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Levels-of-Growing-Stock Cooperative Study in Douglas-Fir: Report No. 8 —

The LOGS Study: Twenty-Year Results

Levels-of-growing-stock study treatment schedule, showing percent of gross basal area increment of control plot to be retained in growing stock

	Treatment							
Thinning	1	2	3	4	5	6	7	8
	Percent							
First	10	10	30	30	50	50	70	70
Second	10	20	30	40	50	40	70	60
Third	10	30	30	50	50	30	70	50
Fourth	10	40	30	60	50	20	70	40
Fifth	10	50	30	70	50	10	70	30

Background

Public and private agencies are cooperating in a study of eight thinning regimes in young Douglas-fir stands. Regimes differ in the amount of basal area allowed to accrue in growing stock at each successive thinning. All regimes start with a common level-of-growing-stock established by a conditioning thinning.

Thinning interval is controlled by height growth of crop trees, and a single type of thinning is prescribed

Nine study areas, each involving three completely random replications of each thinning regime and an unthinned control, have been established in western Oregon and Washington, U S.A., and on Vancouver Island, British Columbia, Canada. Site quality of these areas varies from I through IV

This is a progress report on this cooperative study.

LEVELS-OF-GROWING-STOCK COOPERATIVE STUDY IN DOUGLAS-FIR

Report No. 8—The LOGS Study: Twenty-Year Results

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Abstract

Curtis, Robert O.; Marshall, David D. Levels-of-growing-stock cooperative study in Douglas-fir: Report No. 8—The LOGS study: twenty-year results. Res. Pap. PNW-356. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station; **1986.** 113 p.

This progress report reviews the history and status of the cooperative levels-of-growing-stock study in coast Douglas-fir, begun in 1961, in Oregon, Washington, and British Columbia. It presents new analyses, including comparisons among some installations. Data now available are primarily from the site II installations, which are approaching completion of the study. Growth is strongly related to growing stock. Thinning treatments have produced marked differences in volume distribution by tree sizes. During the fourth treatment period, current annual increment was still about double the mean annual increment, and differences in volumes and size distributions among treatments have been increasing rapidly. There are considerable differences in productivity among installations, beyond those accounted for by site index differences. The LOGS study design is evaluated.

Keywords: Thinnings, (-stand volume, growing stock, (-increment/yield, Douglas-fir, *Pseudotsuga menziesii,* series—Douglas-fir LOGS.

Summary

This is a progress report on the cooperative levels-of-growing-stock (LOGS) study in coast Douglas-fir, begun in 1961, in Oregon, Washington, and British Columbia. The program objective is to determine the relationships of volume growth, basal area growth, and diameter growth to growing stock levels, for a standard set of eight thinning regimes, begun in stands 20-40 feet tall and continued through 60 feet of height growth.

Nine installations were established. None had completed the planned course of the experiment as of 1983, although four installations were close to completion. This report describes the program and presents interim results based on the data now available, which are primarily from the site II installations. Principal findings are:

1. Observed height growth agrees well with King's (1966) height growth curves.

2. For the LOGS thinning regimes, growth in both volume and basal area has increased with the level of growing stock. Slope of the curves is much steeper for volume growth than for basal area growth; for basal area growth, curves are relatively flat over a range of moderate to high densities. This difference is attributed to the rapid and sustained height growth which is characteristic of young Douglas-fir on good sites.

3. Curves of volume increment over relative density (RD) (Curtis 1982) appear to be approximately proportional, within and between installations. The same appears true of the corresponding curves for basal area and for diameter growth.

4. Generalized curves are derived that express relationships of relative growth rates in volume, basal area, and diameter to RD.

5. So far, controls exceed all thinning treatments in gross volume production. Thinned stands, however, have (except in one poorly responding installation) produced much more volume in merchantable sizes and much larger diameters. Diameter growth of crop trees and of the 40 largest trees per acre has also been substantially greater in thinned stands. Trends in net growth indicate that this advantage will be maintained and will probably increase over time.

6. This report emphasizes comparisons among the fixed percentage treatments. Until the planned end of the experiment is reached, only limited conclusions can be drawn concerning the results of the variable percentage treatments.

7. There are unexplained differences in volume production and response to thinning among installations. Of five site II installations, three are behaving similarly; one has markedly lower production and response to thinning; and one (which has a large hemlock component and was older at the start of thinning) is intermediate.

8. As of the fourth treatment period (age range 32-42 in the site II installations), current annual volume increment was about twice mean annual increment. Stands were far short of culmination of mean annual increment. Rotations considerably longer than the ages in the LOGS studies will be required to realize the full gains attainable from thinning.

9. The LOGS study is not a comparison of operational thinning regimes, but was designed to establish relationships between growth and growing stock. The most effective means of applying LOGS study results will probably be their use, in combination with other data, in construction and refinement of stand simulators. The LOGS study provides a unique set of high-quality data from young stands maintained at relatively low densities, a condition for which very little other data are presently available.

10. Although the short thinning cycle used in the LOGS studies is not realistic for management application, similar results would probably be obtained with considerably longer cycles and analogous regimes that have similar trends of period mean growing stock over height.

11. LOGS results appear generally consistent with past stand management recommendations that were based on other data. These recommendations provide for low density and rapid growth in diameter during early development when volume growth is of little concern. Once trees reach merchantable size and volume growth becomes important, higher density is needed to provide high volume growth per acre. The relationships between growth and growing stock established by the LOGS study provide guides for choosing density levels appropriate for young stands that had early control of stocking.

12. Further thinnings, beyond those originally planned, are not feasible because of the limitations due to small plot size. The originally planned thinnings will have a strong and continuing effect on later stand development. After completion of the 60 feet of height growth specified in the study plan, these installations should be retained without further treatment and should be remeasured for a minimum of two additional growth periods (20 feet of additional height growth).

13. Strengths and weaknesses of the LOGS study design are discussed and suggestions are made for design of future studies.

Acknowledgments

Many people have contributed to the LOGS study and to this report. Data and valuable assistance in preparation of this report have been provided by John F. Bell of Oregon State University; Gerald E. Hoyer of the Washington Department of Natural Resources; James E. King of Weyerhaeuser Company; James T. Arnott and Dennis Beddows of the Canadian Forestry Service; and David Bruce (formerly of the Pacific Northwest Research Station, now retired). Extremely important contributions to LOGS have also been made by Richard L. Williamson, who coordinated the LOGS work from its inception until his recent retirement from the Pacific Northwest Research Station; and by George R. Staebler, who originally conceived and planned the LOGS study.

Other LOGS (Levels-Of-Growing-Stock) Reports

Williamson, Richard L.; Staebler, George R. A cooperative level-of-growing-stock study in Douglas-fir. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; **1965.** 12 p.
Describes purpose and scope of a cooperative study which is investigating the relative merits of eight different thinning regimes. Main features of six study areas installed since 1961 in young stands are also summarized.

Williamson, Richard L.; Staebler, George R. Levels-of-growing-stock cooperative study on Douglas-fir: Report No. 1—Description of study and existing study areas. Res. Pap. PNW-111. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; **1971.** 12 p.
Thinning regimes in young Douglas-fir stands are described. Some characteristics of individual study areas established by cooperating public and private agencies are discussed.

Bell, John F.; Berg, Alan B. Levels-of-growing-stock cooperative study in Douglas-fir: Report No. 2—The Hoskins study, 1963-1970. Res. Pap. PNW-130. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; **1972.** 19 p.
A calibration thinning and the first treatment thinning in a 20-year-old Douglas-fir stand at Hoskins, Oregon, are described. Data tabulated for the first 7 years of management show that growth changes in the thinned stands were greater than anticipated.

Diggle, P.K. The levels-of-growing-stock cooperative study in Douglas-fir in British Columbia (Report No. 3, Cooperative L.O.G.S. study series). Inf. Rep. BC-X-66. Victoria, BC: Canadian Forestry Service, Pacific Forest Research Centre; **1972.** 46 p.

Williamson, Richard L. Levels-of-growing-stock cooperative study in Douglas-fir: Report No. 4—Rocky Brook, Stampede Creek, and Iron Creek. Res. Pap. PNW-210. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; **1976.** 39 p.
The USDA Forest Service maintains three of nine installations in a regional, cooperative study of influences of levels of growing stock (LOGS) on stand growth. The effects of calibration thinnings are described for the three areas. Results of first treatment thinning are described for one area.

Berg, Alan B.; Bell, John F. Levels-of-growing-stock cooperative study on Douglas-fir: Report No. 5—The Hoskins Study, 1963-1975. Res. Pap. PNW-257. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; **1979.** 29 p.
The study dramatically demonstrates the capability of young Douglas-fir stands to transfer the growth from many trees to few trees. It also indicates that at least some of the treatments have the potential to equal or surpass the gross cubic-foot volume of the controls during the next treatment periods.

Arnott, J.T.; Beddows, D. Levels-of-growing-stock cooperative study in Douglas-fir: Report No. 6—Sayward Forest, Shawnigan Lake. Inf. Rep. BC-X-223. Victoria, BC: Canadian Forestry Service, Pacific Forest Research Centre; **1981.** 54 p.

Data are presented for the first 8 and 6 years at Sayward Forest and Shawnigan Lake, respectively. The effects of the calibration thinnings are described for these two installations on Vancouver Island, British Columbia. Results of the first treatment thinning at Sayward Forest for a 4-year response period are also included.

Williamson, Richard L.; Curtis, Robert O. Levels-of-growing-stock cooperative study in Douglas-fir: Report No. 7—Preliminary results at the Stampede Creek LOGS study, and some comparisons with the Iron Creek and Hoskins LOGS studies. Res. Pap. PNW-323. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; **1984.** 42 p.

Summaries are given through the first treatment period for the Stampede Creek LOGS study in southwest Oregon. Results are compared with two more advanced LOGS studies and, in general, are similar. To age 43, thinning in this low site III Douglas-fir stand resulted in some reduction in volume growth and moderate gains in diameter growth. Growth was strongly related to level of growing stock. Desirable density levels are recommended for young Douglas-fir stands.

Contents

Introduction

In 1962, representatives of State, Federal, and industrial forestry organizations began a cooperative effort to determine how the amount of growing stock retained in repeatedly thinned young stands of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) affects cumulative wood production, tree size, and ratios of growth to growing stock. A study plan was adopted that was designed to examine cumulative wood production, tree size development, and growth-to-growing stock ratios under eight different thinning regimes.[1] The original study plan was developed at Weyerhaeuser Company, Centralia, Washington. Procedural details to ensure consistency among cooperators were developed by the Pacific Northwest Research Station, USDA Forest Service, Portland, Oregon.

Nine field installations have since been established in Oregon, Washington, and British Columbia (fig.1; also see appendix 2). A coordinating committee including representatives of all cooperators meets periodically to review progress, standardize procedures among cooperators, and arrange for analyses and for publication of results.

Brief descriptions of the levels-of-growing-stock (LOGS) program and of individual installations are given by Williamson and Staebler (1965, 1971). Subsequent progress reports for individual installations are by Bell and Berg (1972), Diggle (1972), Williamson (1976), Berg and Bell (1979), Arnott and Beddows (1981) , Tappeiner and others (1982), and Williamson and Curtis (1984). These progress reports are primarily summaries for individual installations with only limited interpretation, and (except for Williamson and Curtis 1984) no attempt was made to compare results among different installations.

In 1982 the LOGS committee reviewed the status of the program and decided a report was needed that would summarize progress to date, examine consistency of results among installations, make some general interpretations, and draw conclusions from those studies that are well along in the planned course of the experiments.

This report is a joint effort by the cooperators and provides (1) a general description of the LOGS program, (2) some comparisons of results across installations, and (3) some generalizations and discussion of implications. Comparisons are necessarily incomplete, both because these studies have not yet run their full course and because all analyses of interest cannot be included in a single report. Reports on individual installations will continue to appear and will provide much more detail than is possible here.

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[1] Unpublished study plan, 1962, "Plan for a Level-of-Growing Stock Study in Douglas-Fir," by George R. Staebler and Richard L. Williamson. Plan on file at Forestry Sciences Laboratory, 3625-93d Avenue, S.W., Olympia, WA 98502.

Figure 1.—Locations of levels-of-growing-stock study installations.

The LOGS Studies

General Description

Objective.—The objective of the LOGS studies as stated in the original study plan (see footnote 1) was "to determine how the amount of growing stock retained in repeatedly thinning stands of Douglas-fir affects cumulative wood production, tree size, and growth-growing stock ratios."

It was expected that the thinnings would (1) redistribute increment by increasing volume growth of remaining trees, and (2) eliminate or greatly reduce mortality so that the volume normally dying in untended stands would be converted to usable production. It was thought that the planned treatments included a broad enough range in growing stock levels "so that the findings will tell how to produce any combination of factors deemed optimum from a management standpoint" (see footnote 1).

Background.—The origin of the LOGS program and certain features of the study plan go back to concepts advanced by George Staebler in the late 1950's. Staebler (1959) emphasized the importance of growing stock level in determining growth percent and return on capital, the financial undesirability of maintaining unnecessarily large growing stock, and the need to establish acceptable levels of growing stock through definition of the relationship between growth and growing stock in Langsaeter's zone II. This is the transition zone between free growth and a zone in which growth is commonly thought to be independent of growing stock level (Braathe 1957, p. 49).

Staebler (1960) developed a method for calculating thinning schedules and managed stand yields for Douglas-fir based on (1) estimated gross yield of natural stands (Staebler 1954, 1955), (2) assumed diameter growth rates, and (3) some assumptions about relationships between growth and growing stock. These assumptions are:

1. Gross cubic volume yield of a normal (fully stocked), unmanaged stand represents the maximum production of which the site is capable.

2. Periodic gross increment for any age period in the life of a normal stand represents full capacity of the site to produce wood in a stand of the chosen age.

3. Approximately full increment may be produced with widely differing combinations of growing stock, tree size, and radial increment.

Staebler presented his method as an interim procedure for constructing thinning schedules and yield tables. He recognized a need to examine the assumption that gross increment observed in unmanaged stands of normal density approximates increment of thinned stands having widely varying amounts of growing stock. In 1959 Staebler established a thinning trial (Oliver and Murray 1983) as a first attempt to test his concepts and assumptions. Experience with establishment of this study led to later development of the LOGS study plan.

Staebler's original concepts and questions are reflected in a number of features of the LOGS studies. These studies were not designed as tests of specific operational thinning regimes, but were intended to define the quantitative relationships between growth and growing stock for a closely controlled initial stand condition and kind of thinning.

General features of the LOGS study plan.—

Criteria for initial stand selection.—The initial stand should:

1. Have a high degree of uniformity in stocking and site quality over an area sufficient to accommodate the installation (about 9 acres).
2. Be in the range of 20-40 feet in height.[2]
3. Be vigorous and of a density such that individual tree development has not been strongly influenced by competition, as evidenced by live crown extending over most of the bole.
4. Contain sufficient Douglas-fir to constitute 80 percent or more of the basal area after the initial thinning.[3]

Experimental design.—Each installation consists of 27 one-fifth-acre plots (square except in the Francis study), with three replications of eight thinnings treatments plus three untreated control plots, in a completely randomized arrangement. No buffer strips were planned.[4]

Each installation is a repeated-measures experiment that can be viewed as equivalent to a completely random split plot experiment in which each thinning interval (period) is treated as a subplot. The mean of a variable over all periods then becomes a main plot value for that variable, and the main plot itself covers the two dimensions of treatment and time.

Crop trees.—At the time of study establishment, well-spaced, dominant, crop trees were selected at the rate of 16 per plot (80 per acre) and were permanently marked.

Calibration thinning.—The 24 plots assigned to thinning treatments were given a so-called calibration thinning at the time of study establishment. The intent was to adjust all thinning treatment plots within an installation to a common condition prior to the planned treatment thinnings.

Treatment thinnings.—Treatment thinnings were made according to the following specifications:

1. The sequence of thinnings consisted of the initial calibration thinning, which left the same stand on all treated plots within a given installation, and five subsequent treatment thinnings.
2. Thinnings were made whenever average height of crop trees on all treatments had increased 10 feet since the last thinning. This specification relates thinning interval to growth and crown expansion of the crop trees and results in more frequent thinning on good sites than on poor sites.

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[2] Criterion not fully met at the Skykomish and Stampede Creek studies.

[3] Criterion not fully met at the Skykomish study, which was established before completion of the study plan.

[4] Although not provided for in the original study plan, buffer strips were added in the Sayward and Shawnigan Lake installations only.

