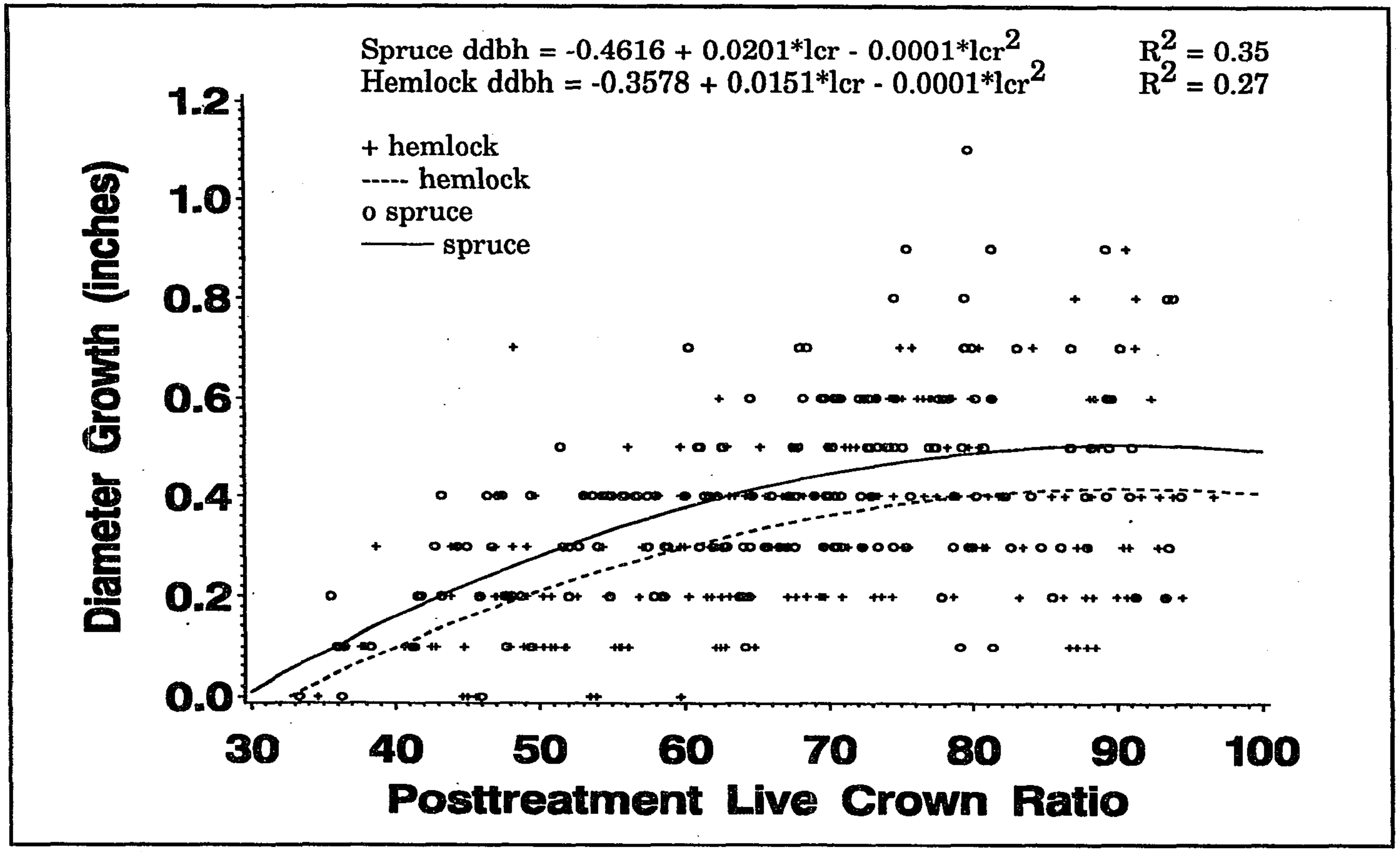


Figure 23. Relationship between live crown ratio after pruning and first year posttreatment diameter growth of western hemlock and Sitka spruce. Diameter growth was significantly decreased when live crown ratios were reduced below 50 percent.

Multiple regression models incorporating percent crown removed, live crown ratio after pruning and diameter at the time of pruning for predicting second year and two-year cumulative posttreatment diameter growth are shown in Tables 18 and 19. Comparisons of the models indicated live crown ratio after pruning was a better predictor of two-year cumulative posttreatment diameter growth than was percent live crown length removed.

Table 18. Multiple regression models incorporating percent crown removed (PCR), live crown ratio after pruning (LCRa), and stem diameter at the time of pruning (DBHp) for predicting second year posttreatment diameter growth (▲DBH2) of western hemlock and Sitka spruce.

#	Multiple Regression Model	R^2
	▲DBH2 = f(PCR, DBHp)	
27.	Hemlock ▲DBH2 = $0.2024 - 0.0001*PCR^2 + 0.0291*DBHp$	0.28
28.	Spruce ▲DBH2 = $0.3555 - 0.0001*PCR^2 + 0.0344*DBHp$	0.45
29.	Hemlock & Spruce ▲DBH2 = $0.2469 - 0.0001*PCR^2 + 0.0367*DBHp$	0.33
	▲DBH2 = f(LCRa, DBHp)	
30.	Hemlock ▲DBH2 = $-0.5057 + 0.0189*LCRa - 0.0001*LCRa^2 + 0.0206*DBHp$	0.38
31.	Spruce ▲DBH2 = $-0.3801 + 0.018*LCRa - 0.0001*LCRa^2 + 0.0286*DBHp$	0.45
32.	Hemlock & Spruce ▲DBH2 = $-0.5317 + 0.0205*LCRa - 0.0001*LCRa^2 + 0.03*DBHp$	0.36

Table 19. Multiple regression models incorporating percent crown removed (PCR), live crown ratio after pruning (LCRa), and stem diameter at the time of pruning (DBHp) for predicting two-year cumulative posttreatment diameter growth (▲DBH2C) of western hemlock and Sitka spruce.

#	Multiple Regression Model	R^2
	▲DBH2C = f(PCR, DBHp)	
33.	Hemlock ▲DBH2C = $0.391 - 0.0001*PCR^2 + 0.069*DBHp$	0.45
34.	Spruce ▲DBH2C = $0.5832 - 0.0002*PCR^2 + 0.078*DBHp$	0.65
35.	Hemlock & Spruce ▲DBH2C = $0.4452 - 0.0002*PCR^2 + 0.08*DBHp$	0.52
	▲DBH2C = f(LCRa, DBHp)	
36.	Hemlock ▲DBH2C = $-0.2683 + 0.0105*LCRa + 0.0492*DBHp$	0.58
37.	Spruce ▲DBH2C = $-0.2827 + 0.0124*LCRa + 0.0666*DBHp$	0.71
38.	Hemlock & Spruce ▲DBH2C = $-0.7939 + 0.0275*LCRa -0.0001*LCRa^2 + 0.064*DBHp$	0.59

Relationships between percent crown removed and two-year cumulative posttreatment diameter growth of hemlock and spruce are shown in Figure 24; relationships between live crown ratio after pruning and two-year cumulative posttreatment diameter growth are shown in Figure 25. Diameter growth was significantly decreased when 40 percent or more of the live crown lengths were removed and when live crown ratios were reduced below 50 percent.

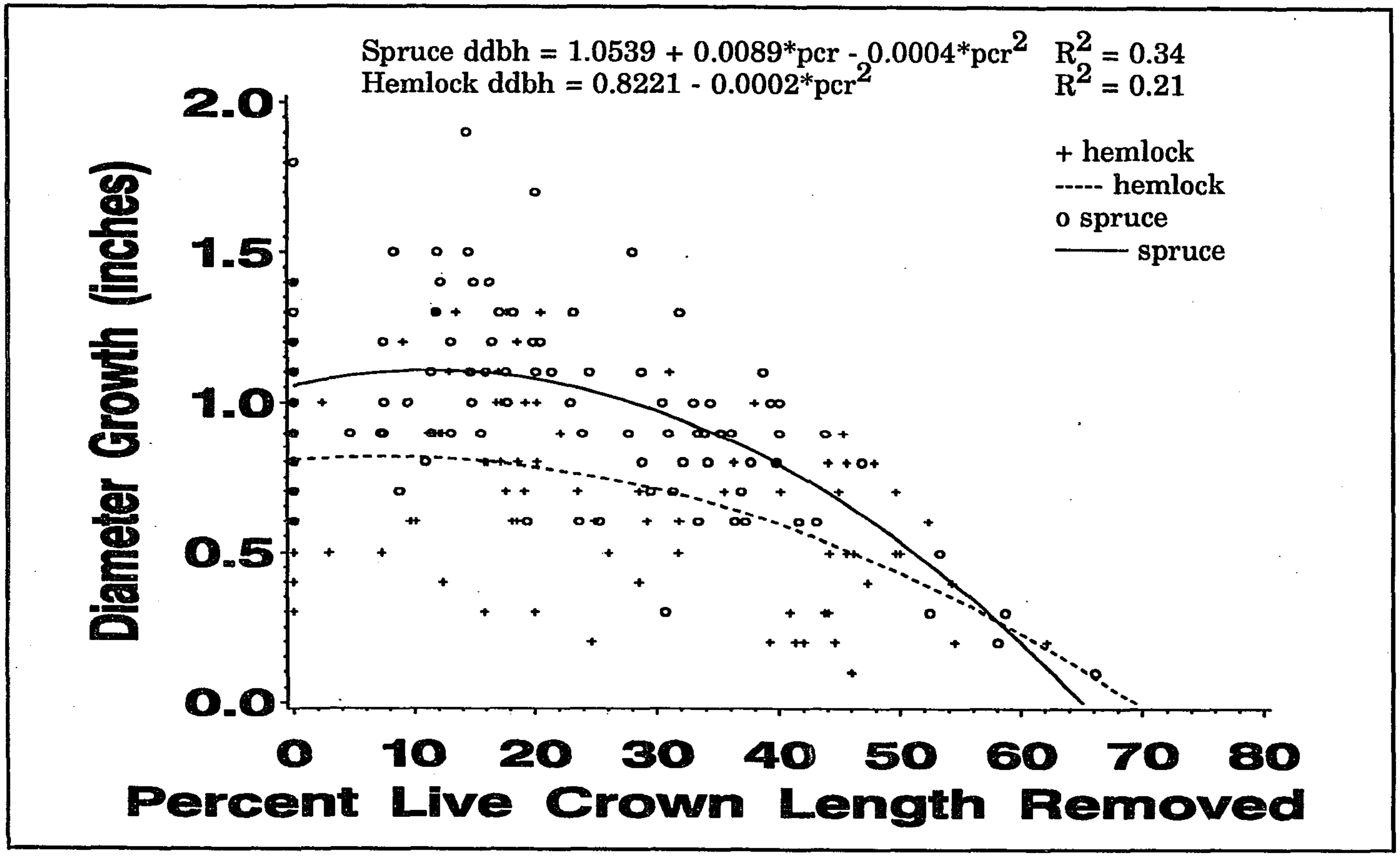


Figure 24. Relationship between percent live crown length removed and two-year cumulative posttreatment diameter growth of western hemlock and Sitka spruce. Significant decreases in diameter growth occurred when 40 percent or more of the live crown lengths were removed.