3. Treatments were defined by the amount of growing stock retained, which is expressed as basal area. After the calibration thinning, all treatment plots within an installation had nearly the same basal areas. In the five subsequent treatment thinnings, the increases in basal areas retained after thinning were specified as percentages of the gross periodic basal area growth as measured on the control plots. Gross increment of the unthinned control plots provided an installation-specific reference point for definition of thinning treatments.

4. Trees to be removed in thinning were determined in part by rules (discussed later) specifying a tree's relation to the crop trees and to the diameter distribution. Merchantability was not a consideration.

Description of the Installations

Nine LOGS studies have been established (table 1). There is a 9-year range in dates of study establishment. Those studies located on good sites progress through the sequence of thinnings much more rapidly than do those located on poor sites. Individual installations, therefore, differ widely in their position within the sequence of thinnings and in the amount of data now available. No studies have yet (as of 1983) reached completion, although four (Skykomish, Hoskins, Clemons, and Francis) will complete the final treatment period in the near future. There are relatively little data now available for Stampede Creek and Shawnigan Lake. The studies on the poorest sites—Rocky Brook and Shawnigan Lake—will not complete the planned treatment sequence until well after 2000.

Initial stand characteristics of the study areas are summarized in table 2. Climatic data, based on nearby weather stations and climatic zone maps, are shown in table 3. Because the study locations are generally at higher elevations and some distance from these weather stations, climatic values given do not fully reflect local conditions. On-site measurements of rainfall and temperature during the growing season have been made at five locations (Rocky Brook, Iron Creek, Stampede Creek, Sayward, and Shawnigan Lake), but this information has not as yet been summarized and will be given in later reports on individual installations.

No systematic and consistent description of ground vegetation or classification by plant association is available for the study areas as of 1983.

Skykomish.—The Skykomish study, located on Weyerhaeuser Company's Skykomish Tree Farm, was the first installed, and many of the details of the LOGS study plan were developed here. The stand is of natural origin and was about 24 years old when the study was established in 1961. (In this report, "age" is estimated years from seed; "age b.h." is years since attainment of breast height.) At that time, no specification had yet been adopted limiting percentage of species other than Douglas-fir, and this stand was about 50 percent western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) after the calibration thinning. It was also slightly taller than the maximum of 40 feet specified in the final study plan. The study contains four control plots, rather than the three used in later installations.

The study is on a north-facing slope along Youngs River, some 4 miles south of Sultan, Washington, at about 500 feet elevation. Average slope is about 35 percent.

Table 1—LOGS installations by year established, location, and number of treatment periods completed

Study	Year established	Location: Township	Range	Section	Treatment periods completed, 1983
Skykomish	1961	T. 27 N.	R. 8 E.	19	1/ 4
Hoskins	1963	T. 10 S.	R. 7 W.	27	1/ 4
Rocky Brook	1963	T. 26 N.	R. 3 W.	13	2
Francis	1963	T. 12 N.	R. 6 W.	16	4
Clemons	1963	T. 15 N.	R. 6 W.	9	4
Iron Creek	1966	T. 11 N.	R. 7 E.	30	3
Stampede Creek	1968	T. 31 S.	R. 1 W.	10	1/ 1
Sayward	1969	--	--	--	2
Shawnigan Lake	1970	--	--	--	1

-- = not applicable.

1/ An additional measurement, representing completion of one additional treatment period, was made at the end of the 1983 growing season. The data were not available in time for inclusion in the analyses discussed in this manuscript.

Table 2—Stand characteristics of study areas at establishment (after calibration thinning)

Study area and year established	Site 1/ class	Origin 2/	Total age	Age b.h.	Height: Crop trees	Height: Largest 40/acre	Quadratic mean d.b.h. all species: Control	Quadratic mean d.b.h. all species: Thinned	Trees per acre, all species: Control	Trees per acre, all species: Thinned	Basal area, all species: Control	Basal area, all species: Thinned	Ratio of Douglas-fir basal area to basal area of all species: Control	Ratio of Douglas-fir basal area to basal area of all species: Thinned
			- years -		- - - feet - - -		- - inches - -				- ft²/acre -			
Skykomish, 1961 3/	II	Nat	24	17	44	48	4/ 4.7 3/(5.6)	5.2 (6.0)	4/ 594 (204)	357 (135)	4/ 72 (35)	51 (26)	0.48	0.50
Hoskins, 1963	II	Nat	20	13	36	40	3.8	5.2	1,727	342	138	50	1.00	1.00
Rocky Brook, 1963 5/	IV	Pl	25	16	28 5/ (32)	34 (36)	3.4 (3.8)	4.0 (4.6)	1,367 (1,335)	399 (382)	87 (107)	36 (44)	.76 (.77)	.95 (.94)
Clemons, 1963	II	Pl	19	12	31	36	4.0	4.1	687	396	60	36	.76	.91
Francis, 1963	II	Pl	18 6/ (15)	8	25	29	3.3	3.6	887	405	52	30	.79	.83
Iron Creek, 1966	II	Pl	19	12	36	39	3.7	5.0	1,128	356	82	48	.86	.97
Stampede Creek, 1968	III	Nat	33	25	56	59	4.7	6.6	997	287	119	68	.90	.99
Sayward, 1969	III	Pl	22	14	38	39	4.0	5.0	1,062	355	91	48	.96	.99
Shawnigan Lake, 1970	IV	Pl	25	16	38	41	3.7	4.5	1,193	375	91	41	1.00	1.00

1/ Most recent estimate using King (1966).

2/ Nat = natural origin; Pl = planted.

3/ Values for Oouglas-fir component shown in parentheses.

4/ Altered by removal of small trees and therefore not comparable to other installations.

5/ Extensive snowbreakage resulted in replacement of several plots in 1965. 1965 means of all plots, after replacement, shown in parentheses.

6/ Value in parentheses is age at b.h. + 7 years, comparable to other site II stands.

Table 3—Climatic data for LOGS study areas

Study area	Weather station	Values from nearest weather station 1/: Precipitation, 1956-65: Annual	Precipitation, 1956-65: April-Sept.	Average frost-free period, 1931-65	Average temperature, frost-free period	Values for climatic zone 2/: Precipitation, April-Sept.	Frost-free period
		- - Inches - -		Days	°F	Inches	Days
Skykomisn	Snoqualmie Falls	60	16	155	59	16	160
Hoskins	Summit	66	12	152	--	12	160
Rocky Brook	Cushman Dam 3/	93	15	--	--	20	4/
Clemons	Oakville	55	12	163	59	16	200
Francis	Willapa Harbor	87	21	197	59	20	200
Iron Creek	Rainier-Longmire	84	22	134	58	20	120
Stampede Creek	Prospect	42	9	98	64	8	120
Sayward	Campbell River	58	--	149	58	4/ 10	5/ 149
Shawnigan Lake	Shawnigan Lake	43	--	168	50	4/ 7	5/ 145

-- = data not available.

1/ Pacific Northwest River Basins Commission (1969).

2/ Dick (1955).

3/ Elevation and topography at Rocky Brook is considerably different. Estimate from isohyetal map is 80 inches precipitation.

4/ Although within Dick's (1955) 160-day zone, local topography produces a considerably shorter frost-free period.

5/ From Diggle (1972). Rainfall given for frost-free period.

Soils are derived from basaltic parent material. They are in the Oso series, which is described by Webster and Steinbrenner (1974) as follows: "Common features of these soils are a dark grayish-brown, gravelly loam, 15- to 20-inch thick surface A horizon which grades into a weakly structured, gravelly loam, dark yellowish-brown B horizon. Beneath this, C horizons containing 40 to 80 percent rock extend to fractured bedrock at 40 to 60 inches."

When this study was installed, small trees less than one-half the average diameter of crop trees were cut on the control plots as well as on the thinned plots, unlike the procedure followed for later LOGS studies. Approximately 360 trees per acre were cut from the control plots. These were less than 3.6 inches in diameter at breast height (d.b.h.) and most were hemlock understory with small numbers of western redcedar (*Thuja plicata* Donn ex D. Don) and miscellaneous hardwoods. This reduced the control plots to an average of 594 trees per acre with about half the remaining basal area in Douglas-fir and half in hemlock. Removal of these small trees probably has had little effect on subsequent growth but does affect stand statistics for number of trees and average diameter.

No serious stand damage has occurred to date.

Hoskins.—The Hoskins study was established by Oregon State University on land made available by T.J. and Bruce Starker (now owned by Starker Forests). The stand was of natural origin following wildfire and was exceptionally uniform in age and stocking. Estimated total age when the study was established in 1963 was 20 years (13 years b.h. as determined by borings).

The study is located just west of the summit of the Coast Range, near Hoskins, Oregon, about 22 miles northwest of Corvallis. Aspect is southerly, with slopes of 15 to 55 percent. Elevation is about 1,000 feet.

The soils are deep well-drained silty clay loams of the Apt series, formed in colluvium from mixed sedimentary and igneous rocks. As described by Knezevich (1975), "Apt soils are more than 60 inches deep over bedrock. . . .In a representative profile the surface layer is very dark brown and very dark grayish-brown silty clay loam about 10 inches thick. The subsoil is dark-brown, dark yellowish-brown, and strong-brown silty clay and clay that extends to a depth of about 60 inches."

Rocky Brook.—The Rocky Brook study was established in 1963 by the USDA Forest Service (Pacific Northwest Research Station and Pacific Northwest Region). It is located in the Hoodsport District, Olympic National Forest, about 8 miles west of Brinnon, Washington.

The area was planted about 1940. No record of seed source or early development is available. Natural fill-in was abundant, and the present stand is a mixture of trees of planted and natural origin. Average age at breast height (age b.h.) of dominant trees in 1963, as estimated by borings, was 16 years.

The stand occupies a glacially formed, gently sloping (average 10 percent, short pitches to 55 percent) terrace near the bottom of a deep glaciated valley at 2,400 feet elevation. Aspect is southerly, but the location of the valley bottom and a high ridge to the south tend to reduce temperatures and shorten the growing season.

The well-drained, gravelly, sandy, loam soils are phases of the Hoodsport series.[5/] Parent material consists of glacial outwash and drift of stratified and unstratified sands, gravels, and coarser material overlying basaltic bedrock.

Several small foci of *Phellinus weirii* were present at the time of study establishment. Although an effort was made to avoid these, several plots have since been seriously damaged by *Phellinus*.

A heavy wet snowfall occurred immediately after the calibration thinning and caused extensive breakage. Several of the more severely damaged plots were replaced by spare plots in 1965.

Clemons.—This study is located at Weyerhaeuser Company's Clemons Tree Farm, near Blue Mountain, about 11 miles west of Oakville, Washington.

The stand was planted in spring 1947 with 2-0 Douglas-fir of unknown seed source. The study was established in autumn 1963 when the stand was 19 years old from seed.

The study is located along a ridge top, has a northerly aspect and slopes of 0 to 15 percent, and is at about 800 feet elevation.

Soils are in the Astoria series, which is derived from deep marine sediments and is generally considered highly productive. The Astoria series is described by Steinbrenner and Duncan (1969) as follows: "Deep, friable, well-drained, moderately fine textured yellowish-brown lateritics developed from coarse Miocene sandstones are characteristic of this series. The A horizons are dark brown, friable loams about 18 inches thick and the subsoils are yellowish-brown silt loams with a weak, fine, sub-angular blocky structure grading into yellowish, highly weathered, massive sandstones. Total depths are 40 to 60 inches with deeper soils more prevalent."

The area was thought to be an exceptionally good site at the time the study was established, but subsequent growth has not met initial expectations.

The plantation had severe animal damage (particularly from mountain beaver) in its early years and was damaged by a severe freeze in 1955. Many deformed and damaged trees were removed in the calibration thinning.

Francis.—The Francis study was established in 1963 by the Washington State Department of Natural Resources. The area was planted in autumn 1947 with 2-0 planting stock from a local seed source and was 18 years from seed when the study was installed.

The study is located about 30 miles west of Chehalis, near Francis, Washington, on the westerly slope of the Willapa Hills at about 1,300 feet elevation. The plots are on north to west aspects and average about 20 percent slope.

[5/] Unpublished report, 1967, "Soil Investigations of the Rocky Brook Experimental Forest Area, Olympic National Forest," by Herman D. Loren. Report on file at Forestry Sciences Laboratory, 3625-93d Avenue, S.W., Olympia, WA 98502.

The soil is classified as Boistfort silt loam, which is described as deep, well-drained silt loam found on nearly level to moderately steep terraces of the uplands of the Coast Range of western Washington. The soil has formed on basalt and developed in a mild, wet, coastal climate. The surface layer is 0-12 inches, dark reddish-brown silt loam with weak medium granular structure; friable when moist, slightly sticky and slightly plastic when wet, and very strongly acid. The subsoil is 12-44 inches, dark brown silt loam, moderately fine subangular blocky structure, friable when moist, sticky and plastic when wet, and strongly acid. The substratum is 44-60 inches, dark brown loam, moderately fine subangular blocky structure, friable when moist, sticky and plastic when wet, and strongly acid.

The stand required 10 years to reach breast height from seed, 3 years more than the average of 7 years for natural stands on site II (King 1966). The reason for this unusually slow early development is not known, although it is known that the area was grazed. For comparability with the other installations, total age shown in subsequent tables is age at b.h. plus 7 years.

Several *Armillaria* root rot foci, which appeared after establishment of the plots, have been successfully controlled by removal of stumps.

Iron Creek.—This Forest Service study is located in the Randle District, Gifford Pinchot National Forest, about 9 miles south of Randle, Washington.

The stand was planted in 1949 using stock of unknown seed source. Although there has been some natural fill-in, the planted trees have maintained their lead and make up most of the stand.

The stand is in a midslope position at about 2,500 feet elevation. Aspect is easterly, with slopes averaging about 25 percent.

The deep, well-drained soil (series undetermined) is derived from volcanic ash and lapilli overlying a residual soil developed on fractured volcanic rock. Surface soils range from sandy loam to loam, with interbedded pumice.

At the time the study was established, many trees in the area had been damaged by bear. Approximately 20 percent of the trees remaining after the calibration thinning had some injury. The area was then fenced, and further injury has been limited to one episode following damage to the fence about 1975.

Approximately 1 inch of ash from the Mount St. Helens eruption on May 18, 1980, fell on the study area. Foliage was still ash covered the following September. The effect on stand growth has not been determined.

Stampede Creek.—The Stampede Creek study was established by the Forest Service near Tiller, Oregon, in the Tiller District, Umpqua National Forest. The stand is of natural origin following wildfire in 1929. There was considerable delay in regeneration, and development of brush species may have contributed to relatively low initial density and otherwise influenced early development.

Average age at breast height of dominants, as determined by boring crop trees, was 25 years when the study was established in 1968. Estimated total age in 1968 was 33 years.

The study area is situated on a broad slope near the head of Stampede Creek. Slopes are gentle, averaging about 25 percent, and aspect is generally northeast. Elevation is 2,700 feet.

The soil is Freezener clay loam over clay loam and clay and is derived from well-weathered volcanic tuffs and breccias. The Freezener series is described as well-drained soils formed in colluvium from volcanic rocks. The surface layer is dark reddish-brown, gravelly loam about 16 inches thick. The subsoil is reddish-brown clay about 40 inches thick. The substratum is reddish-brown cobbly clay loam and is 16 inches or more thick.

Height in 1968 (about 55 feet) exceeded study plan specifications, but competition was not severe because of the initial relatively wide spacing. Tree distribution was fairly uniform, and the stand was accepted for the LOGS program as no better alternative stand could be found in southwestern Oregon.

No serious stand damage has occurred to date.

Sayward.—This study was established in 1969 by the Canadian Forestry Service and is located on Vancouver Island, about 15 miles west of Campbell River, British Columbia. The stand is a plantation, established in spring 1950 using 2-0 stock. Seed source was Merville, British Columbia, at latitude 49°48′N., longitude 125°00′W.

The study is situated on a gently rolling slope with a westerly aspect, at about 900 feet elevation. The soil, a gravelly, loamy sand, is a well-drained young podzol developed on sandy, gravelly, glacial till. It is classified as a mini humo-ferric podzol (Canada Department of Agriculture 1970). Soil profiles show little variation. The average depth to the underlying till is 30 inches.

There has been some minor fill-in by western hemlock, western redcedar, western white pine (*Pinus monticola* Dougl. ex D. Don), and lodgepole pine (*Pinus contorta* Dougl. ex Loud.).

The plantation was very uniform at the time of establishment. Some pockets of root rot were present but were avoided in laying out plots. To date there has been no major damage.

The study plan procedure was modified to provide 33-foot buffers around each plot in this installation.

Shawnigan Lake.—This study, located on Vancouver Island, British Columbia, about 5 miles southwest of Shawnigan Lake, was established by the Canadian Forestry Service during winter 1970-71 in a 25-year-old Douglas-fir stand. The stand had been planted in spring 1948 with 2-0 seedlings. Seed source was Merville, British Columbia, as in the Sayward installation.