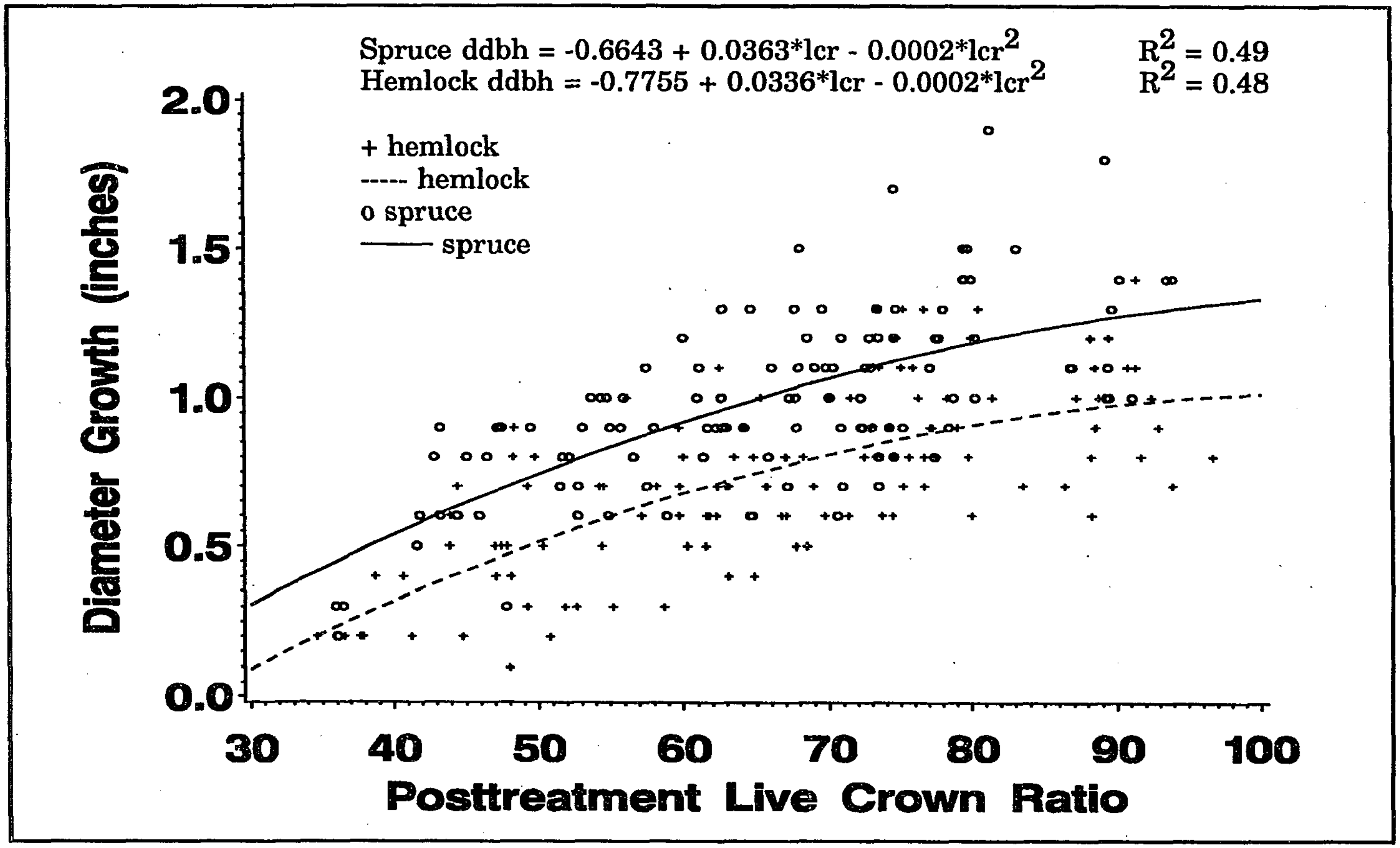


Figure 25. Relationship between live crown ratio after pruning and two-year cumulative posttreatment diameter growth of western hemlock and Sitka spruce. Diameter growth was significantly decreased when live crown ratios were reduced below 50 percent.

Stem Taper Two Years After Pruning

Stem diameter growth was measured at 1.0, 4.5, 9.2, and 17.4 feet (0.3, 1.4, 2.8, and 5.3 m) above the ground on 40 western hemlocks and 40 Sitka spruces at Cave Creek and Lemon Creek. Two-year cumulative diameter growth along the stem of hemlock and spruce combined are shown in Table 20; two-year cumulative diameter growth of hemlock is shown in Table 21 and two-year cumulative diameter growth of spruce is shown in Table 22. Diameter growth from 1.0 to 9.2 feet (0.3 to 2.8 m) in the 17.4-foot (5.3 m) lift for hemlock and spruce combined was significantly less than the control. Hemlock diameter growth at 1.0 foot (0.3 m) in both the 12- and 17.4-foot (3.7 and 5.3 m) lifts was significantly less than the control. In addition, diameter growth at 4.5 and 9.2 feet (1.4 and 2.8 m) in the 17.4-foot (5.3 m) lift was significantly less than the control. Spruce diameter growth at 1.0 and 4.5 feet (0.3 and 1.4 m) in the 17.4-foot (5.3 m) lift was significantly less than the control. Differences in hemlock and spruce diameter growth at 17.4 feet were statistically nonsignificant in all treatments.

Table 20. Two-year cumulative posttreatment diameter growth by stem height for western hemlock and Sitka spruce combined at Cave Creek and Lemon Creek.

	Pruning Treatments			
Stem Height	Control	8-ft lift	12-ft lift	17.4-lift
(feet)	-- diameter growth (inches) --			
17.4	1.1	1.1	1.1	1.0
9.2	1.0	1.0	0.9	0.7^{+}
4.5	1.0	0.9	0.8	0.6^{*}
1.0	1.3	1.3	1.0	0.8^{*}

* Statistically significant at alpha=0.05
+ Statistically significant at alpha=0.1

Table 21. Two-year cumulative posttreatment diameter growth by stem height for western hemlock at Cave Creek and Lemon Creek.

	Pruning Treatments			
Stem Height	Control	8-ft lift	12-ft lift	17.4-ft lift
(feet)	-- diameter growth (inches) --			
17.4	0.9	0.9	0.9	0.8
9.2	0.8	0.8	0.7	0.5^{*}
4.5	0.8	0.8	0.6	0.5^{*}
1.0	1.1	0.9	0.7*	0.6^{*}

* Statistically significant at alpha=0.05

Table 22. Two-year cumulative posttreatment diameter growth by stem height for Sitka spruce at Cave Creek and Lemon Creek.

	Pruning Treatments			
Stem Height	Control	8-ft lift	12-ft lift	17.4-ft lift
(feet)	-- diameter growth (inches) --			
17.4	1.2	1.3	1.3	1.2
9.2	1.1	1.2	1.1	0.9
4.5	1.2	1.1	1.1	0.7*
1.0	1.5	1.6	1.4	0.9*

* Statistically significant at alpha=0.05

Maximum diameter increment occurs near the base of the live crown; when growth decreases on the lower stem and is maintained on the upper stem a change in stem taper results. Stem taper two years after pruning hemlock and spruce combined is shown in Table 23; hemlock stem taper is shown in Table 24 and spruce stem taper is shown in Table 25. Stem taper from 9.2 to 17.4 feet (2.8 to 5.3 m) in the 17.4-foot (5.3 m) lift for hemlock and spruce combined was significantly less than the control. Hemlock stem taper from 9.2 to 17.4 feet (2.8 to 5.3 m) in the 17.4-foot (5.3 m) lift was significantly less than the control. Differences in spruce stem taper between treatments were statistically nonsignificant.

Table 23. Mean stem taper two years after thinning and pruning western hemlock and Sitka spruce combined at Cave Creek and Lemon Creek.

Stem Section (feet)	Pruning Treatment Control	 8-ft lift	 12-ft lift	 17.4-ft lift
	-- stem taper (inches/foot) --			
9.2-17.4	0.18	0.20	0.20	0.14*
4.5-9.2	0.16	0.18	0.16	0.14
1.0-4.5	0.43	0.41	0.41	0.42

* Statistically significant at alpha=0.05

Table 24. Mean stem taper two years after thinning and pruning western hemlock at Cave Creek and Lemon Creek.

Stem Section (feet)	Pruning Treatments Control	 8-ft lift	 12-ft lift	 17.4-ft lift
	-- stem taper (inches/foot) --			
9.2-17.4	0.18	0.20	0.18	0.12+
4.5-9.2	0.11	0.13	0.09	0.09
1.0-4.5	0.34	0.24	0.21*	0.30

* Statistically significant at alpha=0.05
+ Statistically significant at alpha=0.1

Table 25. Mean stem taper two years after thinning and pruning Sitka spruce at Cave Creek and Lemon Creek.

Stem Section (feet)	Control	8-ft lift	12-ft lift	17.4-ft lift
	-- stem taper (inches/foot) --			
9.2-17.4	0.19	0.21	0.23	0.16
4.5-9.2	0.21	0.23	0.23	0.18
1.0-4.5	0.52	0.57	0.60	0.55

Mean two-year posttreatment change in stem taper from 4.5 to 17.4 feet (1.4 to 5.3 m) for hemlock and spruce combined are shown in Table 26. Negative changes in stem taper indicate less taper after pruning than before pruning. Significant changes in stem taper occurred in the 12- and 17.4-foot (3.7 and 5.3 m) lifts.

Table 26. Mean two-year posttreatment change in stem taper from 4.5 to 17.4 ft for western hemlock and Sitka spruce at Cave Creek and Lemon Creek.

Pruning Treatments			
Control	8-ft lift	12-ft lift	17.4-ft lift
-- change in taper (inches/foot) --			
0	-0.01	-0.02*	-0.03*

* Statistically significant at alpha=0.05

Basal Area Growth Responses

Mean basal area growth responses one and two years after thinning and pruning western hemlock and Sitka spruce are shown in Table 27.

Table 27. Mean posttreatment basal area (BA) growth responses of western hemlock and Sitka spruce. Stands at Cave Creek, Lemon Creek, and Salamander Lake were included in the first year measurements and stands at Cave Creek and Lemon Creek were included in the second year measurements.

Pruning Treatments	First Year BA Growth (n=377)		Second Year BA Growth (n=231)		Two-Year Cumulative Growth (n=231)	
	(ft^2)	s.d.	(ft^2)	s.d.	(ft^2)	s.d.
Control	0.029	0.020	0.034	0.022	0.069	0.042
8-ft lift	0.035	0.023	0.040	0.023	0.077	0.046
12-ft lift	0.034	0.027	0.039	0.029	0.074	0.055
17.4-ft lift	0.018*	0.015	0.029	0.023	0.051*	0.037

* Statistically significant at alpha=0.05

It was hypothesized that basal area growth responses would be a function of pruned height, percent live crown length removed, live crown ratio after pruning, and stem diameter at the time of pruning. The null hypothesis were: there are no functional relationships between basal area growth and pruning.

Hypothesis 12.0: First year (▲BA1), second year (▲BA2), and two-year cumulative (▲BA2C) posttreatment basal area growth may be a function of pruned height (PH).

Hypothesis 12.1: $\{\blacktriangle BA1 \neq f(PH)\}$ -- was rejected.
Hypothesis 12.2: $\{\blacktriangle BA1 = f(PH)\}$.
Hypothesis 12.3: $\{\blacktriangle BA2 \neq f(PH)\}$ -- was not rejected.
Hypothesis 12.4: $\{\blacktriangle BA2 = f(PH)\}$.
Hypothesis 12.5: $\{\blacktriangle BA2C \neq f(PH)\}$ -- was rejected.
Hypothesis 12.6: $\{\blacktriangle BA2C = f(PH)\}$.

The general linear models procedure was used to perform analysis of variance to assess the influence of pruned height on first year, second year, and two-year cumulative posttreatment basal area growth. Classification variables included blocks, pruned height classes, species, and diameter classes. Significant analysis of variance models are shown in Table 28.

Table 28. The general linear models procedure was used to perform analysis of variance (ANOVA) to assess the influence of pruned height on first year (▲BA1), second year (▲BA2), and two-year cumulative (▲BA2C) posttreatment basal area growth. Classification variables included blocks (BLK), species (SPP), pruned height classes (PHC), crown removal classes (PCRC), live crown ratio classes (LCAC), and stem diameter classes (DC).

#	ANOVA Model	Prob > F	R^2
39.	$\blacktriangle BA1 = f(BLK, PHC)$	0.0001	0.18
40.	$\blacktriangle BA1 = f(BLK, PHC, SPP, DC)$	0.0001	0.75
41.	$\blacktriangle BA2 = f(BLK, PHC, SPP, DC)$	0.0001	0.78
42.	$\blacktriangle BA2C = f(BLK, PHC, SPP, DC)$	0.0001	0.86

Treatments (pruned heights) were significant in the analysis of variance of first year posttreatment basal area growth. First year basal area growth in the 17.4-foot (5.3 m) lift was 38 percent less than the control;

the difference was statistically significant and hypothesis 12.1 was rejected. Blocks and pruned height alone were statistically nonsignificant in the analysis of variance of second year basal area growth and hypothesis 9.3 was not rejected. Two-year cumulative basal area growth in the 17.4-foot (5.3 m) lift was 25 percent less than the control; the difference was statistically significant and hypothesis 12.5 was rejected.

Hypothesis 13.0: First year (▲BA1), second year (▲BA2), and two-year cumulative posttreatment basal area growth (▲BA2C) may be a function of percent live crown length removed (PCR) and stem diameter at the time of pruning (DBHp).