The stand is located on a low ridge at about 1,100 feet elevation. Topography is flat to very gently rolling with an easterly aspect. The soil is a well-drained sandy loam developed from underlying glacial till and is classified as a mini humo-ferric podzol (Canada Department of Agriculture 1970). Soil profiles vary little throughout the stand, and depth to the till averages 24 inches.

Natural fill-in has been light. To date, there has been no major stand damage.

The study plan procedure was modified to provide 33-foot buffers around each plot.

The Data

Installations included.—All treatment regimes start from a common condition within any one installation, and differences develop gradually over successive treatment periods. The first one or two treatment periods are not expected to yield much information.

Analyses and comparisons made in this report are confined to those studies for which data are available for several treatment periods. Those studies are the five site II installations: Skykomish, Hoskins, Clemons, Francis, and Iron Creek (table 1). Data for two treatment periods are available from two installations on sites III and IV—Sayward and Rocky Brook: these may provide some indication of consistency of results across site classes. Data from one treatment period only are available for Stampede Creek and Shawnigan Lake: these study sites are omitted from all analyses and discussions in the remainder of this report.

Tree and stand measurements.—All leave trees 1.6 inches d.b.h. and larger were numbered and tagged at the time of the calibration thinning. Diameters to the nearest 0.1 inch were recorded following the calibration thinning and at each subsequent thinning date (at Hoskins, and at Sayward since 1975, diameters were measured annually). Ingrowth trees (present on control plots only) were tagged and measured as they attained 1.6 inches d.b.h.

Total heights were measured on a sample of trees at each measurement date. The study plan specified height measurements for a minimum of eight crop trees per plot, with additional noncrop trees measured as needed to cover portions of the diameter range not represented by crop trees. About two-thirds of the trees measured were to be from the upper one-half of the diameter range. Measurements were to be taken on the same tree at successive measurements, except that another tree of similar diameter was to be substituted for any tree that died or was cut. The height sampling procedure actually used has varied considerably, however, among cooperators and among installations. In many cases, samples have been considerably larger than suggested by the study plan. In others (notably Clemons), even the basic standard of eight crop trees was not met consistently—a deficiency that probably contributed to some peculiarities encountered in the analyses.

Length of live crown was measured on height sample trees in some installations and periods. Although this information was not required by the study plan and has not been recorded for all installations and periods, considerable data exist.

Table 4—Dates of thinning and measurement for 7 LOGS studies[1]

Study	Date of thinning and associated measurement						
	Calibration	1st treatment	2d treatment	3d treatment	4th treatment	5th treatment	"Final" measurement
Skykomish	1961	1965	1968	1971	1976	1979	2/ 1983
Hoskins	1963	1966	1970	1973	1975	1979	2/ 1983
Rocky Brook	3/ 1963 (1965)	1969	1976	1982	--	--	--
Clemons	1963	1966	1970	1973	1976	1980	--
Francis	1963	1966	1969	1973	1977	1981	--
Iron Creek	1966	1970	1973	1977	1980	--	--
Sayward	1969	1973	1977	1981	--	--	--

-- = not available.

1/ Data from Stampede Creek and Shawnigan Lake excluded.

2/ Data summaries not yet available.

3/ Study established in 1963, but spare plots were substituted in 1965 following severe snow breakage, and a complete remeasurement was made at that time.

The sampling procedure for stand age determination was not specified in detail in the study plan and has varied among installations. The age estimate was usually based on planting date for plantations and on borings or stump ring counts in natural stands and later converted to age at b.h. or to total age. Sampling and conversion procedures were not always consistent among installations, and the time required to reach b.h. has been affected by factors such as browsing and vegetative competition, in addition to site. Although there are some inconsistencies in the presently available estimates, we think it unlikely that absolute errors exceed 2 years in age.

Thinning dates and the corresponding measurements now available are shown in table 4 for the seven installations included in this report.

Data summarization.—Sample tree volumes were calculated using the Douglas-fir equation by Bruce and DeMars (1974) for total cubic volume of stem including stump and tip (V). Table 7 in Browne (1962) was used at Skykomish for western hemlock. Plot volumes were estimated using equations of the form:

$$\ln V = a + b \ln(dbh) ;$$

fit to the sample tree values. An equation was fit separately for each plot in all installations except Clemons and Skykomish. In these two instances, because of inadequate height samples in some periods, all sample trees for the three plots in each treatment were combined and a single volume equation for that treatment was used to estimate individual plot volumes. Separate volume equations were used for Douglas-fir and western hemlock at Skykomish because of the large hemlock component. The Douglas-fir equation was used for all species at the other installations.

Plot volumes were expressed as total stem volume in cubic feet per acre. Standard plot statistics of number of trees (N), basal area (G), quadratic mean diameter (Dg), and volume were calculated for the Douglas-fir component and for all species combined, and for crop trees and for noncrop trees. Stand height was expressed as average height of crop trees and as average height of the largest (by diameter) 40 trees per acre (abbreviated as H40). Periodic annual increments and stand statistics at the midpoint of each growth period were calculated from the period beginning and ending values.

The Treatments

Calibration thinning.—

Objectives.—All plots in an installation other than the three control plots were given an initial calibration thinning. Treatment thinnings were applied when the crop trees had grown an average of 10 feet since the calibration thinning. The purpose of the calibration thinning was to reduce all plots scheduled for treatment to a common density and to allow time for trees to adjust to the changed condition. All treatment thinnings within a given installation would then be applied to a common initial stand condition.

Specifications.—Stand density following the calibration thinning was specified by the equation:

$$s = 0.6167Dg + 8 ;$$

where:

s = average spacing in feet, and

Dg = quadratic mean d.b.h. of the remaining trees.

This equation corresponds to the following numbers of trees and basal areas per acre:

Diameter of leave trees	Number of trees per acre	Basal area
(Inches)		(Square feet per acre)
3.0	449	22.0
4.0	398	34.8
5.0	355	48.4
6.0	318	62.4

The study plan recommended that the calibration thinning be controlled by the number of trees in those stands where the estimated average diameter of leave trees was under 4.5 inches and by basal area in stands of larger diameter.

Following initial selection of crop trees (80 per acre, 16 per plot), quadratic mean diameter (Dg) of crop trees was calculated and a first estimate made of Dg for leave trees. Noncrop leave trees were then marked according to the rules that (1) no tree should be retained whose diameter was less than one-half the average diameter of the crop trees in the installation, and (2) spacing of leave trees should be as uniform as feasible. Further restrictions were that (3) when control was by number of trees, the average diameter of leave trees should be within 15 percent of the installation mean, and (4) when control was by basal area, average diameter of leave trees should be within 10 percent of the installation mean. The initial marking was modified as needed to meet the density specifications for leave trees and the above restrictions.

Density control was by number of trees at Rocky Brook, Clemons, Francis, Sayward, and Shawnigan Lake and by basal area at the other four installations.

Stand characteristics after calibration thinning.—Average stand values for control plots and for thinned plots, immediately after the calibration thinning, are shown in table 2.

Although prethinning values for the thinned plots are not available, these stands were quite uniform and control plot averages should closely approximate average prethinning condition of the thinned plots. There were considerable differences among installations in prethinning density with numbers of trees per acre ranging from 594 at Skykomish to 1,727 at Hoskins, and diameters from 3.3 inches at Francis to 4.7 inches at Skykomish. Values at Skykomish are not directly comparable to those at other installations, both because of the large hemlock component and because on this installation—unlike all others—trees less than one-half the average diameter of crop trees were cut on the control plots as well as on plots intended for later thinning treatments.

The calibration thinning left plots that were more uniform within individual installations than was the original stand, although plots in different studies were not made identical because of differences among installations in initial height, diameter, and number of trees. Diameter distributions left after the calibration thinning are shown in table 5.

Ratios of numbers, basal areas, and average diameters of trees cut in the calibration thinning to corresponding values before thinning (as represented by the control plots) are shown in table 6. Despite wide variations in proportion of trees removed, d/D ratios (diameter of trees cut divided by original stand diameter) are very similar for all installations except Iron Creek and Clemons. The low d/D ratio at Iron Creek reflects removal of considerable numbers of small stems of associated species (mainly western hemlock). The d/D ratio for Clemons was close to 1, and may be a result of removing damaged trees present in the initial stand.

Summary values at the end of the calibration period—before the first treatment thinning—are shown in table 7. There are some differences among installations in relative density prior to the first treatment thinning. These differences are related to stand height and stand average diameter and are a consequence of the spacing rule used in the calibration thinning.

Treatment thinnings.—Eight thinning regimes were applied after completion of the calibration period. These regimes differed only in amount of growing stock retained; other factors were held as nearly constant as feasible.

Results of thinning are influenced by (1) the amount of growing stock retained, (2) the interval between thinnings, (3) the type of thinning, (4) site quality, and (5) initial stand conditions. Amount of growing stock is the variable of primary interest in the LOGS studies and the only one purposely varied within an installation. The interval between thinning is specified as the time required for 10 feet of crop tree height growth and varies with site and age. The type of thinning is controlled by specifications discussed later, which are comparable across regimes and installations. Site quality is nearly constant within an installation but varies among installations. Initial stand conditions were nearly constant within an installation and were restricted to as narrow a range as feasible among installations.

Table 5—Number of trees by 1-inch d.b.h. classes, for stand after calibration

D.b.h. class	Number of trees per acre, by installation and treatment category (control vs. thinned) 1/													
	Skykomish		Hoskins		Rocky Brook 2/		Clemons		Francis		Iron Creek		Sayward	
	C	Th	C	Th	C	Th	C	Th	C	Th	C	Th	C	Th
2	--	--	503	--	362	4	128	12	312	59	407	--	170	--
3	139	40	470	37	437	74	233	131	272	159	239	44	292	18
4	231	144	357	91	243	136	192	149	220	127	247	97	302	114
5	128	88	225	108	152	107	65	79	75	50	175	123	238	141
6	44	41	113	70	95	48	37	20	8	9	53	70	50	67
7	20	22	48	32	32	13	17	3	--	1	15	19	10	13
8	26	12	5	4	13	1	7	1	--	--	2	2	--	2
9	3	5	2	1	2	--	5	--	--	--	--	--	--	--
10	4	3	2	--	--	--	2	--	--	--	--	--	--	--
11	--	2	0	--	--	--	2	--	--	--	--	--	--	--
12	--	--	2	--	--	--	--	--	--	--	--	--	--	--
Total 3/	594	357	1,727	342	1,335	382	687	396	887	405	1,128	356	1,062	355

1/ C = mean of control plots; Th = mean of thinned plots.

2/ After replacement of damaged plots in 1965.

3/ Small discrepancies in column totals come from rounding to whole numbers.

Table 6—Ratios of numbers, basal areas, and average diameters of trees cut in calibration thinning to prethinning stand values

Study	n/N 1/	g/G 2/	d/D 3/
Skykomish 4/	--	--	--
Hoskins	0.80	0.64	0.89
Rocky Brook	.71	.59	.87
Clemons	.42	.40	.97
Francis	.54	.42	.88
Iron Creek	.68	.42	.78
Sayward	.67	.47	.84

1/ n/N = ratio of number cut to prethinning number of trees.

2/ g/G = ratio of basal area cut to prethinning basal area.

3/ d/D = ratio of diameter of cut trees to stand diameter before thinning.

4/ Skykomish values are not comparable to those from other studies because of removal of small trees from control plots at time of calibration thinning and are therefore omitted.

Table 7—Stand characteristics of study areas at the end of the calibration period (prior to first treatment thinning)

Study	Age		Height		Quadratic mean d.b.h.		Number of trees per acre		Basal area		Volume		RD 1/	
	Total	B.h.	Crop trees	Largest 40/acre	Control	Thinned	Control	Thinned	Control	Thinned	Control	Thinned	Control	Thinned
	- years -		- - - feet- - -		- - inches - -				- - ft^2/acre - -		- - ft^3/acre - -			
Skykomish 2/	28	21	58	60	5.79	6.57	594	356	108.7	86.1	2,460	1,980	45	34
					(6.80)	(7.64)	(204)	(134)	(51.4)	(41.9)	(1,152)	(861)		
Hoskins	23	16	46	50	4.54	6.82	1,640	341	184.7	86.5	3,362	1,596	87	33
Rocky Brook	31	22	39	45	4.24	5.35	1,317	374	128.9	58.3	1,995	938	63	25
Clemons	22	15	41	46	4.90	5.28	683	394	89.5	60.1	1,596	1,023	40	26
Francis	18	11	34	39	4.05	5.22	1,075	403	96.1	60.1	1,317	864	48	26
Iron Creek	23	16	48	50	5.23	6.68	745	326	110.9	79.5	2,035	1,507	48	31
Sayward	26	18	46	49	4.62	6.20	1,100	355	128.1	74.6	2,270	1,402	60	30

1/ Relative density measure from Curtis (1982).

2/ Values for Douglas-fir component given in parentheses.

Crop trees were selected and marked at study establishment. They retain their identity as crop trees throughout the experiment, except for occasional replacement of trees that are dying, damaged, or showing marked decline in vigor.

The kind of thinning is controlled by specifications that (1) no crop tree shall be cut until all noncrop trees have been cut, (2) quadratic mean diameter of trees cut shall approximate quadratic mean diameter of all trees available for cutting, and (3) trees cut during thinning shall be distributed as evenly as practicable across the range of diameters of trees available for cutting, without regard to merchantability. These specifications imply d/D ratios of less than 1.0 until all noncrop trees have been cut.

Growing stock levels are defined by the basal area allowed to accumulate in the growing stock. Basal area retained after any thinning is that retained after the previous thinning, plus a predetermined percentage (see table, inside front cover) of the gross basal area growth occurring on the unthinned plots since that previous thinning. This can be expressed as:

$$\text{basal area retained} = G_{calib} + \Sigma\, p_i dG_i \,;$$

where:

G_{calib} = mean basal area of all thinned plots in the installation after the calibration thinning;

p_i = fraction of control plot growth to be retained for the respective period and treatment (table, inside front cover); and

dG_i = mean gross increment in basal area of control plots in growth period "i."

If, at the end of a growth period, attained basal area of a plot was less than the leave basal area calculated as above, no thinning was made on that plot at that thinning date. This situation has occurred occasionally, usually in the highest density treatment.

Definition of growing stock levels in terms of observed growth of the control makes growing stock levels specific to the individual installation. There are four fixed-percentage regimes (1, 3, 5, and 7) that retain 10, 30, 50, and 70 percent of control plot gross basal area growth; two regimes (2 and 4) that retain successively increasing percentages of control plot growth over successive periods; and two regimes (6 and 8) that retain decreasing percentages of control plot growth. These are referred to in later discussion as "fixed" treatments, 1, 3, 5 and 7; and "variable" treatments consisting of "increasing" treatments, 2 and 4, and "decreasing" treatments, 6 and 8.

The pattern of growing stock levels expected as the stand develops is schematically illustrated in figure 2. Treatment regimes will show the same pattern and relative position in each of the studies, although numerical stocking levels for a given treatment vary somewhat among installations because of differences in initial conditions and in control plot growth. Stand condition after the calibration cut is illustrated by figure 3 and that near the end of the planned experiment by figure 4.