Hypothesis 13.1: {▲BA1 ≠ f(PCR, DBHp)} -- was rejected.
Hypothesis 13.2: {▲BA1 = f(PCR, DBHp)}.
Hypothesis 13.3: {▲BA2 ≠ f(PCR, DBHp)} -- was rejected.
Hypothesis 13.4: {▲BA2 = f(PCR, DBHp)}.
Hypothesis 13.5: {▲BA2C ≠ f(PCR, DBHp)} -- was rejected.
Hypothesis 13.6: {▲BA2C = f(PCR, DBHp)}.

The general linear models procedure was used to perform analysis of variance to assess the influence of percent crown removal on first year, second year, and two-year cumulative posttreatment basal area growth. Classification variables included blocks, percent live crown removed, species, and diameter classes. Significant analysis of variance models are shown in Table 29. Percent live crown length removed and initial stem diameter were statistically significant in the analysis of variance of first year, second year, and two-year cumulative posttreatment basal area growth and hypotheses 13.1, 13.3, and 13.5 were rejected.

Table 29. The general linear models procedure was used to perform analysis of variance (ANOVA) to assess the influence of percent live crown length removed on first year (▲BA1), second year (▲BA2), and two-year cumulative (▲BA2C) posttreatment basal area growth. Classification variables included blocks (BLK), crown removal classes (PCRC), species (SPP), and stem diameter classes (DC).

#	ANOVA Model	Prob > F	R^2
43.	▲BA1 = f(BLK, PCRC)	0.0001	0.35
44.	▲BA1 = f(BLK, PCRC, SPP, DC)	0.0001	0.76
45.	▲BA2 = f(BLK, PCRC, SPP, DC)	0.0001	0.79
46.	▲BA2C = f(BLK, PCRC, SPP, DC)	0.0001	0.87

Hypothesis 14.0: First year (▲BA1), second year (▲BA2), and two-year cumulative basal area growth (▲BA2C) may be a function of live crown ratio after pruning (LCRa) and stem diameter at the time of pruning (DBHp).

Hypothesis 14.1: {▲BA1 ≠ f(LCRa, DBHp)} -- was rejected.
Hypothesis 14.2: {▲BA1 = f(LCRa, DBHp)}.
Hypothesis 14.3: {▲BA2 ≠ f(LCRa, DBHp)} -- was rejected.
Hypothesis 14.4: {▲BA2 = f(LCRa, DBHp)}.
Hypothesis 14.5: {▲BA2C ≠ f(LCRa, DBHp)} -- was rejected.
Hypothesis 14.6: {▲BA2C = f(LCRa, DBHp)}.

The general linear models procedure was used to perform analysis of variance to assess the influence of posttreatment live crown ratio on first year, second year, and two-year cumulative posttreatment basal area growth. Classification variables included blocks, live crown ratio, species, and diameter classes. Significant analysis of variance models are shown in Table 30.

Table 30. The general linear models procedure was used to perform analysis of variance (ANOVA) to assess the influence of live crown ratio after pruning on first year (▲BA1), second year (▲BA2), and two-year cumulative (▲BA2C) posttreatment basal area growth. Classification variables included blocks (BLK), live crown ratio classes (LCAC), species (SPP), and stem diameter classes (DC).

#	ANOVA Model	Prob > F	R^2
47.	▲BA1 = f(BLK, LCAC)	0.0001	0.37
48.	▲BA1 = f(BLK, LCAC, SPP, DC)	0.0001	0.76
49.	▲BA2 = f(BLK, LCAC, SPP, DC)	0.0001	0.78
50.	▲BA2C = f(BLK, LCAC, SPP, DC)	0.0001	0.87

Live crown ratio after pruning and initial stem diameter were statistically significant in the analysis of variance of first year, second year, and two-year cumulative posttreatment basal area growth and hypotheses 14.1, 14.3, and 14.5 were rejected.

Multiple regression models incorporating percent crown removed, live crown ratio after pruning, and initial stem diameter for predicting first year basal area growth are shown in Table 31. Models 51-53 included percent crown removed and initial diameter as independent variables; models 54-56 included posttreatment live crown ratio after pruning and initial stem diameter as independent variables. Percent crown removed and live crown ratio were equally as useful for predicting first year basal area growth. Multiple comparison tests indicated basal area growth was significantly reduced when 40 percent or more of live crown length was removed and when live crown ratios were reduced below 50 percent.

Table 31. Multiple regression models incorporating percent crown removed (PCR), live crown ratio after pruning (LCRA), and stem diameter at the time of pruning (DBHp) for predicting first year posttreatment basal area growth (▲BA1) of western hemlock and Sitka spruce.

#	Multiple Regression Model	R^2
	▲BA1 = f(PCR, DBHp)	
51.	Hemlock ▲BA1 = -0.0105 - 0.0003*PCR + 0.0063*DBHp	0.53
52.	Spruce ▲BA1 = -0.0117 - 0.0003*PCR + 0.0074*DBHp	0.61
53.	Hemlock & Spruce ▲BA1 = -0.0131 - 0.0003*PCR + 0.0071*DBHp	0.59
	▲BA1 = f(LCRa, DBHp)	
54.	Hemlock ▲BA1 = -0.0324 + 0.0003*LCRa + 0.0055*DBHp	0.53
55.	Spruce ▲BA1 = -0.0404 + 0.0004*LCRa + 0.0068*DBHp	0.61
56.	Hemlock & Spruce ▲BA1 = -0.0372 + 0.0003*LCRa + 0.0065*DBHp	0.59

Multiple regression models incorporating percent live crown length removed, posttreatment live crown ratio, and initial stem diameter for predicting second year posttreatment basal area growth are shown in Table 32. Percent crown removed and live crown ratio were equally as useful for predicting second year basal area growth.

Table 32. Multiple regression models incorporating percent live crown removed (PCR), live crown ratio after pruning (LCRa), and initial diameter (DBHp) for predicting second year posttreatment basal area growth (▲BA2) of western hemlock and Sitka spruce.

#	Multiple Regression Model	R^2
	▲BA2 = f(PCR, DBHp)	
57.	Hemlock ▲BA2 = -0.0103 - 0.0001*PCR + 0.0066*DBHp	0.67
58.	Spruce ▲BA2 = -0.0174 - 0.0003*PCR + 0.0102*DBHp	0.79
59.	Hemlock & Spruce ▲BA2 = -0.0172 - 0.0002*PCR + 0.009*DBHp	0.68
	▲BA2 = f(LCRa, DBHp)	
60.	Hemlock ▲BA2 = -0.0271 + 0.0003*LCRa + 0.006*DBHp	0.69
61.	Spruce ▲BA2 = -0.0434 + 0.0004*LCRa + 0.0096*DBHp	0.79
62.	Hemlock & Spruce ▲BA2 = -0.0358 + 0.0003*LCRa + 0.0084*DBHp	0.69

Multiple regression models incorporating percent live crown length removed, posttreatment live crown ratio, and initial stem diameter for predicting two-year cumulative posttreatment basal area growth are shown in Table 33. Percent crown removed and live crown ratio were equally as useful for predicting second year basal area growth.

Table 33. Multiple regression models for predicting two-year cumulative posttreatment basal area growth (▲BA2C) of western hemlock and Sitka spruce at Cave Creek and Lemon Creek. Independent variables included percent crown removed (PCR), live crown ratio after pruning (LCRa), and DBH at the time of pruning (DBHp).

#	Multiple Regression Model	R^2
	▲BA2C = f(PCR, DBHp)	
63.	Hemlock ▲BA2C = -0.0244 - 0.0004*PCR + 0.0143*DBHp	0.79
64.	Spruce ▲BA2C = -0.0398 - 0.0007*PCR + 0.0202*DBHp	0.86
65.	Hemlock & Spruce ▲BA2C = -0.0366 - 0.0005*PCR + 0.018*DBHp	0.80
	▲BA2C = f(LCRa, DBHp)	
66.	Hemlock ▲BA2C = -0.0683 + 0.0007*LCRa + 0.0127*DBHp	0.82
67.	Spruce ▲BA2C = -0.1028 + 0.0009*LCRa + 0.0186*DBHp	0.88
68.	Hemlock & Spruce ▲BA2C = -0.0858 + 0.0007*LCRa + 0.0166*DBHp	0.81

Butt Log Volume Growth Response

Volumes of 16.4-foot butt logs were computed using diameters at 1.0, 9.2, and 17.4 feet (0.3, 2.8, and 5.3 m) in Newton's cubic foot volume equation (Husch *et al.* 1972). Butt log volume growth responses one and two years after thinning and pruning western hemlock and Sitka spruce are shown in Table 34.

Table 34. Mean posttreatment butt log volume (VOL) growth responses of western hemlock and Sitka spruce. Stands at Cave Creek, Lemon Creek, and Salamander Lake were included in the first year measurements and stands at Cave Creek and Lemon Creek were included in the second year measurements.

Pruning Treatments	First Year VOL Growth (n=71)		Second Year VOL Growth (n=67)		Two-Year Cumulative Growth (n=67)	
	(ft^3)	s.d.	(ft^3)	s.d.	(ft^3)	s.d.
Control	0.499	0.206	0.599	0.260	1.099	0.455
8-ft lift	0.544	0.311	0.673	0.347	1.217	0.649
12-ft lift	0.457	0.282	0.690	0.450	1.147	0.718
17.4-ft lift	0.273*	0.229	0.531	0.381	0.860	0.602

* Statistically significant at alpha=0.05

It was hypothesized that first year, second year, and two-year cumulative posttreatment butt log volume growth responses would be a function of pruned height, percent live crown length removed, live crown ratio after pruning, and stem diameter at the time of pruning. The null hypothesis were: there are no functional relationships between butt log volume growth and pruning.

Hypothesis 15.0: First year (▲VOL1), second year (▲VOL2), and two-year cumulative volume growth may be a function of pruned height (PH).

Hypothesis 15.1: {▲VOL1 ≠ f(PH)} -- was rejected.

Hypothesis 15.2: {▲VOL1 = f(PH)}.

Hypothesis 15.3: {▲VOL2 ≠ f(PH)} -- was not rejected.

Hypothesis 15.4: {▲VOL2 = f(PH)}.

Hypothesis 15.5: {▲VOL2C ≠ f(PH)} -- was not rejected.

Hypothesis 15.6: {▲VOL2C = f(PH)}.

The general linear models procedure was used to assess the influence of pruned height on first year, second year, and two-year cumulative posttreatment butt log volume growth. Classification variables included blocks, pruned height classes, species, and diameter classes. Significant analysis of variance models are shown in Table 35.

Table 35. The general linear models procedure was used to perform analysis of variance (ANOVA) to assess the influence of pruned height on first year (▲VOL1), second year (▲VOL2), and two-year cumulative (▲VOL2C) posttreatment butt log (16.4-foot) volume growth. Classification variables included blocks (BLK), pruned height classes (PHC), species (SPP), and initial stem diameter classes (DC).

#	ANOVA Model	Prob > F	R^2
69.	▲VOL1 = f(BLK, PHC)	0.0001	0.17
70.	▲VOL1 = f(BLK, PHC, SPP, DC)	0.0001	0.84
71.	▲VOL2 = f(BLK, PHC, SPP, DC)		
72.	▲VOL2C = f(BLK, PHC, SPP, DC)	0.0001	0.86

Treatments (pruned heights) were significant in the analysis of variance of first year posttreatment volume growth. First year volume growth in the 17.4-foot (5.3 m) lift was 45 percent less than the control. The difference in volume growth was statistically significant and hypothesis 15.1 was rejected. Blocks and pruned height were statistically nonsignificant in the analysis of variance in second year and two-year cumulative volume growth; hypotheses 15.3 and 15.5 were not rejected.

Pruned height was statistically significant when used in combination with blocks, species, and diameter classes for predicting volume growth; multiple classification models had higher coefficients of variation than the model with only blocks and pruned heights.

Hypothesis 16.0: First year (▲VOL1), second year (▲VOL2), and two-year cumulative (▲VOL2C) posttreatment volume growth may be a function of percent live crown length removed (PCR) and stem diameter at the time of pruning (DBHp).

Hypothesis 16.1: {▲VOL1 ≠ f(PCR, DBHp)} -- was rejected.
Hypothesis 16.2: {▲VOL1 = f(PCR, DBHp)}.
Hypothesis 16.3: {▲VOL2 ≠ f(PCR, DBHp)} -- was rejected.
Hypothesis 16.4: {▲VOL2 = f(PCR, DBHp)}.
Hypothesis 16.5: {▲VOL2C ≠ f(PCR, DBHp)} -- was rejected.
Hypothesis 16.6: {▲VOL2C = f(PCR, DBHp)}.