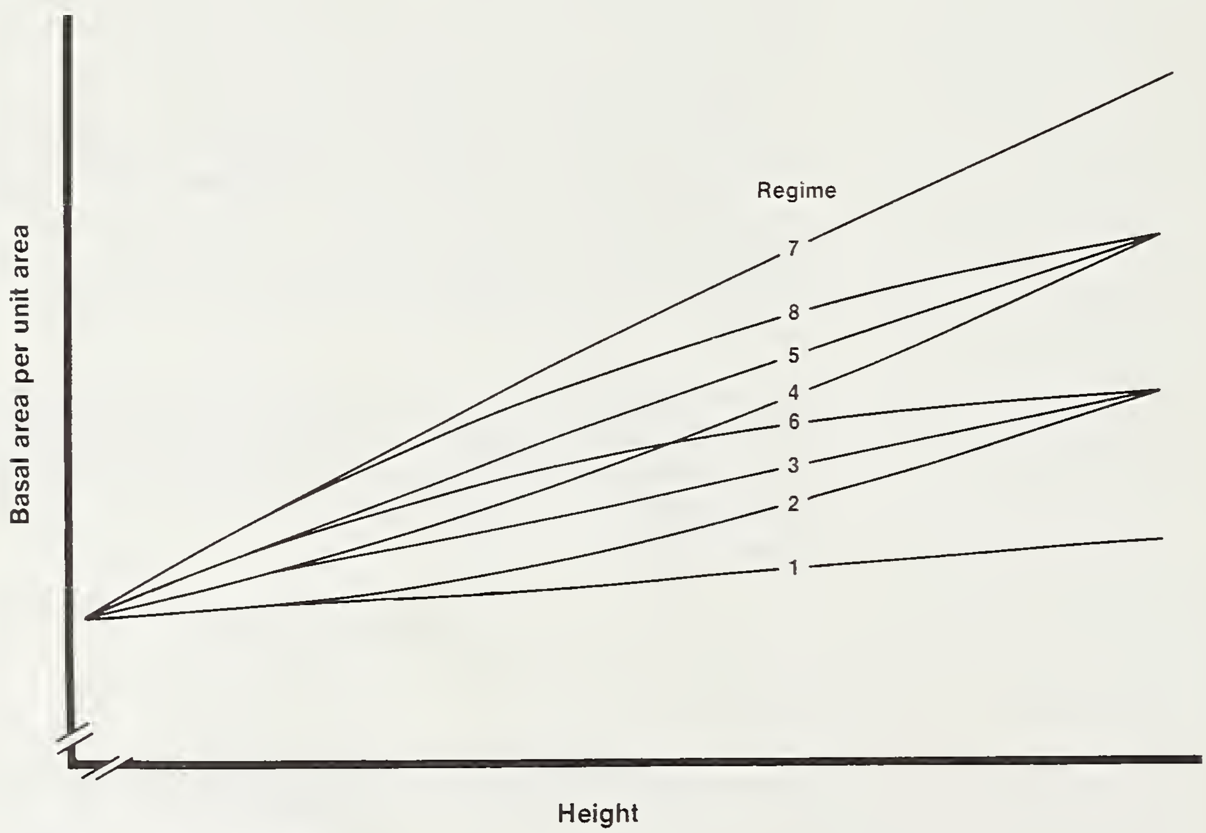
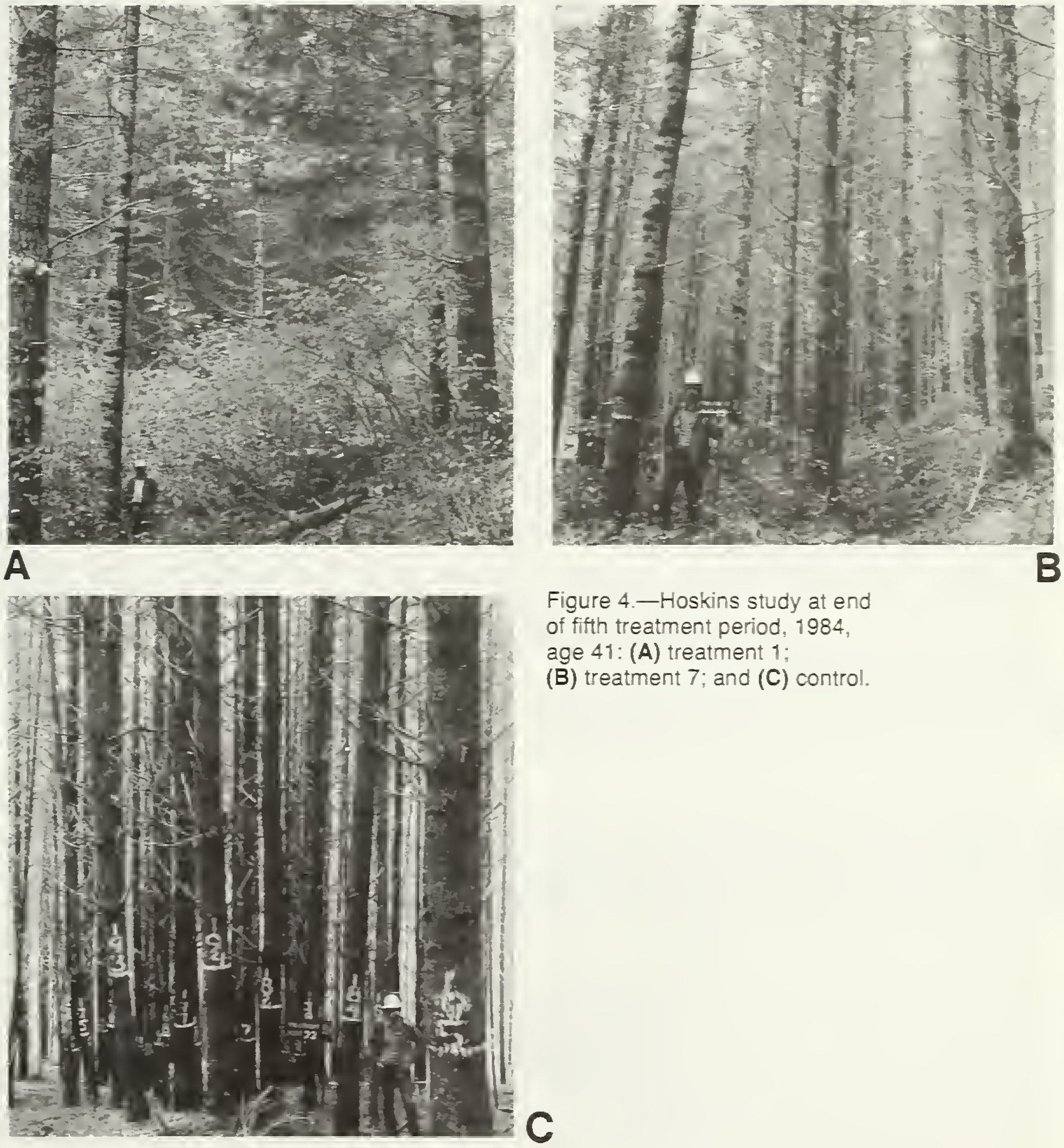


Figure 2.—Idealized trends of basal area for the eight thinning regimes.

Figure 3.—Hoskins study after calibration cut, 1963, age 20.



A

B

C

Figure 4.—Hoskins study at end of fifth treatment period, 1984, age 41: **(A)** treatment 1; **(B)** treatment 7; and **(C)** control.

Analyses

The LOGS study plan specified analyses of variance (ANOVA) for gross volume growth, basal area growth, and net diameter growth. There are, however, other and perhaps more informative ways of analyzing the data, and other relationships of interest. The planned analyses of variance are included in this report, but we do not confine ourselves to them.

Most analyses of volume and basal area growth are for gross growth of trees 1.6 inches and larger d.b.h. Gross rather than net growth and values for trees 1.6 inches and larger rather than some higher measurement limit are used because:

1. These provide more biologically meaningful expressions of stand productivity.
2. Gross growth is less influenced by mortality than is net growth.
3. Inclusion of all trees 1.6 inches and larger eliminates the need to account for ingrowth on the thinned plots.

Height, Height Growth, and Site Index

Definition of stand height.—Past reports in the LOGS series used average height of crop trees as the summary measure of stand height. This has several limitations. First, it does not correspond with the basis of the applicable regional site curves, nor with any procedure in general use. Second, in the present LOGS summary program this value is calculated as an arithmetic mean of measured heights of those crop trees included in the sample; it is therefore influenced by the selection of trees for height measurement. Third, in later treatment periods this value may be altered by removal of crop trees in thinning, aside from actual growth. To avoid these difficulties, we used average height of the 40 largest trees per acre by d.b.h. (previously defined as H40) as the basic stand height statistic (Curtis and others 1981). This value (also frequently referred to as "top height") is little affected by thinning and has a long history of use, particularly in Europe.

Computation of H40.—Because the present LOGS summary program does not provide height-diameter equations, we adopted the following computation procedure:

1. Calculate quadratic mean diameter of the largest eight trees per 0.2-acre plot.
2. Calculate corresponding tree volume using the plot local volume equation.
3. Calculate H40 by substituting mean volume and diameter of the largest eight trees per plot in the Bruce and DeMars (1974) volume equation and solving for height.[6]

Trial computations with plot data indicated that this procedure gave estimates of H40 that were very close to those obtained with plot height-diameter equations.

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[6] The equation can be rearranged as:

$$H = \frac{-B + (B^2 - 4AC)^{1/2}}{2A};$$

where: $A = 0.480961 - 0.00409083D$,
$B = -(V/(0.00545415D^2) + 0.107809)$,
$C = 42.46542 - 10.99643D$,

and

V = volume in cubic feet,
D = d.b.h. in inches, and
H = total height in feet.

Height in relation to treatments.—

Graphs of H40 over time.—H40 was calculated for each plot at each measurement date. For each installation, treatment means of H40 were plotted over the year of measurement. Inspection indicated that:

1. Trends over time are nearly linear.
2. There is no consistency in relative position of thinning treatments among installations.
3. The Rocky Brook study has a considerably greater dispersion of H40 values than do other studies. This may be related to known early snowbreakage and to a greater range in site index in this study than others.
4. In the Clemons study, H40 for controls is markedly and consistently higher than for thinned plots. Trends for control and thinned plots appear parallel.
5. In the Hoskins study, H40 for controls is also above and parallel to values for thinned plots, although the difference is much less than at Clemons.
6. In the Skykomish study, mean H40 for controls was initially lower than for any thinning treatment. Slope of the trend for controls was, however, considerably steeper than for thinned plots, and by 1979 the controls had the highest mean H40. A similar though less pronounced trend was present at Iron Creek.

Effect of calibration thinning on H40.—The hypothesis of no difference between means of H40 for thinned plots and for controls after the calibration thinning, for each installation, was tested (t-test). A significant difference (p less than 0.01) was found only for Clemons, where the mean of controls was 6.2 feet greater than for thinned plots, and for Hoskins, where the difference was 3.1 feet.

A probable explanation is suggested by the diameter distributions shown in table 5. A considerable number of large trees were evidently removed in the calibration thinning at Clemons, probably a result of known prior damage. Similar but lesser differences can be seen for Hoskins and for Rocky Brook. (At Rocky Brook, H40 of controls was 2.7 feet greater than for thinned plots, although the difference was not statistically significant.)

At the most recent measurement, the difference between H40 of controls and of thinned plots was no longer significant at Hoskins. It was still significant at Clemons where, in 1980, H40 of controls was 7.6 feet greater than the mean H40 of thinned plots.

Mean increases in H40 over the entire period of observation were also compared between controls and thinned plots. t-tests indicated significant differences (p less than 0.05) only for Iron Creek and Skykomish, where the controls grew 3.0 and 5.7 feet more, respectively, than did the average of thinned plots.

These results indicated that in a few installations the calibration thinning probably did introduce real differences in H40 between controls and thinned plots. These differences were generally minor and of little importance over the course of the experiment, with the possible exception of the Clemons study.

Effect of removal of trees on H40.—Removal of occasional large trees in thinning should tend to reduce H40 for thinned plots, compared to H40 for control plots, aside from real differences in growth. H40 values were calculated before and after treatment thinnings.[7] Results suggest a small reduction associated with thinning. Changes in means were small, however—a few tenths of a foot at each thinning—and will be ignored in subsequent analyses. We will use values of H40 calculated after thinning.

Height growth patterns and site index estimates.—Past site index estimates for the LOGS studies have most frequently used average height of crop trees, but sometimes selected remeasured site trees have been used. Average height of crop trees is not consistent with the regional site curves (King 1966), which specify the largest 10 trees from a group of 50 as the basis for site index estimates. The latter selection rule was not intended for use in thinned stands and would probably bias comparisons between thinned and control plots.

We needed a procedure that could be applied consistently to all installations and that used only currently available data. We chose to calculate site index by entering King's curves with mean H40 and mean estimated age at b.h. for the installation. Numerical site index values given here may therefore differ slightly from previously published values. Trends of site index estimates over age at b.h. are shown in figure 5.

Although Iron Creek and Francis showed sharp declines in site index estimates over time at the younger ages, at such young ages small errors in estimates of ages b.h. and short-term variations in growth can easily introduce large errors in site index estimates. Little importance can be attached to trends below at least age 15 b.h.

Conformity with the regional site index curves appears reasonably good overall. The best available site index estimates are those from the most recent measurements (table 8).

Comparisons Among Controls

Purpose.—Comparisons of the behavior of controls among installations provide indications of differences in growth associated with location; location may also influence thinned plots. To the extent that differences in initial conditions influence growth of controls, the differences may also affect the definition of thinning treatments because the LOGS study plan uses observed basal area growth on the controls as the basis for defining thinning regimes. We therefore examined characteristics and development of controls for consistency among installations and for differences that may be attributable to differences in initial conditions, real differences in site productivity, or other factors.

Graphs of stand attributes over H40 provide a convenient way to compare on common scales the development of stands which differ in age and site index. This general procedure has a long history of use in yield studies in Europe, where yield tables have frequently been prepared using the assumption that total production is primarily a function of attained height (the so-called "Eichhorn's law"). The relationship to height may differ somewhat among site classes, especially at advanced ages; and production of individual stands in relation to height may differ from regional averages in response to differences in climate, soil, or other factors (see p. 161 ff., Assmann 1970).

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[7] Unpublished report, 1982, "Preliminary Work on the Cooperative Levels-of-Growing-Stock Study in Douglas-Fir," by David D. Marshall and John F. Bell. Report on file at Forestry Sciences Laboratory, 3625-93d Avenue, S.W., Olympia, WA 98502.

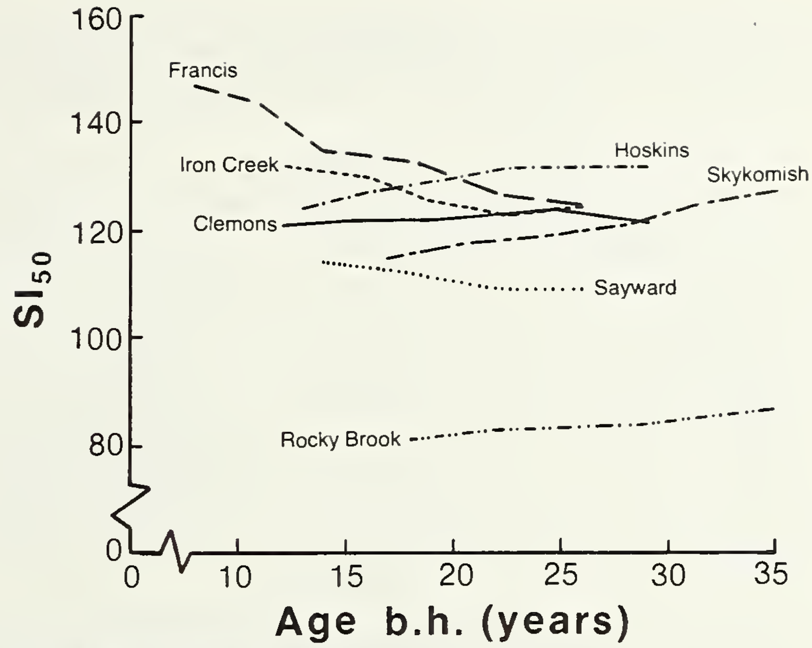


Figure 5.—Estimates of SI_{50} (King 1966) by installation and age b.h., based on height of 40 largest trees per acre (by d.b.h.).

Table 8—Site index estimates from King's (1966) site curves, based on installation means of H40 and ages b.h. at most recent measurement

Installation	Age b.h.	Estimated SI_{50}
Skykomish	35	128
Hoskins	29	132
Rocky Brook	35	87
Clemons	29	1/ 122
Francis	26	125
Iron Creek	26	125
Sayward	26	109

1/ Mean H40 of controls differed significantly from H40 of thinned stands at Clemons. SI_{50} estimated from mean H40 of controls is 132.

For stands treated alike, stand attributes other than volume also tend to be functions of height. Conversely, differences in development in relation to height are indicative of differences in stand treatment, initial conditions, or other factors.

Comparisons of trends.—Table 2 gives means of initial stand values for the control plots, by installation. Trends of number of trees over H40 are shown in figure 6 for all trees, and in figure 7 for Douglas-fir only. Rocky Brook, Francis, and Iron Creek have large numbers of trees of other species (mostly western hemlock), many of which are in the understory and contribute little to volume and basal area totals. When only the Douglas-fir component is considered, initial differences are much less, except at Hoskins and Skykomish. Hoskins had by far the greatest number of stems, Skykomish the least. Skykomish, unlike other studies, was about 50 percent hemlock by basal area. Values of initial number and average diameter at Skykomish were not directly comparable to those for other installations, because at Skykomish (and only at Skykomish) small stems were cut on the control plots.

Trends in average diameter over H40 are shown in figure 8 for all trees, and in figure 9 for Douglas-fir only. The many small trees of other species present at Rocky Brook, Francis, and Iron Creek markedly affect the number of trees and average diameter, but contribute little to basal area and volume. There are, therefore, considerable shifts in relative position of installations in figure 9 as compared to figure 8.