The general linear models procedure was used to assess the influence of percent crown removed on first year, second year, and two-year cumulative posttreatment butt log volume growth. Classification variables included blocks, percent crown removal classes,, species, and diameter classes. Significant analysis of variance models are shown in Table 36. Percent crown removed was statistically significant in the analysis of variance of first year, second year, and two-year cumulative posttreatment volume growth; hypotheses 16.1, 16.3, and 16.5 were rejected.

Table 36. The general linear models procedure was used to perform analysis of variance (ANOVA) to assess the influence of percent live crown length removed on first year (▲VOL1), second year (▲VOL2), and two-year cumulative (▲VOL2C) posttreatment butt log (16.4-foot) volume growth. Classification variables included blocks (BLK), crown removal classes (PCRC), species (SPP), and initial stem diameter classes (DC).

#	ANOVA Model	Prob > F	R^2
73.	▲VOL1 = f(BLK, PCRC)	0.0001	0.43
74.	▲VOL1 = f(BLK, PCRC, SPP, DC)	0.0001	0.87
75.	▲VOL2 = f(BLK, PCRC, SPP, DC)	0.0001	0.85
76.	▲VOL2C = f(BLK, PCRC, SPP, DC)	0.0001	0.88

The general linear models procedure was used to assess the influence of live crown ratio after pruning on first year, second year, and two-year cumulative posttreatment butt log volume growth. Classification variables included blocks, percent crown removal classes,, species, and diameter classes. Significant analysis of variance models are shown in Table 37.

Hypothesis 17.0: First year (▲VOL1), second year (▲VOL2), and two-year cumulative (▲VOL2C) posttreatment volume growth may be a function of live crown ratio after pruning (LCRa) and stem diameter at the time of pruning (DBHp).

Hypothesis 17.1: {▲VOL1 ≠ f(LCRa, DBHp)} -- was rejected.
Hypothesis 17.2: {▲VOL1 = f(LCRa, DBHp)}.
Hypothesis 17.3: {▲VOL2 ≠ f(LCRa, DBHp)}. -- was rejected.
Hypothesis 17.4: {▲VOL2 = f(LCRa, DBHp)}.
Hypothesis 17.5: {▲VOL2C ≠ f(LCRa, DBHp)}. -- was rejected.
Hypothesis 17.6: {▲VOL2C = f(LCRa, DBHp)}.

Table 37. The general linear models procedure was used to perform analysis of variance (ANOVA) to assess the influence of live crown ratio after pruning on first year (▲VOL1), second year (▲VOL2), and two-year cumulative (▲VOL2C) posttreatment butt log (16.4-foot) volume growth. Classification variables included blocks (BLK), pruned height classes (PHC), crown removal classes (PCRC), live crown ratio classes (LCAC), species (SPP), and initial stem diameter classes (DC).

#	ANOVA Model	Prob > F	R^2
77.	▲VOL1 = f(BLK, LCAC)	0.0001	0.44
78.	▲VOL1 = f(BLK, LCAC, SPP, DC)	0.0001	0.85
79.	▲VOL2 = f(BLK, LCAC, SPP, DC)	0.0001	0.84
80.	▲VOL2C = f(BLK, LCAC, SPP, DC)	0.0001	0.87

Live crown ratio after pruning was statistically significant in the analysis of variance of first year, second year, and two-year cumulative posttreatment volume growth; hypotheses 17.1, 17.3, and 17.5 were rejected.

Multiple regression models incorporating percent crown removed, live crown ratio after pruning, and initial diameter for predicting first year posttreatment butt log volume growth are shown in Table 38.

Table 38. Multiple regression models incorporating percent crown removed (PCR), live crown ratio after pruning (LCRa), and initial diameter (DBHp) for predicting first year 16.4-foot butt log volume growth (▲VOL1) of western hemlock and Sitka spruce.

#	Multiple Regression Model	R^2
	▲VOL1 = f(PCR, DBHp)	
81.	Hemlock ▲VOL1 = -0.2567 - 0.003*PCR + 0.1188*DBHp	0.77
82.	Spruce ▲VOL1 = -0.3078 - 0.0067*PCR + 0.147*DBHp	0.81
83.	Hemlock and Spruce ▲VOL1 = -0.3323 - 0.0046*PCR + 0.1416*DBHp	0.81
	▲VOL1 = f(LCRa, DBHp)	
84.	Hemlock ▲VOL1 = -0.4757 + 0.0037*LCRa + 0.1055*DBHp	0.77
85.	Spruce ▲VOL1 = -0.9175 + 0.0083*LCRa + 0.1349*DBHp	0.84
86.	Hemlock and Spruce ▲VOL1 = -0.7121 + 0.0057*LCRa + 0.1277*DBHp	0.82

Multiple regression models incorporating percent crown removed, live crown ratio, and initial stem diameter for predicting two-year cumulative posttreatment butt log volume growth are shown in Table 39.

Table 39. Multiple regression models for predicting two-year cumulative posttreatment butt log volume growth (▲VOL2C) of western hemlock and Sitka spruce at Cave Creek and Lemon Creek. Independent variables included percent crown removed (PCR), live crown ratio after pruning (LCRa), and DBH at the time of pruning (DBHp).

#	Multiple Regression Model	R^2
	▲VOL2C = f(PCR, DBHp)	
87.	Hemlock ▲VOL2C = -0.6029 - 0.0041*PCR + 0.2618*DBHp	0.82
88.	Spruce ▲VOL2C = -0.687 - 0.0098*PCR + 0.3324*DBHp	0.81
89.	Hemlock and Spruce ▲VOL2C = -0.9114 - 0.006*PCR + 0.3406*DBHp	0.83
	▲VOL2C = f(LCRa, DBHp)	
90.	Hemlock ▲VOL2C = -0.9553 + 0.0064*LCRa + 0.2376*DBHp	0.84
91.	Spruce ▲VOL2C = -1.6948 + 0.0131*LCRa + 0.3208*DBHp	0.84
92.	Hemlock and Spruce ▲VOL2C = -1.4888 + 0.0088*LCRa + 0.3219*DBHp	0.85

Conclusions

Forest pruning is a viable silvicultural practice for the western hemlock-Sitka spruce forest type. Pruning prescriptions should take into account the amount of live crown removed as well as the posttreatment live crown ratio to minimize risk.

Branch Characteristics and Time Required to Prune

Relationships between number of branches cut and time required to prune were statistically nonsignificant. The regression model based on basal area of cut branches for predicting pruning time was statistically significant but did not account for more than 40 percent of the variation in time required to prune. Stem diameter at breast height was a significant variable for predicting time required to prune but did not account for more than 37 percent of the variation in time required to prune. Pruned height was a highly significant variable for predicting time required to prune. Pruned height in combination with stem diameter were better predictors of pruning time than were number of branches cut or basal area of cut branches.

Frequency of Epicormic Shoots on Spruce After Treatment

Differences in numbers of epicormic sprouts between treatments were statistically nonsignificant in the first two years after treatment. Lateral growth of epicormics was not measured but there may be differences between treatments. Development of epicormics on spruce may reduce expected returns from pruning investments.

Height Growth After Treatment

Height growth differences between treatments were statistically nonsignificant in the first two years after treatment.

Diameter Growth After Treatment

Diameter growth was most affected by the pruning treatments in the first year after treatment. Blocks, pruned height, species, and initial stem diameter were significant variables in the general linear models for predicting posttreatment stem diameter growth. Percent live crown length removed in combination with initial stem diameter and live crown ratio in combination with initial stem diameter were significant variables in the multiple regression models for predicting posttreatment stem diameter growth. Growth was significantly reduced when 40 percent or more live crown length was removed and when live crown ratios were reduced to less than 50 percent.

Changes in Stem Taper

Significant changes in stem taper from 4.5 to 17.4 feet occurred after pruning hemlock and spruce. Mean stem diameter growth in the 17.4-foot lift was significantly reduced at 4.5 feet above the ground but not at 17.4 feet. Differential growth responses along the stem resulted in reduced stem taper.

Basal Area Growth After Treatment

Basal area growth was most affected in the first year after pruning; differences between treatments were statistically nonsignificant in the second year after pruning. Blocks, pruned height, species, and initial stem diameter were significant variables in the general linear models for predicting posttreatment basal area growth. General linear models for predicting second year basal area growth had higher coefficients of determination than models developed for predicting diameter growth. Percent live crown length removed in combination with stem diameter and live crown ratio in combination with stem diameter were significant variables in multiple regression models for predicting basal area growth. Basal area growth was significantly reduced when 40 percent or more of live crown length was removed and when live crown ratios were reduced below 50 percent.

Butt Log Volume Growth After Treatment

Butt log volume growth was most affected in the first year after pruning; differences between treatments were statistically nonsignificant in the second year after treatment. Percent live crown length removed in combination with stem diameter and live crown ratio in combination with stem diameter were significant variables in the multiple regressions for predicting butt log volume growth.

Part V. Applications to Management

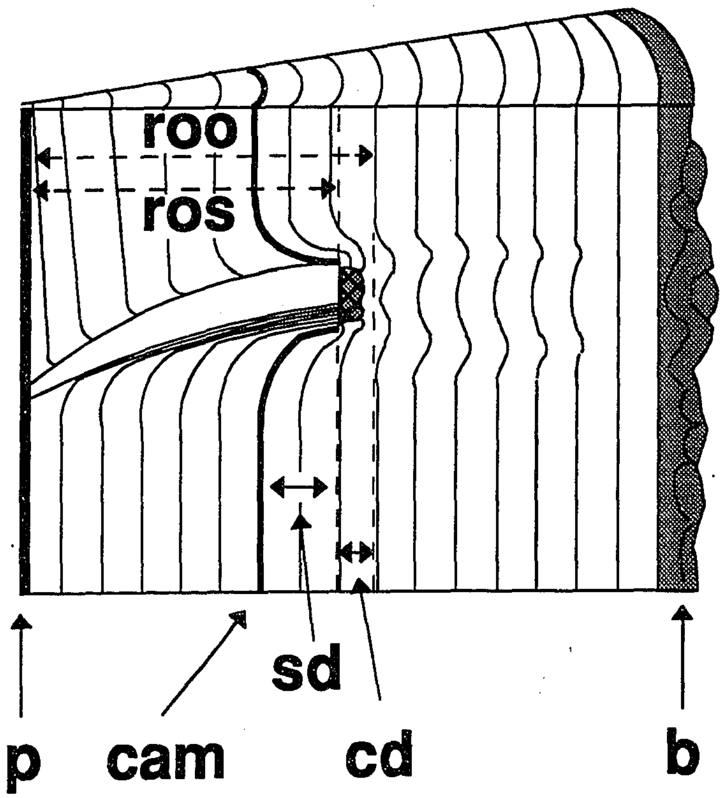
There is a global trend toward establishing forest plantations at lower densities than in the past; likewise, plantations and natural stands are being precommercially thinned to wider spacings. During the stand initiation stage there is enough space and light between the trees for shrubs and herbs to grow. An abundance of seeds and understory vegetation provides food for wildlife during stand initiation. As the trees grow taller and the crowns expand, little light reaches the forest floor and the understory dies; this condition is the stem exclusion stage, so named because new stems are prevented from becoming established and some existing stems die and are excluded from the stands (Oliver 1990). Stands in the stem exclusion stage provide thermal cover and hiding cover for wildlife, but there is little or no browse available. Thinning stands before the crowns close may perpetuate the growth of the understory, enhance biodiversity, and increase diameter growth on the remaining trees; however, at wider spacings, lower branches receive more light and become larger and more persistent. Species such as western hemlock, Sitka spruce, Douglas-fir, and ponderosa pine have very persistent branches that remain on the lower portions of the boles for 70 to 100 years. The persistent branches result in an increase in the size and number of knots in lumber and veneer; knots are structural defects that normally cause losses in value. Knots in timber were described by Pontey as "an evil of immense magnitude" (Pontey 1805).

Abundant reserves of high-quality old-growth timber have historically provided a steady supply of clear wood in the Pacific Northwest. The old-growth resource has been greatly diminished and harvesting is restricted in most remaining stands; therefore, future supplies of clear wood will have to come from well-managed young-growth forests.

wood will have to come from well-managed young-growth forests. Thinning and pruning regimes will be necessary to ensure production of significant volumes of clear wood in young-growth stands. Forest pruning entails the removal of lower branches from crop trees to a predetermined height to promote the growth of clear wood on the boles. The primary objectives of forest pruning are to improve wood quality and to increase value.