Comparisons of trends in basal area, cumulative gross basal area production, and cumulative gross volume production (all trees) over H40 show generally similar relationships among installations (figures 10, 11, 12). Hoskins and Francis have the highest values for a given H40, and those for Skykomish and Clemons are considerably lower than those for the other studies.

The trend of the relative density measure RD (defined as $G/Dg^{1/2}$ (Curtis 1982)) over H40 likewise shows highest values for Hoskins, which has apparently reached an upper limit at an RD of just under 100 (fig. 13). Rocky Brook, Francis, and Iron Creek appear to be headed toward similar limits at, possibly, somewhat lower levels. (Because of the effect of understory hemlock in reducing stand average diameter, the RD values shown are inflated by 5-10 percent in these three installations.) Sayward is slightly lower. Clemons and Skykomish are behaving quite differently and seem unlikely to reach relative densities near those of the other studies.

Kind of Thinning and the d/D Ratio

The study plan specification that "trees removed in thinning shall be distributed as evenly as practicable across the diameters of trees available for cutting without regard to merchantability" has sometimes been interpreted as a statement that the d/D ratio in the LOGS studies is 1.0: this is incorrect. The study plan specifications produce a d/D of 1.0 only after all noncrop trees have been cut, a condition that generally occurs only at the lowest stocking level (treatment 1) and only in the last one or two thinnings. (In these data, mean d/D ratio of treatment 1 at the fifth treatment thinning was in fact 0.98.)

d/D ratios were plotted against age and height, by installation and by treatment. Values were highly variable—particularly as the number of trees available for cutting decreased—and no conclusions could be drawn beyond the expected result that values in later thinnings were higher at the lower stocking levels.

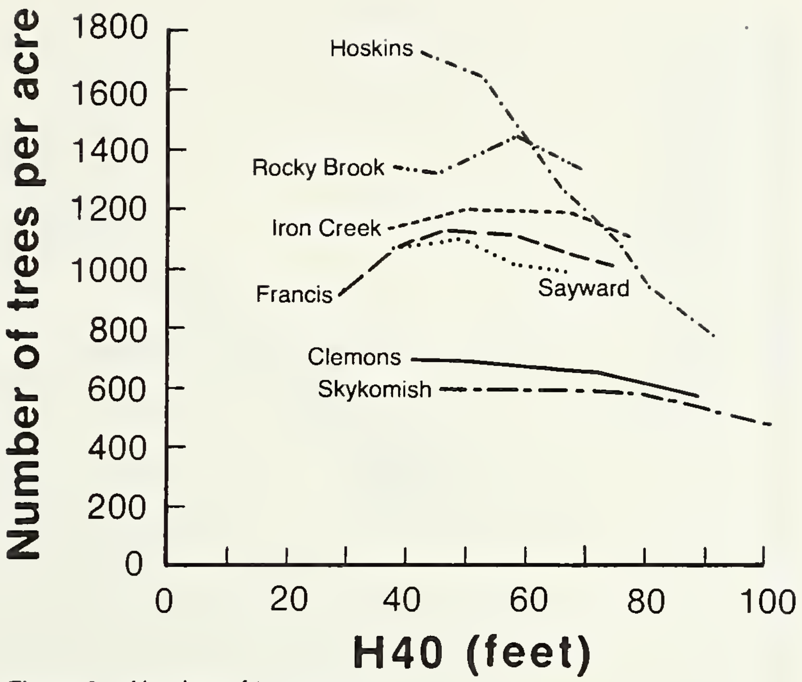


Figure 6.—Number of trees per acre in relation to H40 for control plots, by installation, all species.

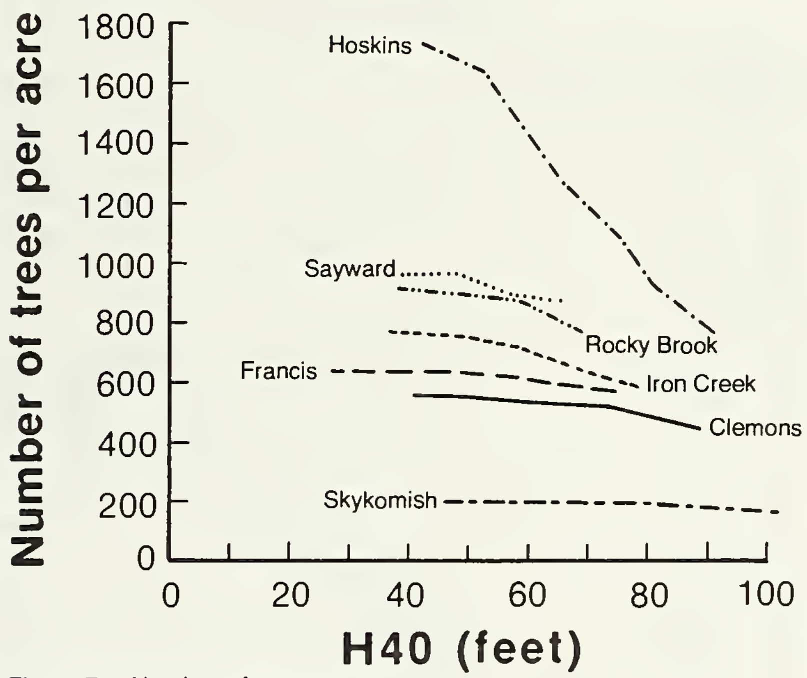


Figure 7.—Number of trees per acre in relation to H40 for control plots, by installation, Douglas-fir only.

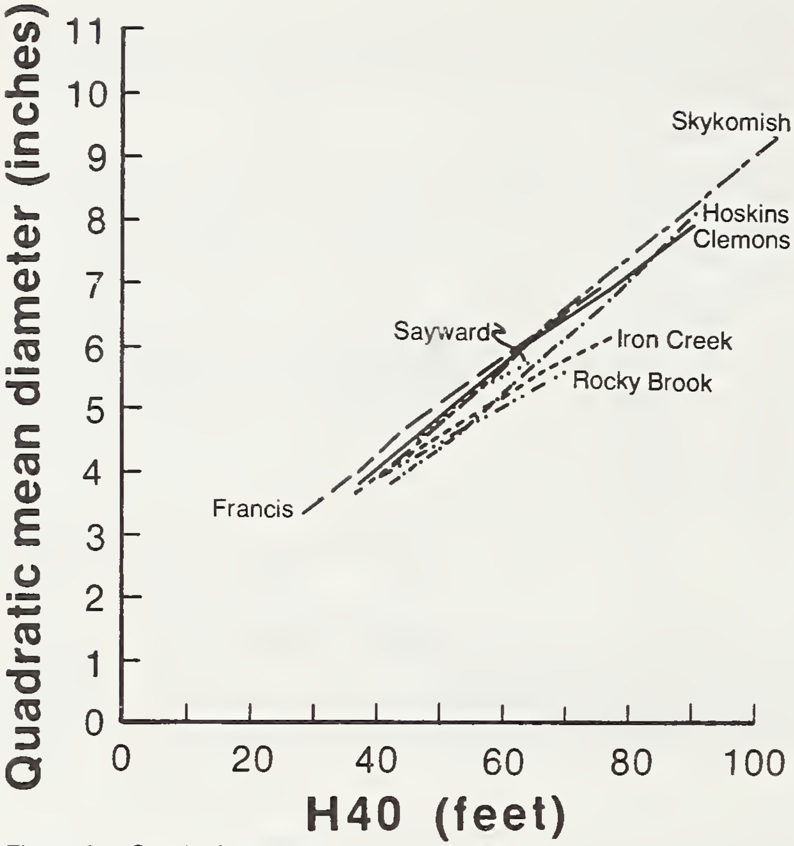


Figure 8.—Quadratic mean diameter in relation to H40 for control plots, by installation, all species.

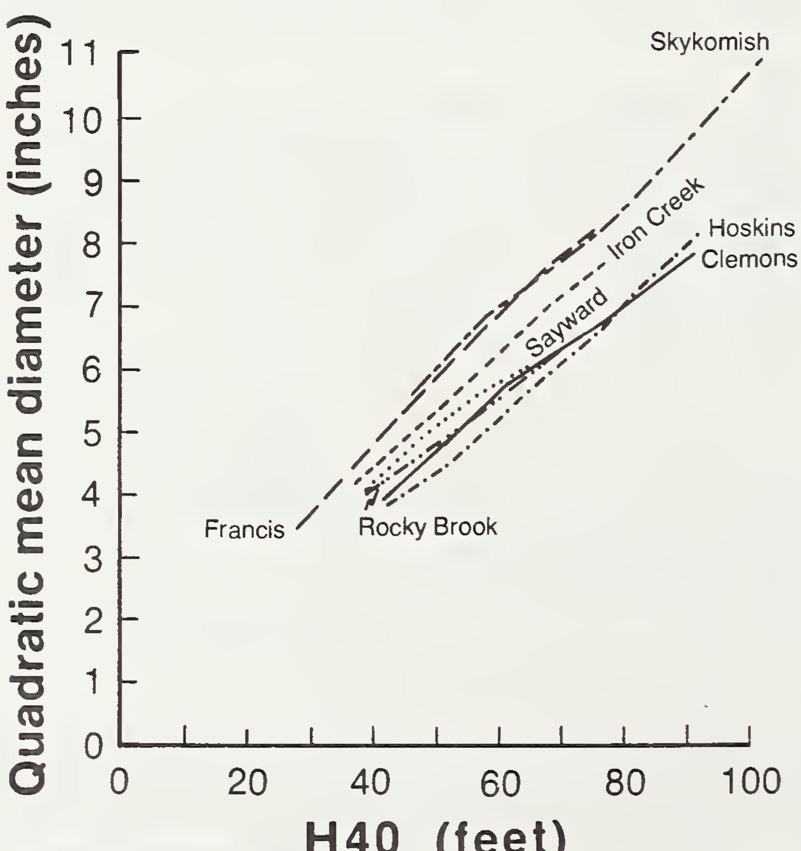


Figure 9.—Quadratic mean diameter in relation to H40 for control plots, by installation, Douglas-fir only.

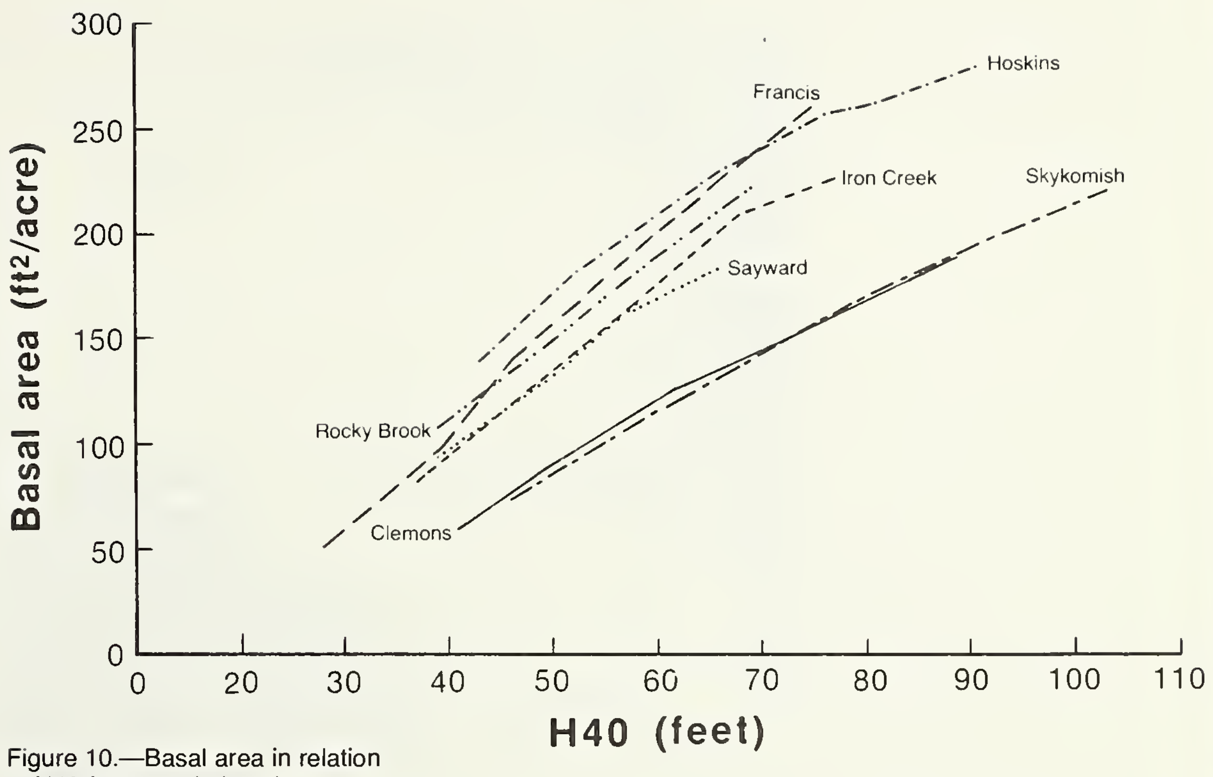


Figure 10.—Basal area in relation to H40 for control plots, by installation, all species.

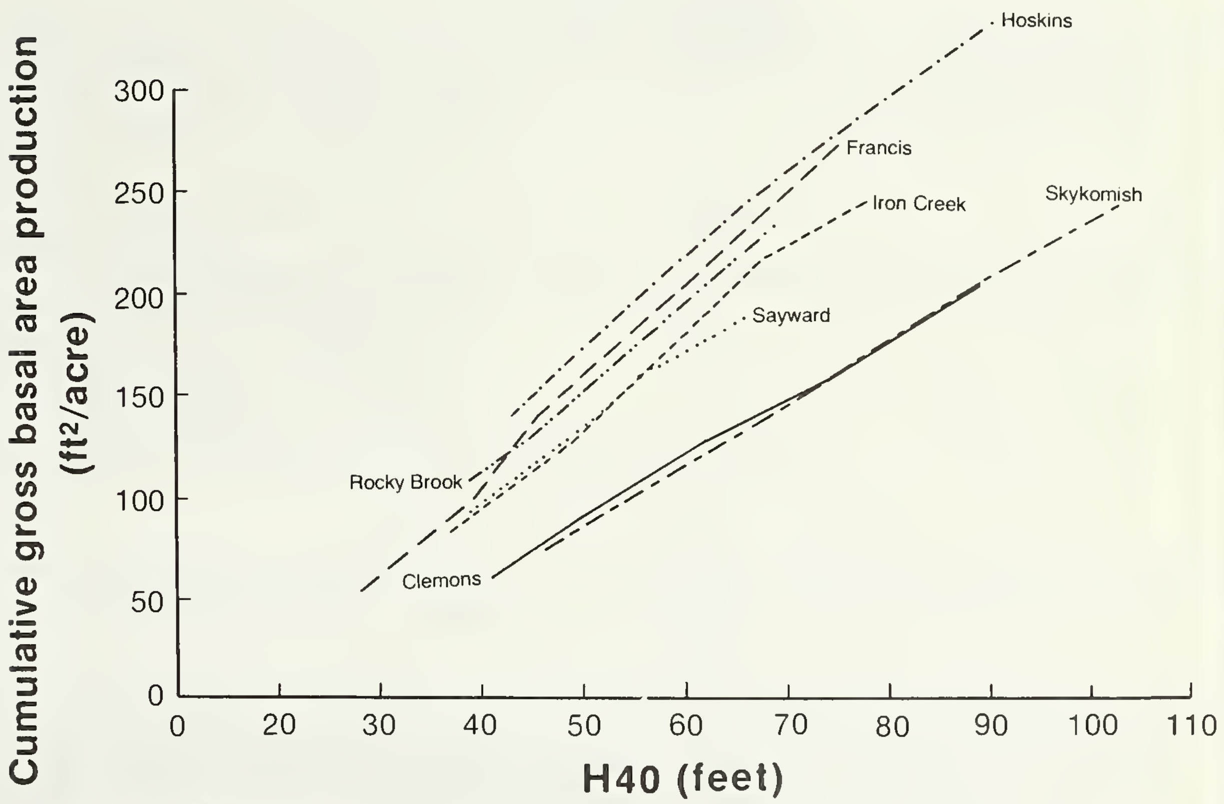


Figure 11.—Cumulative gross basal area production in relation to H40 for control plots, by installation, all species.

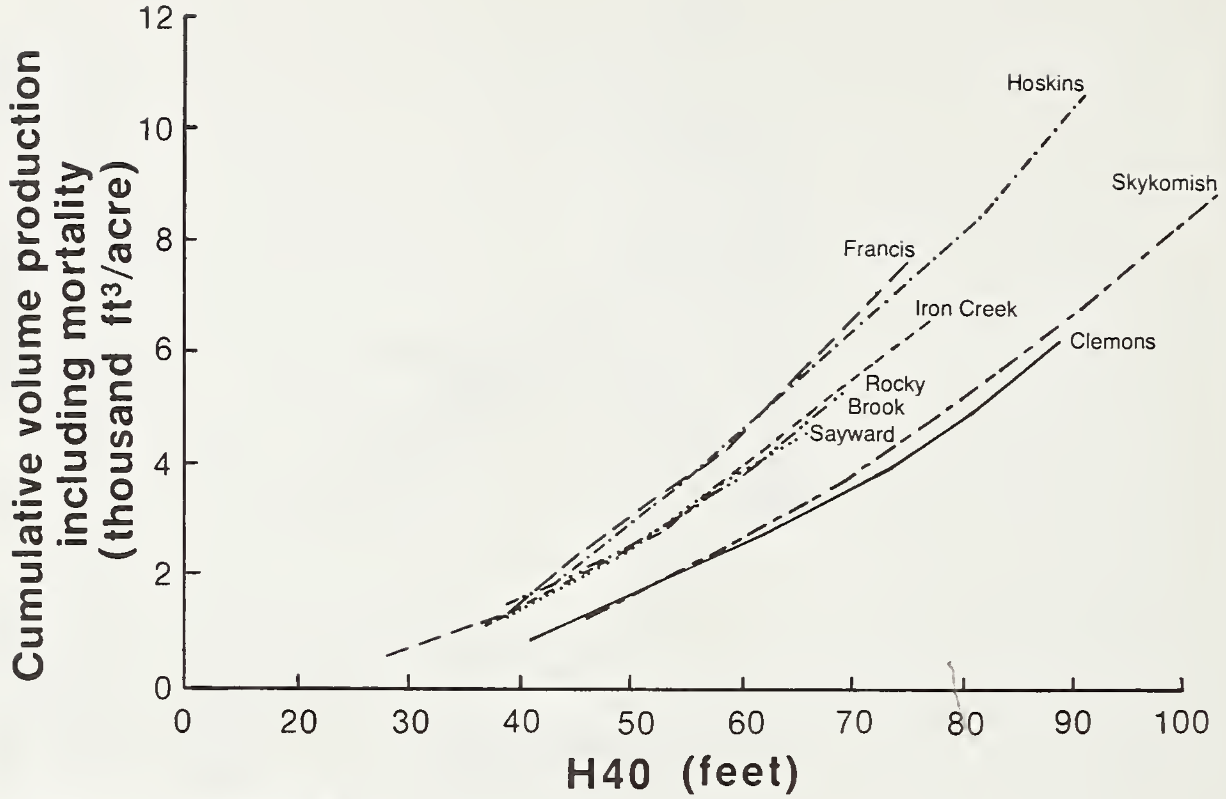


Figure 12.—Cumulative gross volume production in relation to H40 for control plots, by installation, all species.

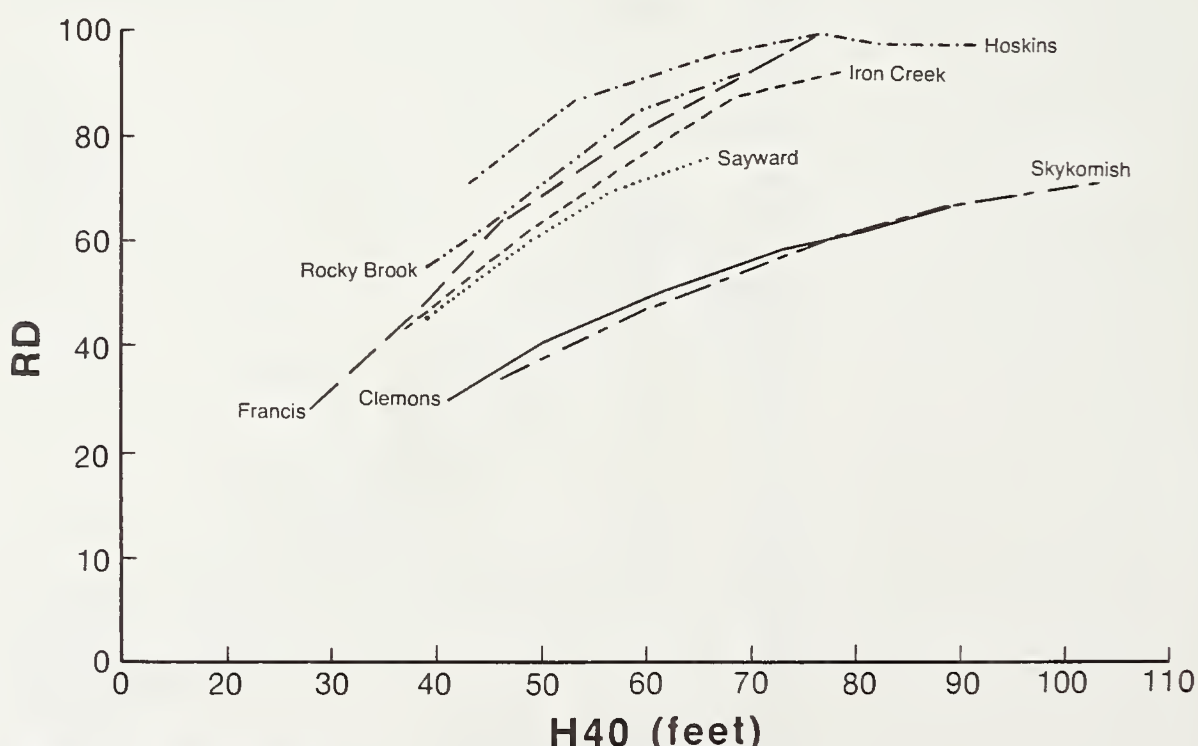


Figure 13.—Trends of RD in relation to H40, by installation, for control plot means, all species.

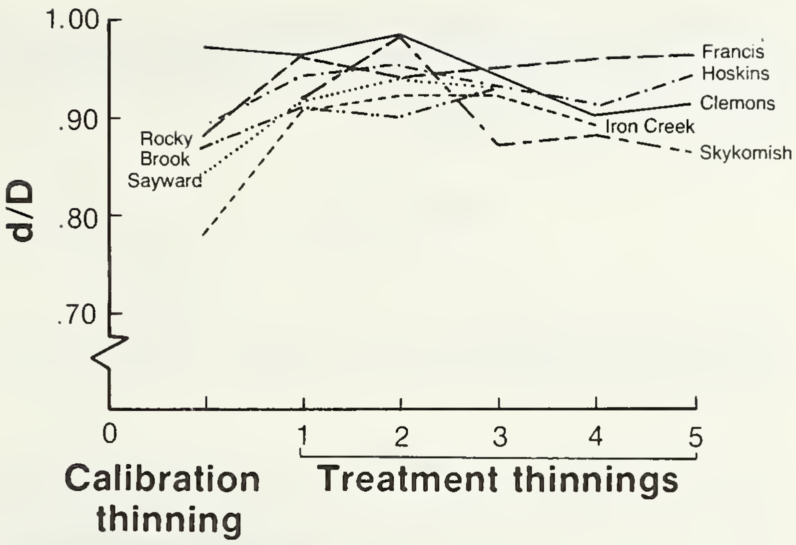


Figure 14.—Ratio of average diameter of trees cut to average diameter of stand before cut (d/D) for successive thinnings, by installation; all thinning treatments combined. Value at calibration thinning is omitted for Skykomish because prethinning diameter is not available.

Mean d/D ratios were calculated over all thinning treatments, for each installation (fig. 14). Wide differences for the calibration thinning resulted from differences in initial conditions. The divergent trend shown for Skykomish may be associated with the large hemlock component. Otherwise, trends are not greatly different among studies.

These cuts are probably best classified as crown thinnings.

Analysis of Variance

The original LOGS study plan specified analysis of variance as the primary method of analysis. Response variables were:

1. Gross periodic basal area growth.
2. Gross periodic volume growth.
3. Periodic change in quadratic mean diameter.

4, 5, and 6. Growth percents in basal area, volume, and diameter.

This analysis has been done for the Skykomish, Hoskins, Clemons, and Francis studies, the only ones for which data are available through the fourth treatment period.

An individual LOGS installation consists of eight thinning treatments replicated three times, with thinning treatments randomly assigned to plots. This is a repeated-measures experiment that is computationally similar to a split-plot design (Snedecor and Cochran 1981). The thinning treatments were randomly assigned to the main plots. Periodic remeasurements of these plots, at intervals defined by 10 feet of height growth, correspond to subplots.

For the ANOVA, gross basal area growth, gross volume growth, and growth in quadratic mean diameter were expressed as periodic annual increments (PAI). Corresponding growth percents were calculated using mean basal area, volume, or diameter for the period as the divisor; that is:

$$\text{Growth percent} = 100' \left[\frac{\text{PAI}}{(Y_1 + Y_2)/2} \right];$$

where Y_1 and Y_2 are values of basal area, volume, or diameter at beginning and end of the growth period. ANOVA computations were done with the SPSS MANOVA program (Hull and Nie 1981).

The seven degrees of freedom in the main (treatments) plot portion of the ANOVA (table 9) were broken down into seven orthogonal contrasts, which test differences among overall means through the fourth treatment period. The first contrast (A) tests the mean of the four fixed treatments versus the mean of the four variable treatments. This is a meaningful comparison because the average growing stock retained (percent of control plot growth) is the same, 40 percent, for all periods (table, inside front cover). Next, because there are four equally spaced treatments (10, 30, 50, 70 percent) in the fixed treatments, up to a third degree polynomial can be used to describe the relationship between response and treatment. The second contrast (B), therefore, tests for significant linear, quadratic, and cubic effects in the fixed treatments. The third contrast (C) tests for differences among means of the increasing and decreasing treatments. At the end of the fifth treatment period average basal area retained for both of these treatments will be 40 percent. Before the fifth treatment period, however, average basal area retained will be greater for the two decreasing treatments. Thus, after four treatment periods average basal area retained is 35 and 45 percent for the increasing and decreasing treatments respectively, making interpretations difficult until both treatments have developed to reach the same average levels of growing stock.

The first test in the subplot (periods) portion of the ANOVA is for differences among periods and is expected to be significant. The other contrasts are the seven period × treatment interactions. These test for differences among individual period responses within the overall average response tested in the main-plot portion of the analysis. A significant interaction indicates a change in response with time.

Results.—

Basal area growth.—The ANOVA for gross basal area PAI is summarized in table 10; means are shown in tables 22-25 (appendix). For all installations, gross basal area growth increased linearly with increased growing stock within the fixed percentage treatments. The means also show that gross basal area PAI decreased with treatment period (age), and the significant ($p \leq 0.05$) period × linear effects interaction for Hoskins and Skykomish suggests that rate of change differs by period. Decreasing treatments had significantly greater average increment than did increasing treatments for all four installations. The period × increasing versus decreasing treatments interactions are significant in three of four installations, which indicates that the pattern of response changes with time.

Table 9—Analysis of variance for a single installation

Source of variation	Degrees of freedom (4 treatment periods)
Treatments:	(7)
A--fixed vs. variable percentage treatments	1
B--among levels of fixed percentage treatments	
linear effects	1
quadratic effects	1
cubic effects	1
C--increasing vs. decreasing percentage treatments	1
D--between levels of increasing percentage treatments	1
E--between levels of decreasing percentage treatments	1
Error a--for testing treatments	16
P--Periods:	3
P X A	3
P X B linear effects	3
P X B quadratic effects	3
P X B cubic effects	3
P X C	3
P X D	3
P X E	3
Error b--for testing period and interactions	48
Total	95

Table 10—Analysis of variance for periodic annual increment in gross basal area, all trees, through fourth treatment period

Source of variation	p-values and error mean squares 1/ Skykomish	Hoskins	Clemons	Francis
Treatments:				
A--Fixed vs. variable	0.965	0.807	0.983	0.919
B--Fixed (linear)	.000**	.000**	.001**	.000**
B--Fixed (quadratic)	.984	.098	.143	.898
B--Fixed (cubic)	.016*	.447	.411	.873
C--Increasing vs. decreasing	.000**	.000**	.021*	.000**
D--Between increasing	.008**	.016*	.049*	.000**
E--Between decreasing	.278	.283	.982	.356
Error a--mean square	.3292	.7232	.9837	.6189
Periods:				
P--Periods	.000**	.000**	.000**	.000**
P X A	.788	.559	.711	.237
P X B (linear)	.002**	.000**	.238	.171
P X B (quadratic)	.066	.002**	.595	.006**
P X B (cubic)	.463	.971	.701	.041*
P X C	.035*	.000**	.456	.000**
P X D	.221	.045*	.364	.016*
P X E	.549	.042*	.173	.745
Error b--mean square	.1288	.0657	.2499	.1866

1/ p is the probability of a larger F, given that the null hypothesis of no difference among means is true. Significance levels: *: $0.01 < p \leq 0.05$; and **: $p \leq 0.01$.

Table 11—Analysis of variance for gross basal area growth percent, all trees, through 4th treatment period

Source of variation	Skykomish	Hoskins	Clemons	Francis
	p-values and error mean squares 1/			
Treatments:				
A--Fixed vs. variable	0.746	0.510	0.508	0.354
B--Fixed (linear)	.000**	.000**	.000**	.000**
B--Fixed (quadratic)	.382	.862	.876	.029*
B--Fixed (cubic)	.030*	.537	.536	.327
C--Increasing vs. decreasing	.002**	.000**	.004**	.000**
D--Between increasing	.010**	.000**	.078	.611
E--Between decreasing	.002**	.000**	.014*	.001**
Error a--mean square	.3279	.3689	1.2390	.6884
Periods:				
P--Periods	.000**	.000**	.000**	.000**
P X A	.840	.186	.289	.333
P X B (linear)	.020*	.051	.005**	.004**
P X B (quadratic)	.224	.024*	.992	.032*
P X B (cubic)	.479	.918	.548	.018*
P X C	.032*	.000**	.155	.002**
P X D	.149	.729	.515	.034*
P X E	.831	.003**	.922	.236
Error b--mean square	.1062	.0293	.3258	.1434

1/ p is the probability of a larger F, given that the null hypothesis of no difference among means is true. Significance levels: *: $0.01 < p \leq 0.05$; and **: $p \leq 0.01$.

Gross basal area growth percent is also linear (table 11 and tables 26-29 (appendix)) and decreases with treatment period and with an increase in growing stock. The period × linear interaction is significant in three of four installations, which indicates that slopes of the linear trends differ with periods. The increasing treatments have significantly larger growth percents than the decreasing treatments because the former have fewer trees. The period × increasing treatments interaction is significant in three of four cases, indicating that differences change with time, as would be expected.

Volume growth.—The ANOVAs for gross volume PAI and for volume growth percent are summarized in tables 12 and 13; means are shown in tables 30-37 (appendix). Results are similar to those for basal area, with linear trends that increase with growing stock for volume growth and decrease with growing stock for growth percent. Increasing versus decreasing treatments differ significantly, as was the case in the basal area analysis. The period × linear interaction for volume growth PAI is significant in three of four installations, indicating that slopes differ by period. Interactions for volume growth percent are significant mainly at Skykomish, suggesting for the other areas that although volume growth percent decreases with age, the trends with growing stock are similar for all treatment periods.

Diameter growth.—The ANOVAs for quadratic mean diameter PAI and growth percent are shown in tables 14 and 15; means are in tables 38-45 (appendix). Again, within fixed treatments, PAI and growth percent decreased linearly with increasing growing stock as the increment was redistributed to fewer and ultimately larger trees in the heavier thinnings. An exception was Skykomish, which has a significant quadratic term for PAI. The means in table 38 show that this arises in this instance from greater growth in treatment 7 than in treatment 5. The reason for this anomaly is unknown.

Table 12—Analysis of variance for periodic annual increment in gross volume, all trees, through 4th treatment period

Source of variation	p-values and error mean squares 1/			
	Skykomish	Hoskins	Clemons	Francis
Treatments:				
A--Fixed vs. variable	0.660	0.779	0.658	0.160
B--Fixed (linear)	.000**	.000**	.000**	.000**
B--Fixed (quadratic)	.120	.060	.431	.426
B--Fixed (cubic)	.362	.657	.610	.192
C--Increasing vs. decreasing	.000**	.000**	.008**	.000**
D--Between increasing	.002**	.000**	.108	.000**
E--Between decreasing	.023*	.002**	.661	.000**
Error a--mean square	.403	.768	.1556	.477
Periods:				
P--Periods	.000**	.000**	.000**	.000**
P X A	.069	.987	.995	.943
P X B (linear)	.000**	.000**	.129	.000**
P X B (quadratic)	.021*	.128	.052	.202
P X B (cubic)	.084	.356	.952	.634
P X C	.014*	.014*	.708	.604
P X D	.000**	.180	.369	.001**
P X E	.001**	.001**	.250	.057
Error b--mean square	.194	.289	.445	.394

1/ p is the probability of a larger F, given that the null hypothesis of no difference among means is true. Significance levels: *: $0.01 < p \leq 0.05$; and **: $p \leq 0.01$.