Price premiums for high-quality wood make pruning an attractive investment opportunity in young-growth stands. Pruning strategies aim to minimize the volume of the defect core and maximize clear wood production; these strategies should take into account the delay from the time of pruning until clear wood is produced. The timing and quality of the pruning operation affect subsequent wood quality. Figure 26 shows a radial cut through a pruned branch stub; sometimes pitch and bark will accumulate at the end of the pruned branch stub, or there may be some discoloration within the occlusion zone just beyond the stub. The defect core includes the stub and the occlusion zone; clear wood is produced beyond the occlusion zone. Branch stub occlusion rates vary with age of the cambium at the time of pruning, branch diameter, growth rate, pruning technique, bark thickness, and stub length.

Pruning technique can greatly affect occlusion rates. At the bases of branches are layers of stem and branch tissues referred to as branch collars. Branches should be cut off just to the outside of the branch collars. In 1756 a German forester, Büchting, said the branch collar should not be damaged (Meyer-Wegelin 1936). Branch protection zones composed of fungi-inhibiting terpene-based substances are usually well-developed within conifer branch collars (Mayer-Wegelin 1936).



p - pith
cam - cambium when pruned
sd - stub distance
cd - clear distance
b - bark
ros - radius over stub
roo - radius over occlusion

Figure 26. Radial cut through a pruned branch stub. The defect core includes the stub and the occlusion zone beyond the stub; clear wood is produced beyond the occlusion zone.

Resin-impregnated compression wood also develops at the bases of branches; and resin offers some protection against most insects and pathogens. Cutting behind the branch collar exposes both the branch wood and the surrounding stem wood, which does not have a protection zone or high amounts of resin. The stem wood will become infected with decay-causing fungi, and the decay will spread up and down the stem. At the other extreme, long stubs should not be left because longer stubs take more time to occlude. If branches are knocked off with a club or an axe the stubs will splinter; bark and pitch often accumulate at the ends of splintered stubs and occlusion is delayed. Pruning costs are carried as an investment; any delay of occlusion reduces the amount of clear wood and the return on the investment. Occlusion is rapid when pruning is done early in the rotation when branches are small and bark is thin. Pruning later in the rotation, when branch collars are larger, results in additional occlusion time and reduced clear wood production.

Pruning can be accomplished with handsaws, polesaws, and/or pruning shears. Modified pruning shears and ladders are preferred by pruners in New Zealand and British Columbia, Canada; shears and ladders are being tested for operational pruning in the Pacific Northwest. Handsaw and polesaw combinations have been used most extensively. A pruner can easily reach to 9 feet (2.7 m) with a handsaw. The same blade can be mounted on an axe handle or a pole. With a 6-foot (1.8 m) pole, a pruner can reach to 14 feet (4.3 m) and with two 6-foot poles a pruner can reach to 18 feet (5.5 m). When deciding how high to prune, there are two factors to consider: 1. marketing objectives, and 2. how much of the live crown can be removed without adversely affecting growth. If the objective is to produce a clear 16-foot (4.9 m) log, the trees should be pruned higher than 16 feet (4.9 m) to allow for height of the stump and trim at the mill -- 18 feet (5.5 m) is a conservative minimum height to prune; some stands in the Pacific Northwest are pruned to 20 feet (6.1 m) or higher.

Pruning early in the rotation, for example, when average stem diameter is four inches (10.2 cm), is recommended to minimize the size of the defect core; but it must be kept in mind that the live crown is the source of photosynthates necessary for growth. Pruning young trees to 18 feet (5.5 m) all at once will reduce growth or kill the trees -- so it is critical to know how much of the crown can be safely removed at one time. When pruning live branches there are two variables to monitor: percent live crown length removed and live crown ratio after pruning (these variables are not additive). Results from this investigation show approximately one-third (up to 40 percent) of the live crown length can be removed without adversely affecting tree growth -- as long as at least a 50 percent live crown ratio remains after pruning.

Recommendations for Pruning Western Hemlock and Sitka Spruce

Hemlock and spruce stands could be precommercially thinned to 300 trees per acre (740 trees per hectare) when the tallest 100 trees per acre (250 trees per hectare) reach 21 feet (6.4 m). In hemlock and spruce stands with 50-year site index of 100 feet (30.5 m), the top 100 trees per acre (250 trees per hectare) will reach 21 feet (6.4 m) at breast height age eight or total age 14 (Farr 1993). Diameter-limit thinning (e.g., cut all trees less than three inches (7.6 cm) dbh) or low thinning (cut from below) could be done rather than fixed-spacing thinning. Thinning to a fixed spacing in stands with a lot of microsite variability often results in the selection of small trees on poor microsites to maintain spacing while some larger trees are cut. Selecting 300 dominant and codominant trees per acre (740 trees per hectare) at variable spacings could provide some hiding and thermal cover for wildlife as well as some open areas with available browse.

One hundred dominant and codominant trees per acre (250 trees per hectare) could be pruned before or after thinning. Shading of the lower boles by adjacent unpruned trees may prevent epicormic sprouting on spruces. Figure 27 shows an example of how a hemlock or spruce could be pruned to 18 feet (5.5 m) in several lifts. At the time of the first lift the tree is 21 feet (6.4 m) tall and some of the lower branches are dead; height to the base of the live crown is three feet (0.9 m). Live crown ratio is determined by dividing crown length by total height of the tree and multiplying by 100. The crown length is determined by subtracting height to the base of the live crown from total height, so the live crown length is 21 feet - 3 feet = 18 feet (6.4 m - 0.9 m = 5.5 m); 18 feet divided by 21 feet and multiplied by 100 = 86 percent live crown ratio before pruning (5.5 m/6.4 m x 100 = 86%). One-third of the live crown length can be safely removed in the first lift; one-third of 18 feet (5.5 m) is 6 feet (1.8 m), add on the 3 feet (0.9 m) to the base of the crown and, in this example, the tree can be pruned to 9 feet (2.7 m) in the first lift. The second lift can be done when the tree reaches 28 feet (8.5 m), the tree can be pruned from 9 feet to 14 feet (2.7 m to 4.3 m), leaving a 50 percent live crown ratio. The third lift is done when the tree reaches 36 feet (11 m), the tree can be pruned from 14 feet to 18 feet (4.3 m to 5.5 m), leaving a 50 percent live crown ratio. In hemlock and spruce stands with 50-year site index of 100 feet (30.5 m), the pruning lifts could be scheduled four years apart. Alternatively, the trees could be pruned to 18 feet (5.5 m) in one or two lifts when the trees reach sufficient heights;

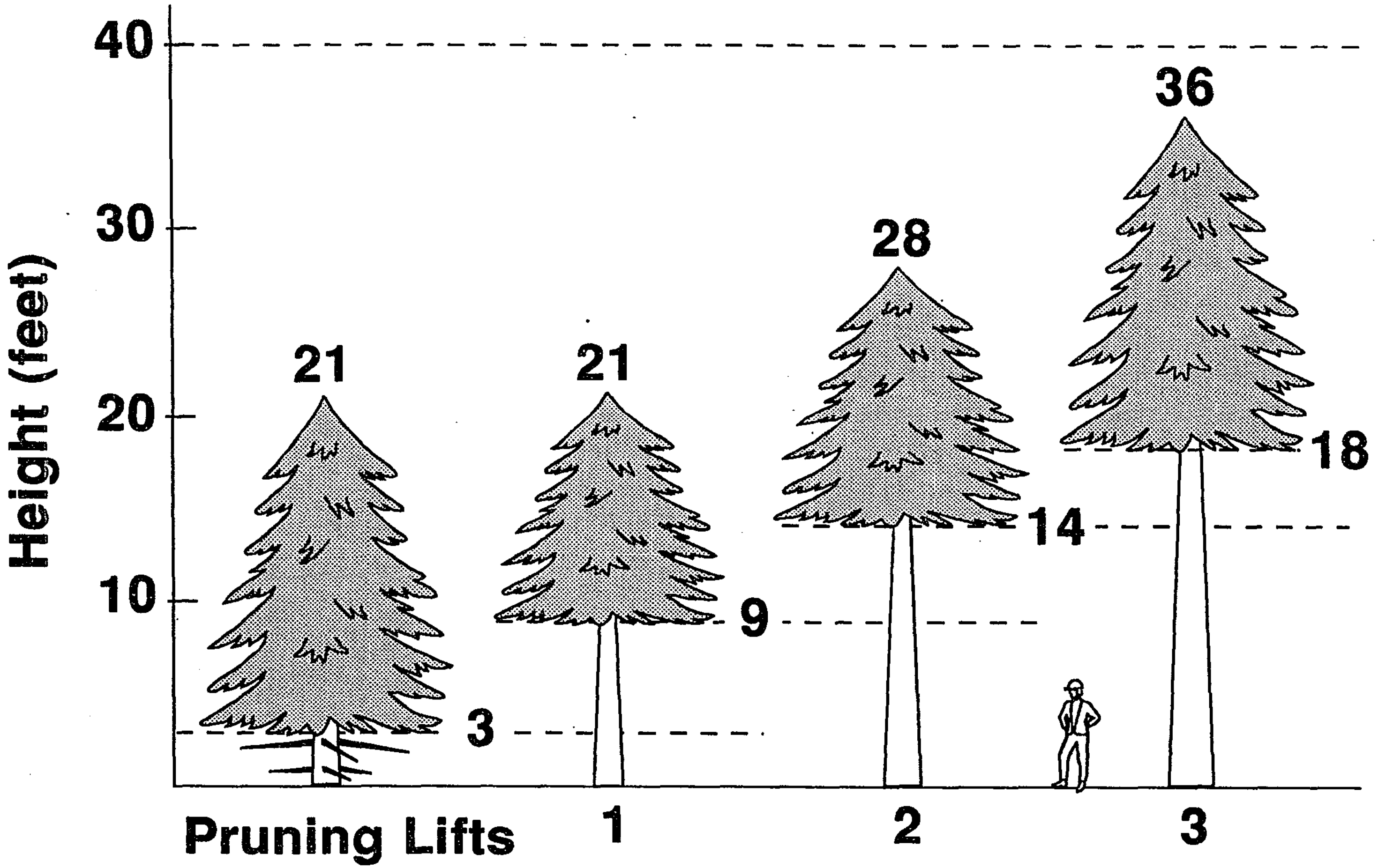


Figure 27. Three-lift pruning regime for hemlock and spruce. One-third of the live crown length is removed in the first lift; in the second and third lifts, 50 percent live crown ratios remain after pruning.

however, delayed pruning would result in larger defect cores.

Pruning is an operation that immediately changes stand structure. Removal of lower branches may improve aesthetics and enhance biological diversity in managed forests; increased amounts of sunlight reaching the forest floor can increase microbial activity, nutrient cycling, and stimulate the growth of understory vegetation. Wildlife forage can be increased by thinning and pruning; and to maintain some hiding cover, a few unpruned trees could be left in scattered clumps throughout the stand.

Planning, Implementing, and Monitoring Forest Pruning Operations

Pruning operations should be well planned and documented with defined criteria for stand selection, operation specifications, and defined criteria for monitoring and evaluation. In addition, the pruning operations should be coordinated with other stand manipulations to achieve a more broad objective of creating and maintaining a diversity of stand structures across landscapes. Instead of trying to maximize diversity in each stand it is more practical to maintain a diverse array of stands across landscapes. Biological diversity over a broad area may be enhanced by maintaining approximately constant proportions of stands in various age classes with diverse structures over time (Oliver 1990; Hunter 1990).

Determining Suitability of Stands for Pruning

Stand selection criteria should include species composition, site quality, age, and accessibility. Species which may be considered for operational forest pruning in northwestern North America include Douglas-fir, ponderosa pine, western hemlock, and Sitka spruce. Forest pruning is a labor intensive intermediate stand treatment; highest returns from pruning investments may be achieved when the pruned crop trees are grown on high quality sites. On high sites, greater interwhorl distances result in fewer branches to prune within a fixed height, and maximum clear wood is produced when trees are growing well. Highest priority should be given to pruning stands of 50-year site index of 100 feet (30.5 m) or higher.

Accessibility is another important factor to consider in planning silvicultural operations. Sites should be accessible by roads suitable for transporting work crews and equipment.

Design Alternatives: Fixed-Lift and Variable-Lift Pruning

Fixed-lift pruning involves removing all branches to a specified height (*e.g.*, 9 feet (2.7 m) in the first lift). Fixed-lift pruning is easy to administer because all crop trees are pruned to the same height. The fixed height to prune is determined by how much of the live crown can be safely removed without significantly decreasing volume growth.