Table 13—Analysis of variance for gross volume growth percent, all trees, through 4th treatment period

Source of variation	p-values levels and error mean squares 1/			
	Skykomish	Hoskins	Clemons	Francis
Treatments:				
A--Fixed vs. variable	0.547	0.475	0.681	0.267
B--Fixed (linear)	.001**	.000**	.000**	.000**
B--Fixed (quadratic)	.086	.530	.763	.076
B--Fixed (cubic)	.519	.674	.737	.528
C--Increasing vs. decreasing	.000**	.001**	.035*	.042*
D--Between increasing	.006**	.001**	.112	.649
E--Between decreasing	.007**	.000**	.016*	.049*
Error a--mean square	.4521	.4832	2.0671	1.3831
Periods:				
P--Periods	.000**	.000**	.000**	.000**
P X A	.013*	.808	.838	.443
P X B (linear)	.010**	.157	.073	.052
P X B (quadratic)	.034*	.353	.147	.344
P X B (cubic)	.004**	.294	.884	.052
P X C	.000**	.124	.463	.127
P X D	.000**	.975	.258	.368
P X E	.000**	.026*	.349	.643
Error b--mean square	.1409	.2894	.7058	.4880

1/ p is the probability of a larger F, given that the null hypothesis of no difference among means is true. Significance levels: *: $0.01 < p \leq 0.05$; and **: $p \leq 0.01$.

Table 14—Analysis of variance for periodic annual increment in quadratic mean diameter, all trees, through 4th treatment period

Source of variation	p-values and error mean squares 1/			
	Skykomish	Hoskins	Clemons	Francis
Treatments:				
A - Fixed vs. variable	0.344	0.639	0.941	0.806
B - Fixed (linear)	.000**	.000**	.000**	.000**
B - Fixed (quadratic)	.007**	.209	.504	.199
B - Fixed (cubic)	.212	.890	.897	.597
C - Increasing vs. decreasing	.000**	.000**	.003**	.000**
O - Between increasing	.704	.000**	.037*	.015*
E - Between decreasing	.010**	.002**	.053	.001**
Error a--mean square	.0021	.0031	.0089	.0048
Periods:				
P - Periods	.000**	.000**	.000**	.000**
P X A	.315	.081	.221	.05B
P X B (linear)	.000**	.000**	.000**	.000**
P X B (quadratic)	.879	.116	.222	.000**
P X B (cubic)	.737	.553	.717	.127
P X C	.016*	.002**	.273	.000**
P X O	.001**	.000**	.375	.001**
P X E	.017*	.001**	.B84	.001**
Error b--mean square	.0002	.0002	.0006	.0003

1/ p is the probability of a larger F, given that the null hypothesis of no difference among means is true. Significance levels: *: 0.01 < p ≤ 0.05; and **: p ≤ 0.01.

Table 15—Analysis of variance for quadratic mean diameter growth percent, all trees, through 4th treatment period

Source of variation	p-values and error mean squares 1/			
	Skykomish	Hoskins	Clemons	Francis
Treatments:				
A - Fixed vs. variable	0.742	0.515	0.485	0.315
B - Fixed (linear)	.000**	.000**	.000**	.000**
B - Fixed (quadratic)	.383	.881	.885	.033*
B - Fixed (cubic)	.032*	.556	.527	.381
C - Increasing vs. decreasing	.002**	.000**	.003**	.000**
O - Between increasing	.013*	.000**	.082	.612
E - Between decreasing	.002**	.000**	.014*	.001**
Error a--mean square	.0858	.0970	.32B1	.1799
Periods:				
P - Periods	.000**	.000**	.000**	.000**
P X A	.870	.239	.312	.269
P X B (linear)	.028*	.171	.010**	.000**
P X B (quadratic)	.207	.016*	.995	.054
P X B (cubic)	.497	.944	.578	.016*
P X C	.041*	.000**	.155	.001**
P X O	.121	.790	.538	.02B*
P X E	.853	.006**	.906	.251
Error b--mean square	.0275	.007B	.0870	.0377

1/ p is the probability of a larger F, given that the null hypothesis of no difference among means is true. Significance levels: *: 0.01 < p ≤ 0.05; and **: p ≤ 0.01.

The period $\times$ linear interaction is consistently significant, with diameter growth decreasing with age except in treatment 1, which has the least growing stock. The increasing percentage treatments (2 and 4) have greater diameter growth than the decreasing treatments (6 and 8) because of the lesser growing stock in the early periods.

Crop trees.—Parallel analyses of variance were run for the 80 well-spaced crop trees on each plot. Results were similar to those for all trees, although F-values were generally less for crop trees. This suggests that averages of the crop trees, which are in general the larger trees, have been somewhat less influenced by the treatments than have the averages of all trees.

Combined analysis.—A combined analysis in which individual installations would be treated as blocks was considered. We concluded that such an analysis is not appropriate because of the probable inconsistencies among treatments in different installations that arise from differences in initial conditions and because of the nonhomogeneity of variance among installations.

Treatment means.—Figures 15 through 18 show treatment means (tables 22-45, appendix) of basal area growth, basal area growth percent, volume growth, and volume growth percent. These are plotted over mean values of basal area for each period. The lines connecting successive means of individual treatments represent trends over time within each treatment. The lines connecting means of different treatments for the same treatment period represent response to basal area level within each treatment period (these lines are omitted for treatment periods 1 and 2 in figure 17 to improve clarity).

The nature of these trends is best seen in the graphs for the Francis study, which has the most regular trends. Skykomish has lower growth percents because of its greater initial volume (table 7). Skykomish, Hoskins (volume only), and Clemons each have anomalies in individual treatment periods (discussed later) that make the patterns less obvious than the patterns for Francis. The trends, none the less, show a general similarity across all installations.

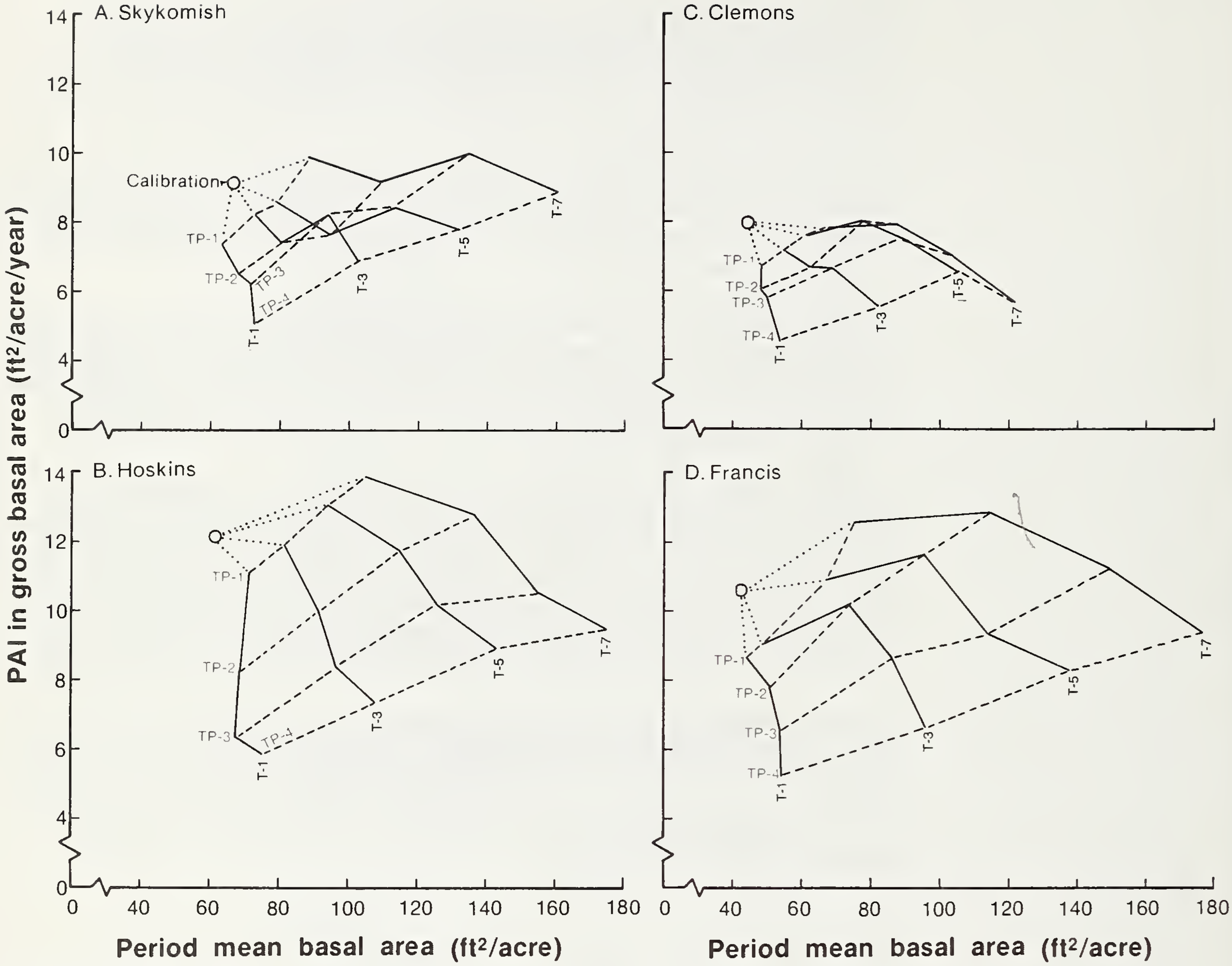


Figure 15.—Periodic annual increment in gross basal area in relation to mean basal area for the growth period: **(A)** Skykomish, **(B)** Hoskins, **(C)** Clemons, and **(D)** Francis. Solid lines connect values for the same treatment (T) in successive growth periods; dashed lines connect values for different treatments in the same growth period (TP). Values shown for fixed percentage treatments (1, 3, 5, and 7) only.

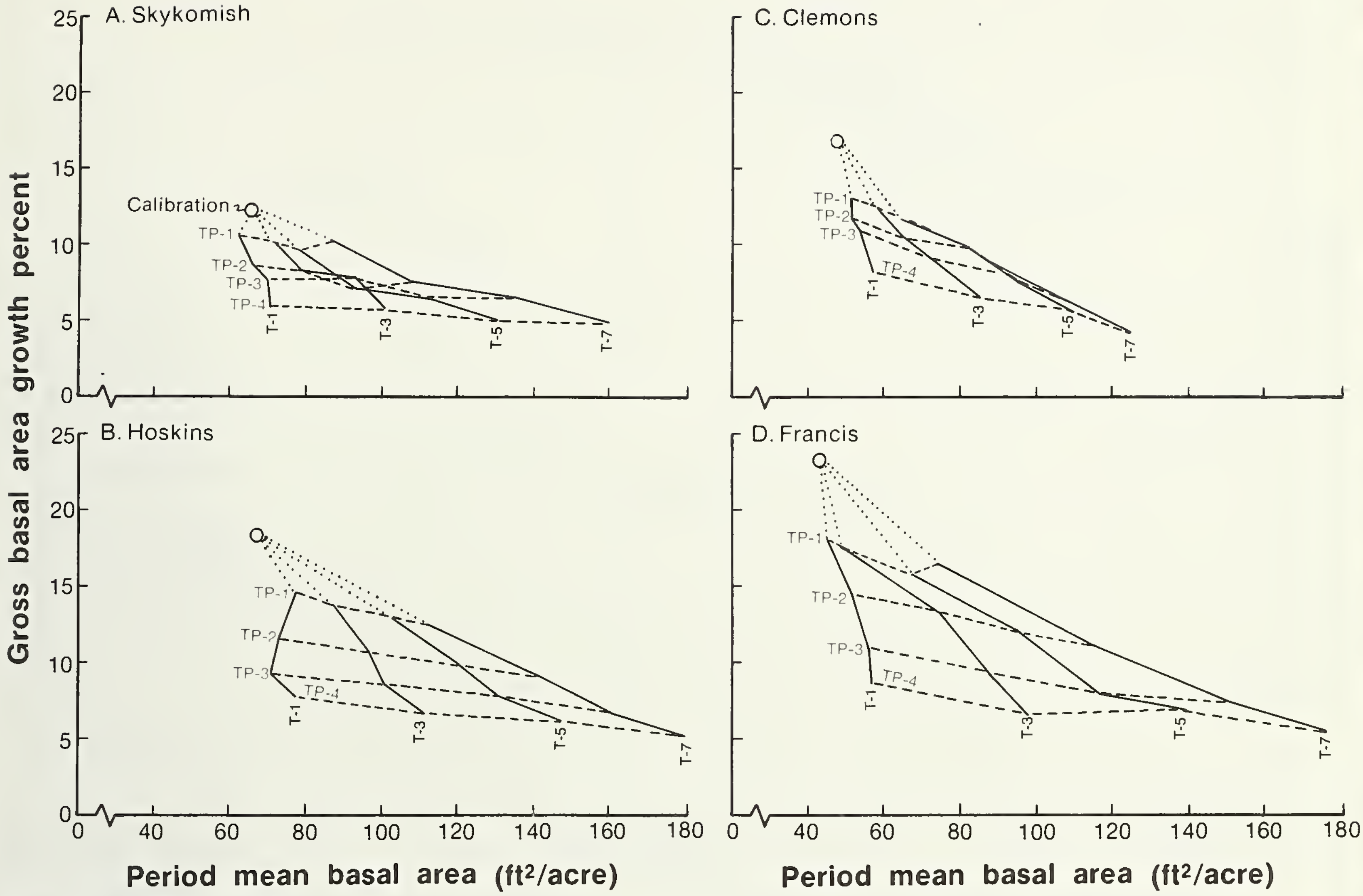


Figure 16.—Basal area growth percent in relation to mean basal area for the growth period: **(A)** Skykomish, **(B)** Hoskins, **(C)** Clemons, and **(D)** Francis. Solid lines connect values for the same treatment (T) in successive growth periods; dashed lines connect values for different treatments in the same growth period (TP). Values shown for fixed percentage treatments (1, 3, 5, and 7) only.