Variable-lift pruning involves removing a specified percentage of the live crown or pruning to a specified upper stem diameter. There is often a lot of variability in tree heights and this method ensures that small trees will not be over-pruned. This method may be more difficult to administer because individual crown lengths and heights to prune have to be calculated or estimated before pruning.

Implementation

Appropriations are made for operational pruning and then the following actions may be taken if the work is performed on a contractual basis:

1. Monitoring is done at the end of the growing season prior to pruning. Total height, height to live crown, and dbh of sample trees are measured and analyzed to determine the optimum time and height to prune.
2. Announcements are made for acceptance of bids for contract work.
3. Contractor is selected and a pre-work meeting is scheduled to discuss the specifications of the pruning contract.
4. Contract inspection is done during and at the end of the pruning operations.

Pruning Time and Costs

Tools: handsaws and polesaws;
labor: $6.00/hour + 50% benefits = $9.00/hour.
First pruning lift: 0 to 9 feet;
pruning time: 2.6 minutes/tree;
walk between trees: 0.4 minutes/tree;
3.0 minutes/tree = $0.45/tree;
20 trees/hour/person;
160 trees/person/8-hour day;
1.6 acres/person/8-hour day (@ 100 pruned trees/acre);
5 hours/acre (@ 100 trees/acre) = $45.00/acre.

Second pruning lift: 9 to 14 feet;
pruning time: 3.2 minutes/tree;
walk between trees: 0.4 minutes/tree;
3.6 minutes/tree = $0.54/tree;
16.7 trees/hour/person;
133 trees/person/8-hour day;
1.3 acres/person/8-hour day (@ 100 pruned trees/acre);
6 hours/acre (@ 100 trees/acre) = $54.00/acre.

Third pruning lift: 14 to 18 feet;
pruning time: 2.5 minutes/tree;
walk between trees: 0.4 minutes/tree;
2.9 minutes/tree = $0.44/tree;
20.7 trees/hour/person;
165 trees/person/8-hour day;
1.65 acres/person/8-hour day (@ 100 pruned trees/acre);
4.83 hours/acre (@ 100 trees/acre) = $43.50/acre.

Contractors will probably bid $1.00 per tree or $100.00 per acre per lift (@ 100 pruned trees/acre). Sensitivity analyses of pruning were performed using pruning cost, site index, fertilization, pruning age, rotation length, and interest rate as the variable factors (Fight *et al.* 1987; Fight *et al.* 1993). The analyses indicated forest pruning is an economically feasible and viable silvicultural practice under a range of stand management regimes. Expected internal rates of return from pruning young stands exceeded a four percent real rate; up to seven percent in ponderosa pine and greater than nine percent in Douglas-fir (Fight *et al.* 1993).

Monitoring and Evaluation

Pruned stands should be monitored for diameter and height growth, stem damage, and insect and disease conditions. The data should be evaluated to determine if the operations are leading to the desired objectives. If the objectives are not being met then adjustments in the timing and methods of pruning may be necessary.

Environmental Considerations

The National Environmental Policy Act of 1969 (NEPA) has two primary aims: (1) to ensure that the environmental impacts of proposed actions are considered in the federal decision-making process, and (2) to provide a means by which the public is informed of and can participate in the analysis of environmental impacts of proposed actions (PL 91-190 1969). The first step is to prepare an environmental assessment (EA). When an EA indicates that the proposed action will not have a significant effect on the human environment then a categorical exclusion from further NEPA review procedures may be considered. Pruning qualifies for a categorical exclusion from NEPA review.

The public may be concerned about the visual impacts of the pruning operations. Pruning in several lifts may lessen the visual impact in high-visibility areas. The public should be informed of the objectives and benefits of forest pruning. Pruning will not be done in every forest but rather only on the high-quality sites designated for intensive management. Thinning and pruning regimes will be necessary to ensure production of significant volumes of clear wood in managed young-growth stands.

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Appendix 1. Topographic Maps

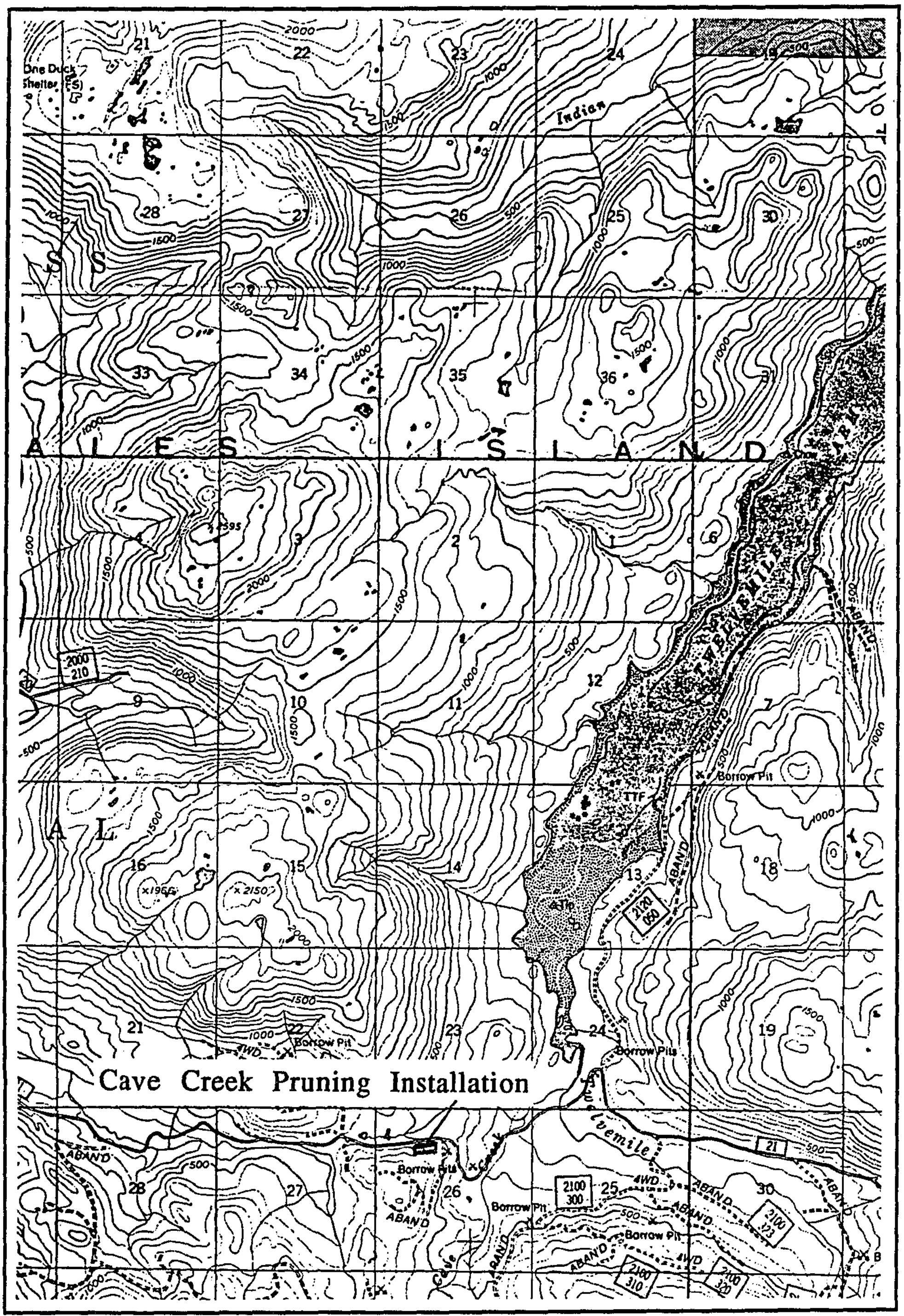

Figure A-1. Location of Cave Creek pruning installation: Section 26, T75S, R83E.

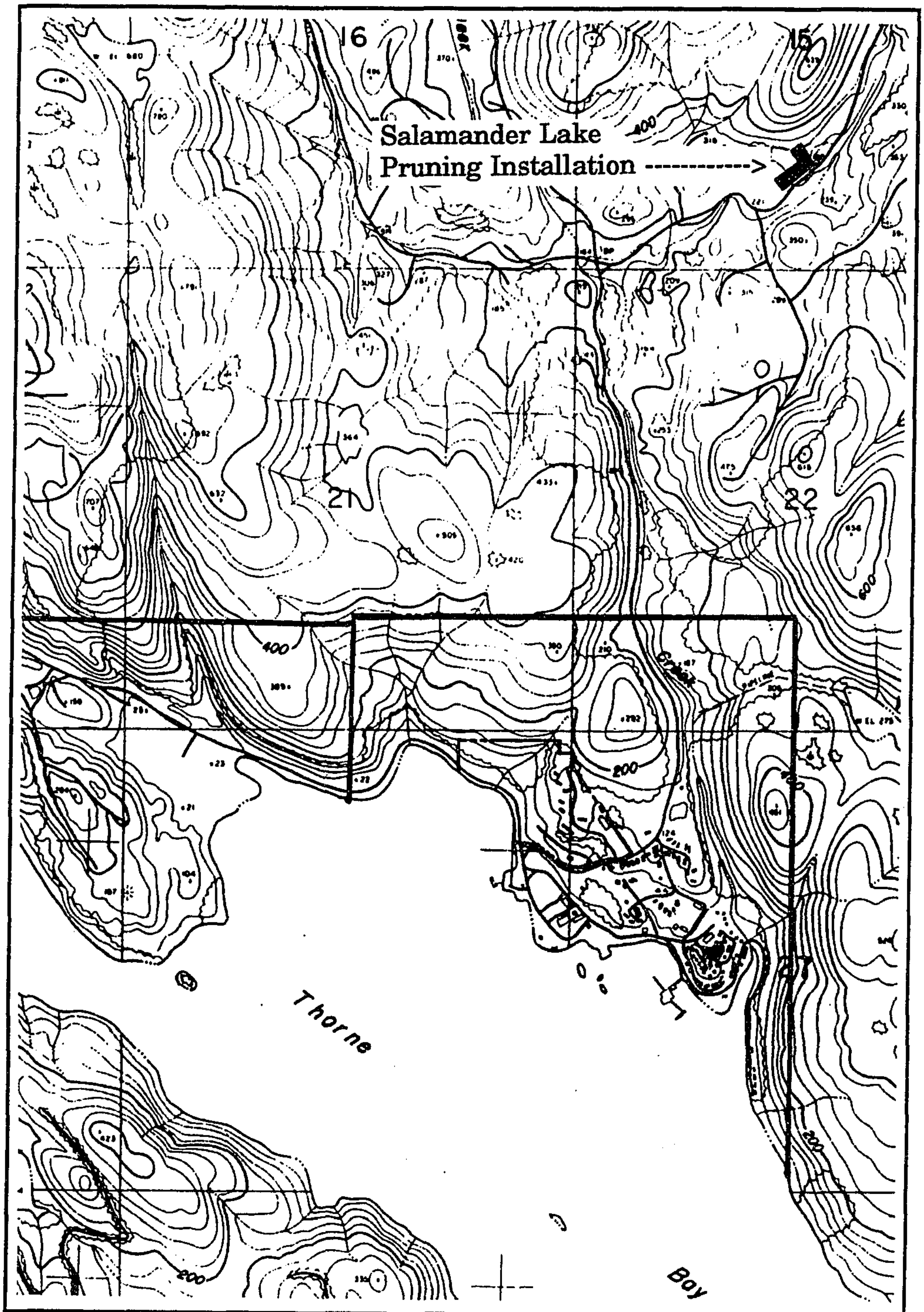

Figure A-2. Location of Salamander Lake pruning installation: north side of Forest Service Road #30, SW¼, SE¼, Section 15, T71S, R84E.

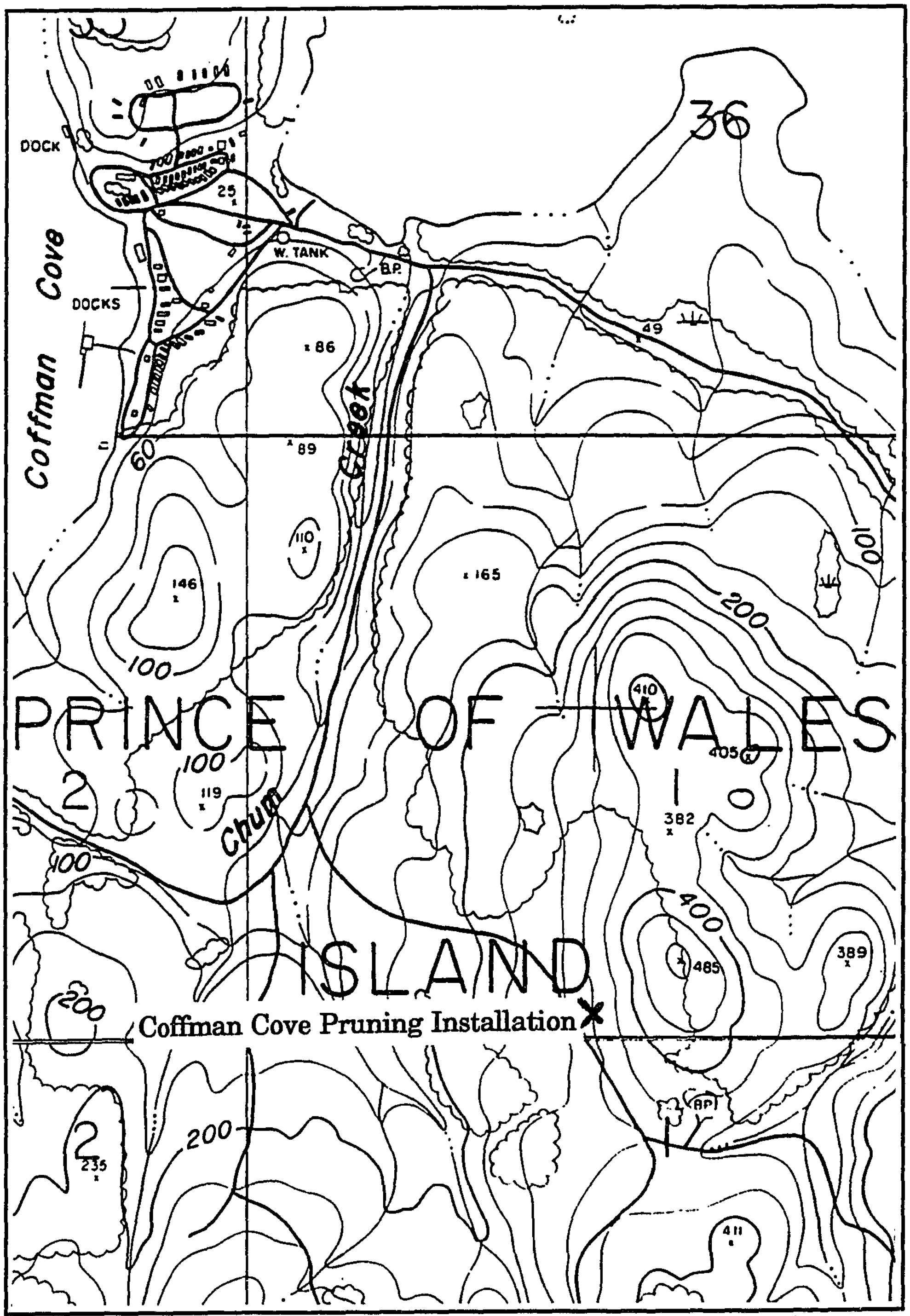

Figure A-3. Location of Coffman Cove pruning installation: Section 1, T68S, R81E.

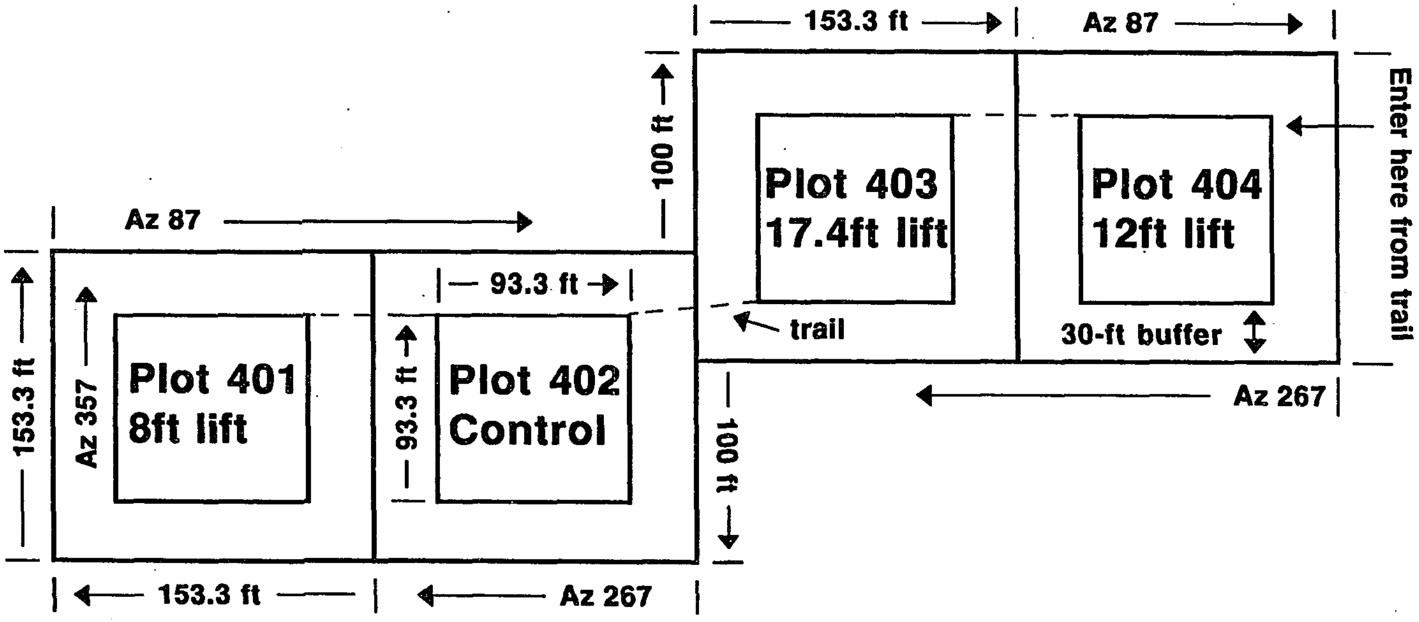

Figure A-4. Layout of Cave Creek pruning installation. Treatment plot dimensions are 153.3 x 153.3 feet (0.54 acre); each treatment plot contains a 0.2-acre measurement plot (93.3 x 93.3 feet) with a 30-feet buffer zone on all sides.

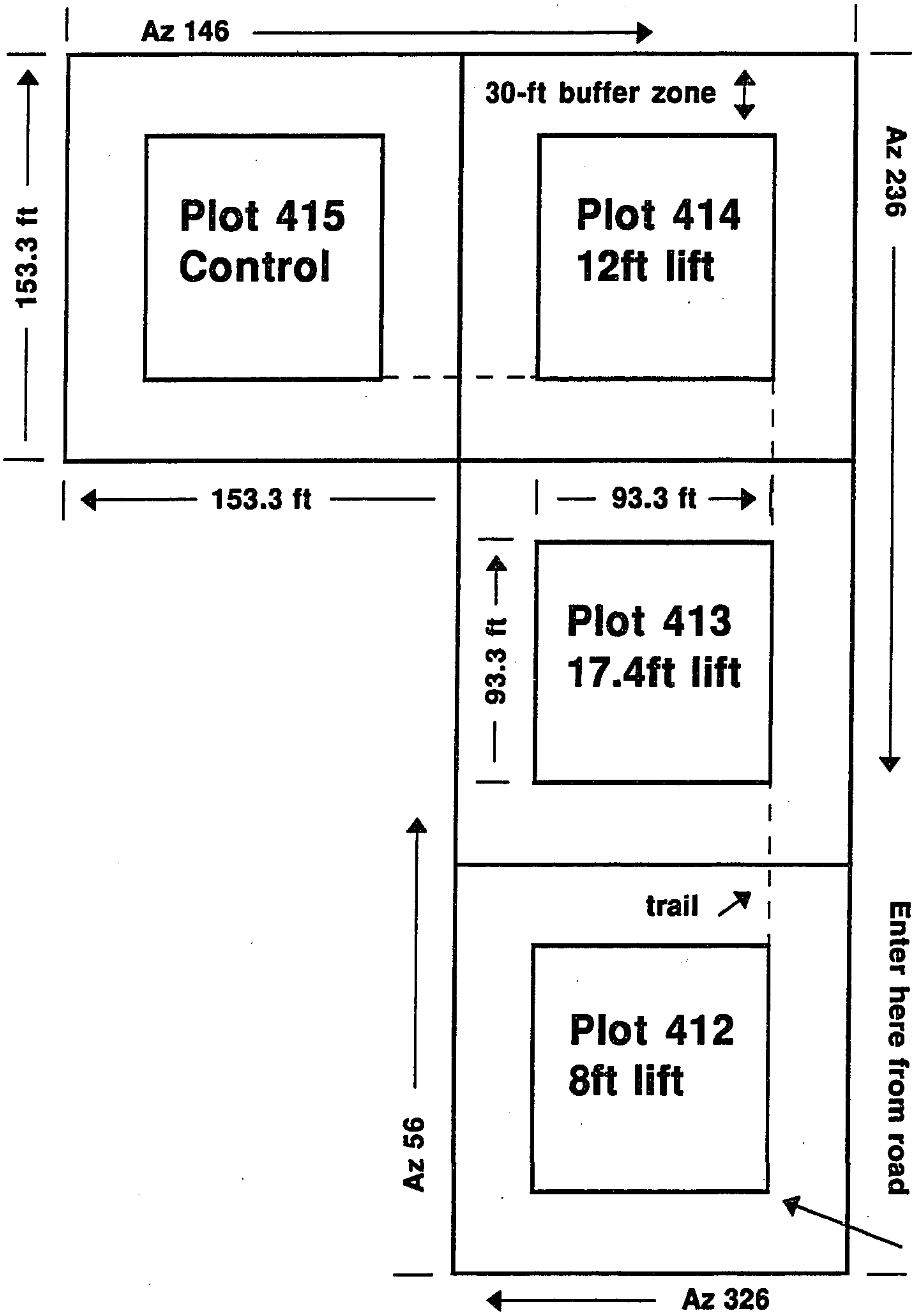

Figure A-5. Layout of Salamander Lake pruning installation. Treatment plot dimensions are 153.3 x 153.3 feet (0.54 acre); each treatment plot contains a 0.2-acre measurement plot (93.3 x 93.3 feet) with a 30-feet buffer zone on all sides.

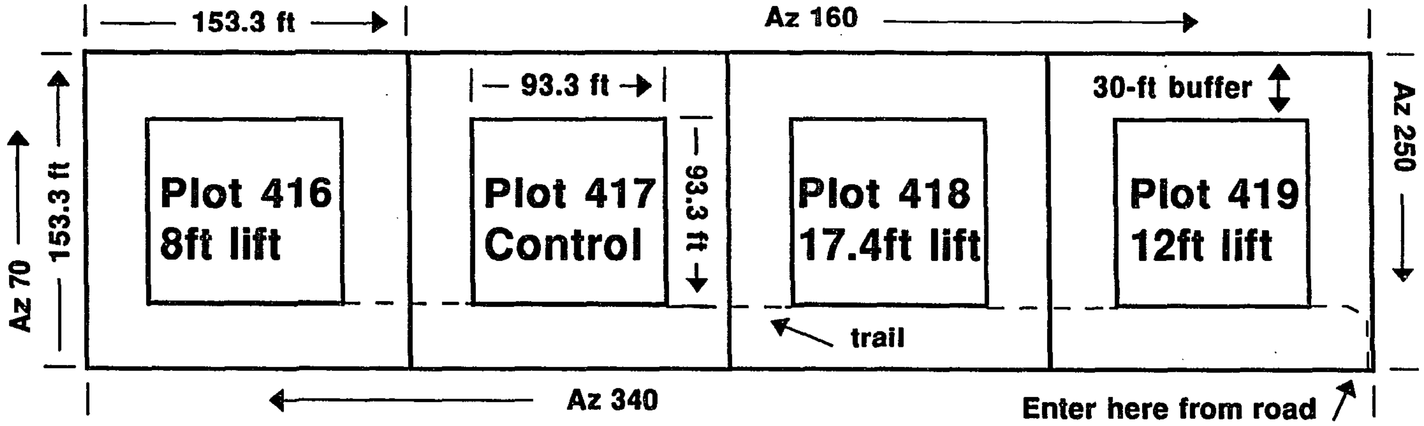

Figure A-6. Layout of Coffman Cove pruning installation. Treatment plot dimensions are 153.3 x 153.3 feet (0.54 acre); each treatment plot contains a 0.2-acre measurement plot (93.3 x 93.3 feet) with a 30-feet buffer zone on all sides.

Table A-1. Means, standard deviations (s.d.), and ranges of stand variables after thinning, but before pruning four stands on the Tongass National Forest.

	Diameter (inches)			Height (feet)			Height to Live Crown (feet)			Live Crown Ratio (%)		
Stands	Mean	s.d.	Range	Mean	s.d.	Range	Mean	s.d.	Range	Mean	s.d.	Range
Cave Creek	6.8	2.6	1.8-16.0	33.3	7.9	13-58	3.3	1.0	0.4-7.2	89.6	3.6	78.8-98.5
Lemon Creek	5.3	1.5	2.7-9.5	35.1	4.7	20-47	10.1	3.2	3.0-18.4	70.8	10.0	35.4-90.5
Salamander Lake	7.4	2.2	3.1-14.4	37.8	7.7	18-58	4.1	1.6	0.2-8.3	88.9	4.4	77.6-99.6
Coffman Cove	9.1	2.2	3.4-15.2	43.6	7.7	23-62	4.2	2.0	0.5-15.0	90.3	4.3	70.5-98.8
All Stands	7.1	2.5	1.8-16.0	37.4	8.1	13-62	5.5	3.5	0.2-18.4	84.9	10.2	35.4-99.6

Table A-2. Hemlock and spruce diameter distributions by individual stands and all stands combined.

Midpoints of DBH classes (inches)	Stands Cave Creek		Lemon Creek		Salamander Lake		Coffman Cove		All Stands	
	hemlock #	spruce #	hemlock #	spruce #	hemlock #	spruce #	hemlock #	spruce #	hemlock #	spruce #
2	1	1	2	1					3	2
4	14	13	32	26	6	7	1		53	46
6	37	14	19	35	28	19	16	1	100	69
8	15	6	3	16	25	16	29	11	72	49
10	4	11		2	8	17	21	25	33	55
12	4	4				2	2	11	6	17
14	1	1				4		6	1	11
16		1						1		2
Total	76	51	56	80	67	65	69	55	268	251

Table A-3. Hemlock and spruce height distributions by individual stands and all stands combined.

Midpoints of height classes (feet)	Stands								All Stands	
	Cave Creek		Lemon Creek		Salamander Lake		Coffman Cove			
	hemlock #	spruce #	hemlock #	spruce #	hemlock #	spruce #	hemlock #	spruce #	hemlock #	spruce #
10	1								1	
20	6	10	3	2	1	5	2		12	17
30	42	18	30	38	23	18	11	1	106	75
40	23	20	23	39	37	25	25	23	108	107
50	3	3		1	6	16	29	25	38	45
60	1					1	2	6	3	7
Total	76	51	56	80	67	65	69	55	268	251

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EDUCATION

Ph.D. 1994. University of Washington, College of Forest Resources, Seattle, WA. Major: Silviculture and Forest Protection.

M.S. 1985. North Carolina State University, College of Forest Resources, Raleigh, N.C. Major: Forestry. Minor: Soil Science.

B.S. 1982. Rutgers University, Cook College, New Brunswick, New Jersey. Major: Forestry. Dean's List: 12/81, 7/81, 5/81, 12/80.

DISSERTATION

Effects of Pruning on Growth of Western Hemlock (*Tsuga heterophylla*) and Sitka spruce (*Picea sitchensis*) in Southeast Alaska.

RESEARCH EXPERIENCE

Silviculturist, 8/94 - present. Yakima Indian Nation, Department of Natural Resources, Toppenish, WA. Conducting silvicultural research on the Yakima Indian Reservation.

Silviculture Research Assistant, 1/90-7/94. Stand Management Cooperative, University of Washington, College of Forest Resources, Seattle, WA. Conducted silvicultural research on the Tongass National Forest in cooperation with the U.S. Forest Service, Forestry Sciences Laboratory, Juneau, AK. Designed, implemented, and evaluated experiments to investigate the effects of thinning and pruning on growth and wood quality of western hemlock (*Tsuga heterophylla*) and Sitka spruce (*Picea sitchensis*) in Southeast Alaska, and Douglas-fir (*Pseudotsuga menziesii*) in Oregon, Washington, and British Columbia.

Research Forester, 5/89-8/89. Suncrest Land and Timber, Waynesville, N.C. Quantified weight loss of stored pulpwood for the development of an optimum wood purchasing, inventory, and chipping strategy; conducted a sawmill efficiency study.

Research Assistant, 5/83-12/84. North Carolina State University-Industry Cooperative Hardwood Research Program, Raleigh, N.C. Implemented a cooperative investigation with Champion International Corporation. Measured and evaluated the effects of residual tree control on the growth and development of hardwood regeneration following clearcut harvesting in the Southern Appalachians.

Research Forester, 5/82-8/82. Rutgers University, Stokes State Forest, N.J. Determined weights and volumes of black oak (*Quercus velutina*) and chestnut oak (*Q. prinus*) for development of board foot and residual volume equations.

TEACHING EXPERIENCE

Assistant Professor, 8/94 - present. Heritage College, Toppenish, WA. Lecturing and conducting field exercises in Silviculture: the theory and practice of controlling forest establishment, composition, structure, growth, and quality.

Teaching Assistant, 3/92-12/92. College of Forest Resources, University of Washington, Seattle. Presented lectures, assisted with lecture assignments, and conducted field exercises for the following courses:

Forestry - The Profession: Survey of human use of forest resources and the impact of social and cultural institutions on resource management; history and the development of forest conservation, forest utilization practices, and policies in the United States; changing patterns of resource use and methods of resolving conflicts among management alternatives. 9/92-12/92.

Silviculture: Studies of silvicultural systems such as clearcutting, seed tree, shelterwood, and selection systems; site preparation, nursery practices, and regeneration methods; intermediate operations including thinning, pruning, fertilization, and the use of chemicals. 3/92-6/92.

Field Measurements: Development of forestry field measurement skills; interpretation of aerial photos; measurement of vegetation including stand examination and timber cruising. 3/92-6/92.

Forest Surveying and Transportation: Concepts of timber harvesting requirements, road-access planning, and forest land surveying; basic elements of road design principles, processes, and practical application of field road location; review of basic road drainage design; overview of road construction techniques and maintenance principles. 3/92-6/92.

Teaching Assistant, 8/87-5/89. North Carolina State University, College of Forest Resources, Raleigh, N.C. Conducted field exercises and assisted with lecture assignments for the following courses:

Silviculture: The theory and practice of controlling forest establishment, composition, structure, growth, and quality. 1/89-5/89 and 1/88-5/88.

Dendrology: Identification and biology of woody plants with studies of their classification, characteristics, and habits. 8/88-12/88 and 8/87-12/87.

Introduction to Field Forestry: Identification of woody plants and techniques of instrumentation used in forest mensuration. 5/88.

Visiting Professor, 5/85-5/87. Tribhuvan University, Institute of Forestry, Pokhara, Nepal. Peace Corps Volunteer. Conducted lectures and field exercises in the following courses:

Physical Geology: Physical processes acting on the Earth; plate tectonics and its relation to volcanoes, earthquakes, and mountain ranges; studies of minerals, rocks, landforms, and topographic maps. 1/87-5/87 and 1/86-5/86.

Introductory Soil Science: Studies of soil formation, physical and chemical properties; conservation and management of soils. 5/86-12/86.

Forest Ecology: Physical, chemical, and biotic factors of the environment; structure, function, and classification of communities and ecosystems. 5/85-12/85.

Teaching Assistant, 8/82-5/83. North Carolina State University, Department of Forestry, Raleigh, N.C. Conducted field exercises and assisted with lecture assignments for the following courses:

Introduction to Forestry Concepts and Measurements: Overview of multiple-use forestry; history, policy, practice, protection, national planning, and forestry careers. Theories, principles, and techniques of instrumentation relative to the collection and presentation of forest data. 1/83-5/83.

Dendrology: Identification and biology of woody plants with studies of their classification, characteristics, and habits. 8/82-12/82.

PRACTICAL EXPERIENCE

Forester, 9/89-11/89. U.S. Forest Service, Wenatchee National Forest, Cle Elum, WA. Field checked and documented conditions and locations of superior trees; revised select tree registers for the Tree Improvement Program; conducted contract inspections for cone collection, site preparation, and fertilization; checked contractor's performance for compliance with technical specifications, plans, and contract work schedules.

Peace Corps Forester, 1/85-5/87. Resource Conservation and Utilization Project, Ministry of Forests and Soil Conservation, Government of Nepal and Peace Corps. Developed and implemented a monitoring and evaluation program for forest nurseries and plantations in coordination with the District Forest Controllers in Myagdi and Mustang Districts in the Himalayas.

Gardener, Summers 1980 & '81. United States Department of the Interior, National Park Service:

The White House: President's Park, Washington, D.C. Conducted an inventory of the park trees; established and maintained display gardens. Summer 1981.

Independence National Historical Park: Philadelphia, PA. Planted, pruned, and fertilized shade trees; established and maintained shrubs, turf, and annuals. Summer 1980.

SKILLS

General forestry and woodsman skills; basic mechanical repairs; field and laboratory research techniques; statistical analyses; personal and mainframe computer operations; scientific and technical writing; teaching techniques.

PROFESSIONAL MEMBERSHIP

Society of American Foresters	1/80-present
Xi Sigma Pi, Forestry Honor Society	5/83-present
International Society of Tropical Foresters	1/85-present

AWARDS

5/93. Agnes Anderson Graduate Fellowship, University of Washington, Seattle, WA.

5/89. Outstanding Graduate Teaching Award, North Carolina State University, Raleigh, N.C.

12/81, 7/81, 5/81, 12/80. Dean's List, Rutgers University, New Brunswick, N.J.

UNIVERSITY SERVICE

1/91-1/94. Member, College Lands Policy Committee, University of Washington, College of Forest Resources, Seattle, WA.

5/85-5/87. Member, Soil Conservation and Watershed Management Curriculum Committee, Tribhuvan University, Institute of Forestry, Pokhara, Nepal.

8/83-12/83. Dendrology Tutor, Xi Sigma Pi, North Carolina State University, College of Forest Resources, Raleigh, N.C.

PUBLICATIONS

Petruncio, M.D. 1994. Effects of Pruning on Growth of Western Hemlock (*Tsuga heterophylla*) and Sitka spruce (*Picea sitchensis*) in Southeast Alaska. Ph.D. dissertation, College of Forest Resources, University of Washington, Seattle, WA.

Petruncio, M. and G. McFadden. 1994. Developments in forest pruning equipment. *In*: C.D. Oliver, editor, Pruning Conifers in Northwestern North America: Opportunities, Techniques, Impacts. College of Forest Resources, University of Washington, Seattle, WA, Institute of Forest Resources Contribution No.--(In press).

Maguire, D.A. and M.D. Petruncio. 1994. Pruning and growth of western Cascade species: Douglas-fir, western hemlock, Sitka spruce. *In*: C.D. Oliver, editor, Pruning Conifers in Northwestern North America: Opportunities, Techniques, Impacts. College of Forest Resources, University of Washington, Seattle, WA, Institute of Forest Resources Contribution No.--(in press).

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Petruncio, M.D. 1985. Natural hardwood regeneration following clearcutting in the Southern Appalachians. M.S. Thesis, North Carolina State University, Raleigh, NC. 54 pp.

Petruncio, M. and R. Lea. 1984. Natural regeneration of hardwoods in the Southern Appalachians. *In*: Proceedings, 3rd Biennial Southern Silvicultural Research Conference, Atlanta, GA, November 7-8, 1984. 4 pp.

TRAVEL

United States, Canada, Germany, Russia, Slovakia, Ukraine, India, Nepal, Tibet, and China.

ACTIVITIES/HOBBIES

Canoeing, backpacking, ice skating, rollerblading, cross-country skiing, softball, and wood carving.

University of Washington Intramural Softball	3/90-5/94
Friends of Nepal, Member	6/90-present
North Carolina State University Intramural Softball	3/83-5/84
Cook College Forestry and Wildlife Club, Member	1/80-5/82
Ukrainian Club, Rutgers University, Member	1/80-5/82
Rutgers Backgammon Tournament Champion	4/79
Rutgers Outdoor Club, President	9/78-12/79