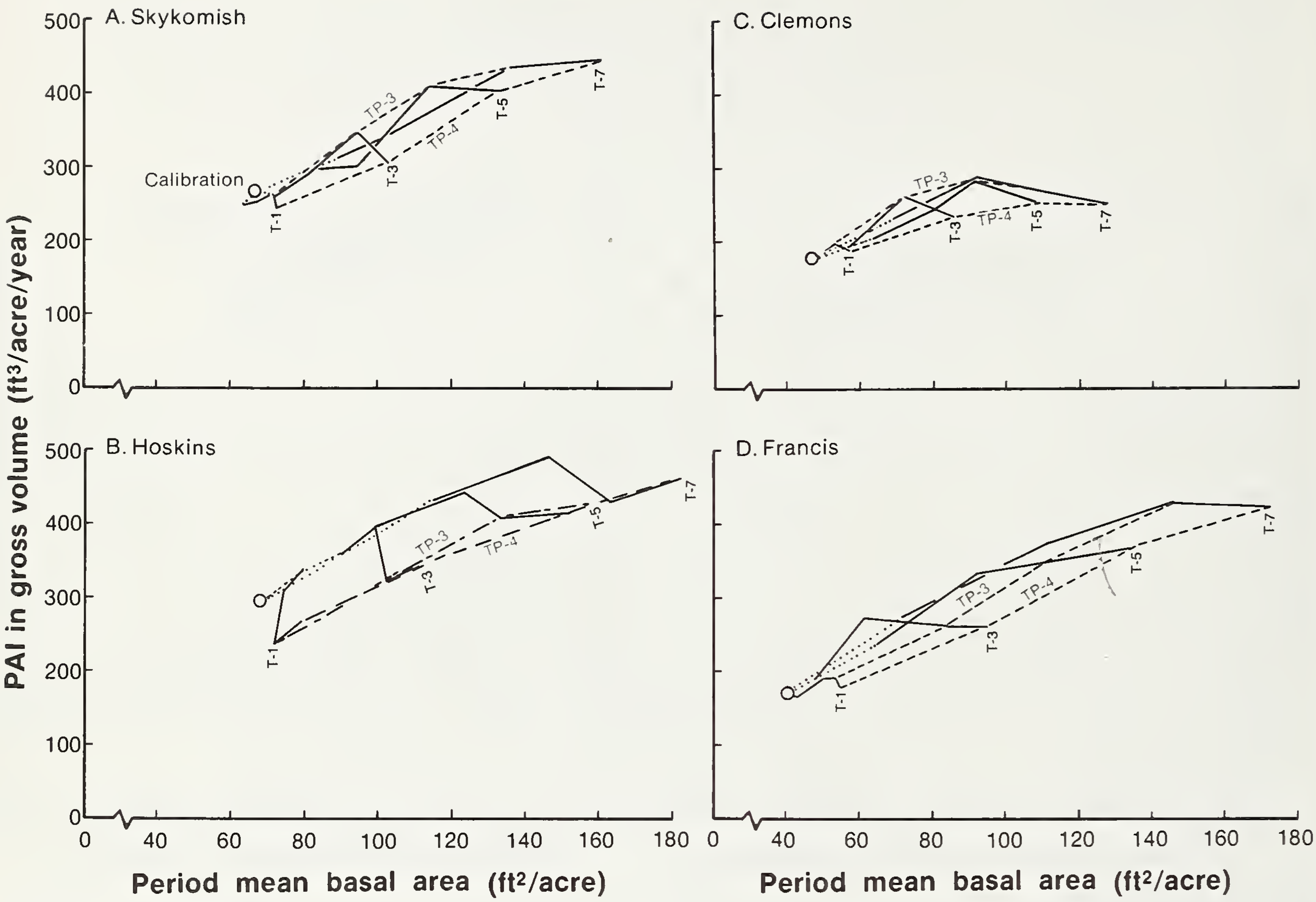


Figure 17.—Periodic annual gross volume increment in relation to mean basal area for the growth period: **(A)** Skykomish, **(B)** Hoskins, **(C)** Clemons, and **(D)** Francis. Solid lines connect values for the same treatment (T) in successive growth periods; dashed lines connect values for different treatments in the same period (TP), for treatment periods 3 and 4 only. Values shown for fixed percentage treatments (1, 3, 5, and 7) only.

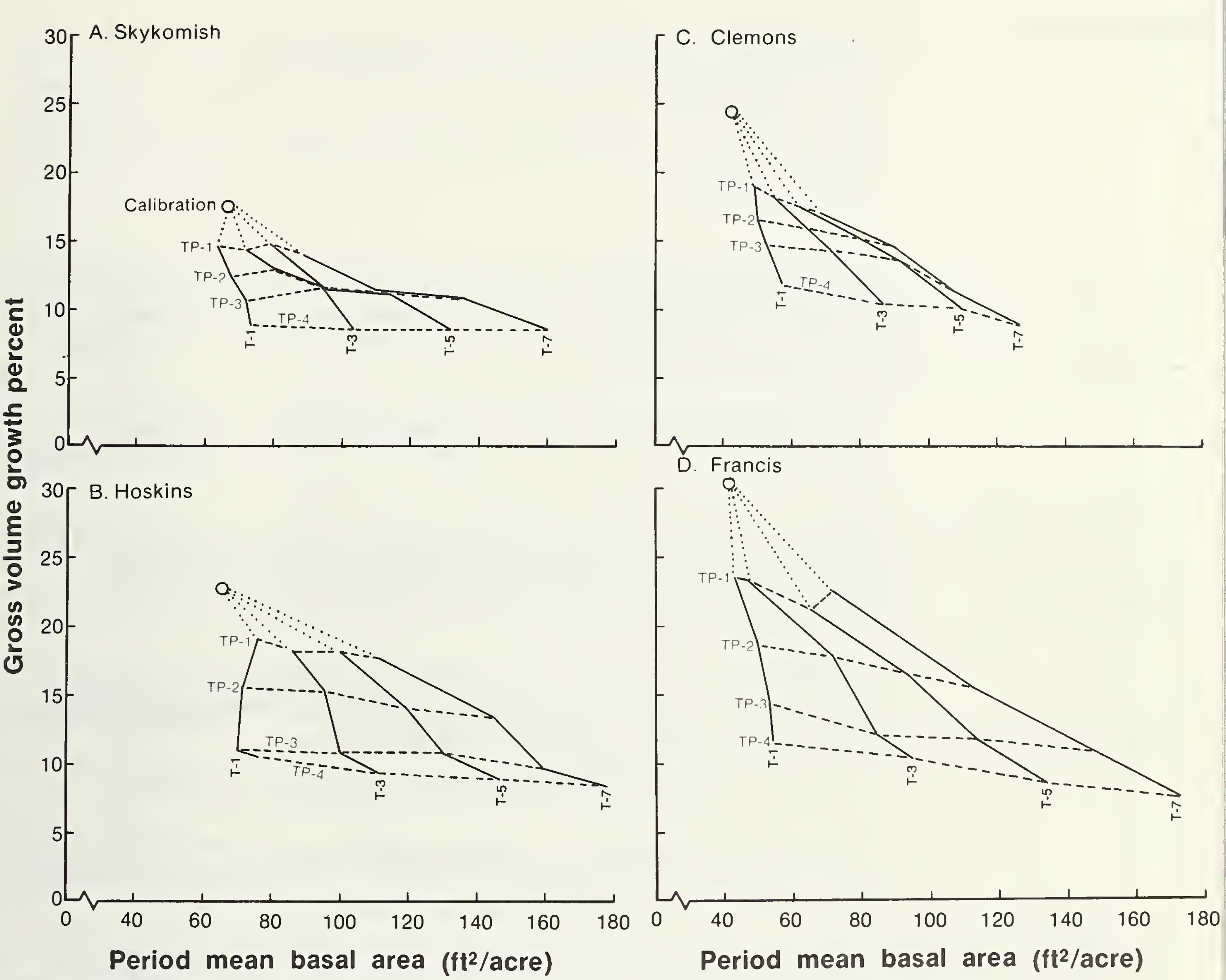


Figure 18.—Volume growth percent in relation to mean basal area for the growth period: **(A)** Skykomish, **(B)** Hoskins, **(C)** Clemons, and **(D)** Francis. Solid lines connect values for the same treatment (T) in successive growth periods; dashed lines connect values for different treatments in the same growth period (TP). Values shown for fixed percentage treatments (1, 3, 5, and 7) only.

Equation Forms

Although analysis of variance was the method of data analysis specified in the original study plan, other ways of looking at the data are informative. In subsequent sections we examine relationships between growth and growing stock using graphic and regression methods. We will not use treatment as a variable, but will use measures of growing stock (which are related to treatment, as each treatment represents a particular sequence of growing stock values over time). In most analyses we use individual plot values rather than treatment means.

The ANOVA of the preceding section led to the conclusion that the relationship of growth of thinned plots (in basal area, volume, diameter, and corresponding growth percents) to basal area growing stock was linear in the sense that addition of squared or cubic terms to the basic relationship, $y = a + bx$, did not give a statistically significant reduction in residual variance.

Logical considerations indicate, however, that all six of these relationships cannot possibly be linear, and other equation forms are therefore used in subsequent analyses. Our reasons are:

1. Curves of growth in relation to growing stock for basal area and volume must pass through the origin. Means of thinned plots in the later treatment periods are not, however, satisfactorily represented by straight lines through the origin, which correspond to the equation, $y = bx$.

2. Functions for growth and for growth percent should be consistent. A linear growth function implies a curvilinear growth percent function. Conversely, a linear growth percent function implies a curvilinear growth function.

3. Growth rates cannot increase indefinitely with increase in growing stock.

Because these stands originally were either plantations or exceptionally uniform natural stands, the controls can be regarded as one extreme of a continuum of possible stocking levels.

A satisfactory function should (1) pass through the origin, (2) give a satisfactory statistical fit to thinned plots, and (3) also approximate the mean of control plots. No straight line can do this.

Williamson and Curtis (1984) use the function, $y = bx - cx^2$, to express the relationship of PAI in volume to volume of growing stock. This fits satisfactorily and implies a linear function for growth percent that is in agreement with data plots. It does, however, frequently give a rather abrupt maximum near the upper margin of the range of stocking, which may or may not be real.

In this report we use the equation:

$$y = e^a x^b e^{cx} ;$$

fitted in the form:

$$\ln y = a + b \ln x + cx ;$$

to express the relationships between growth and growing stock for basal area and for volume. Compared to the equation used by Williamson and Curtis (1984), this is somewhat more flexible and can represent a relationship with a maximum while also giving a reasonable approximation to asymptotic relationships; it extrapolates more plausibly; and it seems to more nearly approximate uniform variance when control plots are included. In most instances curves corresponding to the two equations differ little, however, within the range of data for thinned plots.

Shape of growth-growing stock curves is poorly defined in the early treatment periods because of the very limited range in growing stock present on the thinned plots and because of the wide gap in growing stock that exists between thinned plots and control plots. This gap narrows over successive treatment periods, and definition improves as the thinned plots in some treatments build up growing stock and increase the range of growing stock represented. Relationships are fairly well defined by the fourth treatment period and should be solidly established by the end of the experiment.

Basal Area Growth

We started the analysis of relationships between growth and growing stock with gross basal area growth, principally because we expected more consistent relationships for it than for volume growth (because of effects of errors in height measurements and of sampling errors on estimates of the latter).

Basal area increment as a function of basal area.—

Data plots.—Within each installation, values of periodic annual gross basal area increment (dG) were plotted over mean basal area for the period (G) for all plots including controls, by treatment period. Here, and later, we use mean growing stock for the period rather than growing stock at start of the growth period because this mean represents the average of the growing stocks that produced the observed periodic annual increment. Corresponding midperiod ages are given in table 16. Periodic annual increment can be regarded as an estimate of the slope of the yield curve at the midpoint of the growth period, at which point growing stock is approximated by mean growing stock for the period. Mathematically, if the yield function is $y = f(x)$, periodic annual increment is an estimate of the derivative dy/dx at the midperiod value of x. This facilitates comparisons among experiments that have growth periods of different lengths.

Regressions of basal area increment on basal area.—The equation form,

$$\ln dG = a + b \ln G + cG ,$$

can and in some instances does produce curves with a maximum for basal areas intermediate between those present in the thinned plots and in the controls. (Such a maximum is also suggested by scatter diagrams for the Hoskins and Clemons studies.)

Table 16—Ages at midpoints of growth periods[1/]

Treatment Period	Installation						
	Skykomish	Hoskins	Rocky Brook	Clemons	Francis	Iron Creek	Sayward
	Years						
TP-1 2/	29.5	25.0	34.5	24.0	19.5	24.5	28.0
TP-2	32.5	28.5	41.0	27.5	23.0	28.0	32.0
TP-3	36.0	31.0	--	30.5	27.0	31.5	--
TP-4	40.0	34.0	--	34.0	31.0	--	--

-- = not available.

1/ Ages correspond to curves in figures 17, 18, 21, 22 and 25.

2/ TP-n = treatment period "n."

Regressions were fitted to combined data for thinned and control plots for each treatment period within each installation. Corresponding curves are shown in figure 19. Inspection of these curves, their standard errors of estimate, and the corresponding scatter diagrams (not shown) indicated that:

1. There are considerable differences in residual variances among installations and among periods within installations. In particular, the data from Clemons and Rocky Brook appear more variable than those from other installations.
2. Curves for treatment periods 2 and 3 at Skykomish appear out of line with the position of the curves for periods 1 and 4. The explanation is unknown.
3. With the exception noted in (2), the fitted curves form regular sequences over time within any one installation.

Basal area increment as a function of RD.—

Data plots.—Values of dG were plotted over values of the relative density measure RD for each period. Compared with the previous plots of dG against G, use of RD as the independent variable compresses the horizontal axis proportional to $Dg^{-1/2}$ in a manner such that a given value of RD represents an approximately constant fraction of maximum attainable density. Some users find a scale that can be referenced to such a biological limit to be simpler and more readily interpretable than absolute measures such as basal area. Similar results could be obtained with any of the other common diameter-based measures of relative density.

Period regressions.—Regressions of the form,

$$\ln dG = a + b \ln RD + cRD ,$$

were fitted for each treatment period, by installations (fig. 20). Residuals are compared in table 17. On average, standard errors of estimate were slightly larger with this equation than with similar equations using basal area as the predictor, but differences were not consistent among installations.

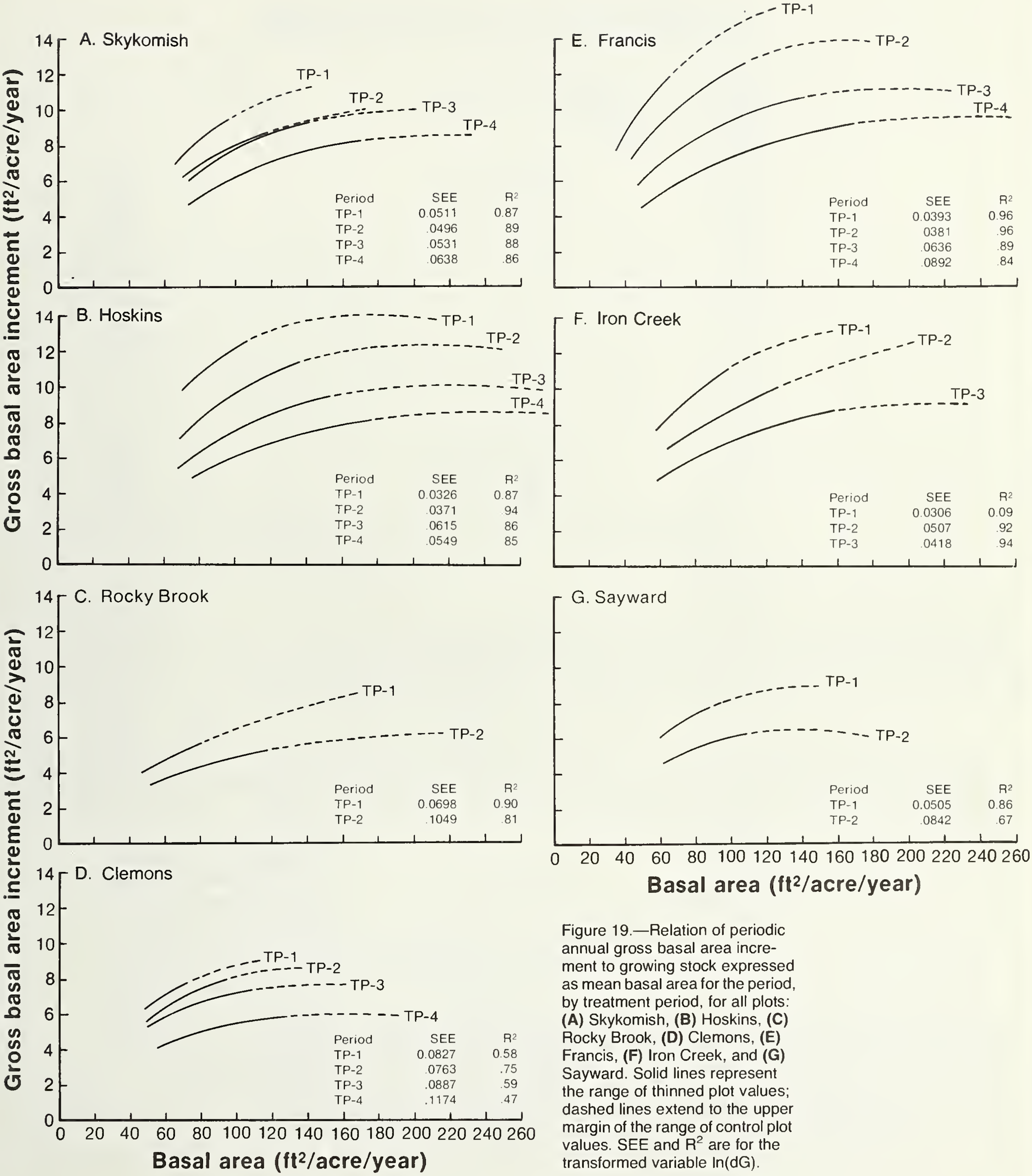


Figure 19.—Relation of periodic annual gross basal area increment to growing stock expressed as mean basal area for the period, by treatment period, for all plots: **(A)** Skykomish, **(B)** Hoskins, **(C)** Rocky Brook, **(D)** Clemons, **(E)** Francis, **(F)** Iron Creek, and **(G)** Sayward. Solid lines represent the range of thinned plot values; dashed lines extend to the upper margin of the range of control plot values. SEE and R^2 are for the transformed variable ln(dG).

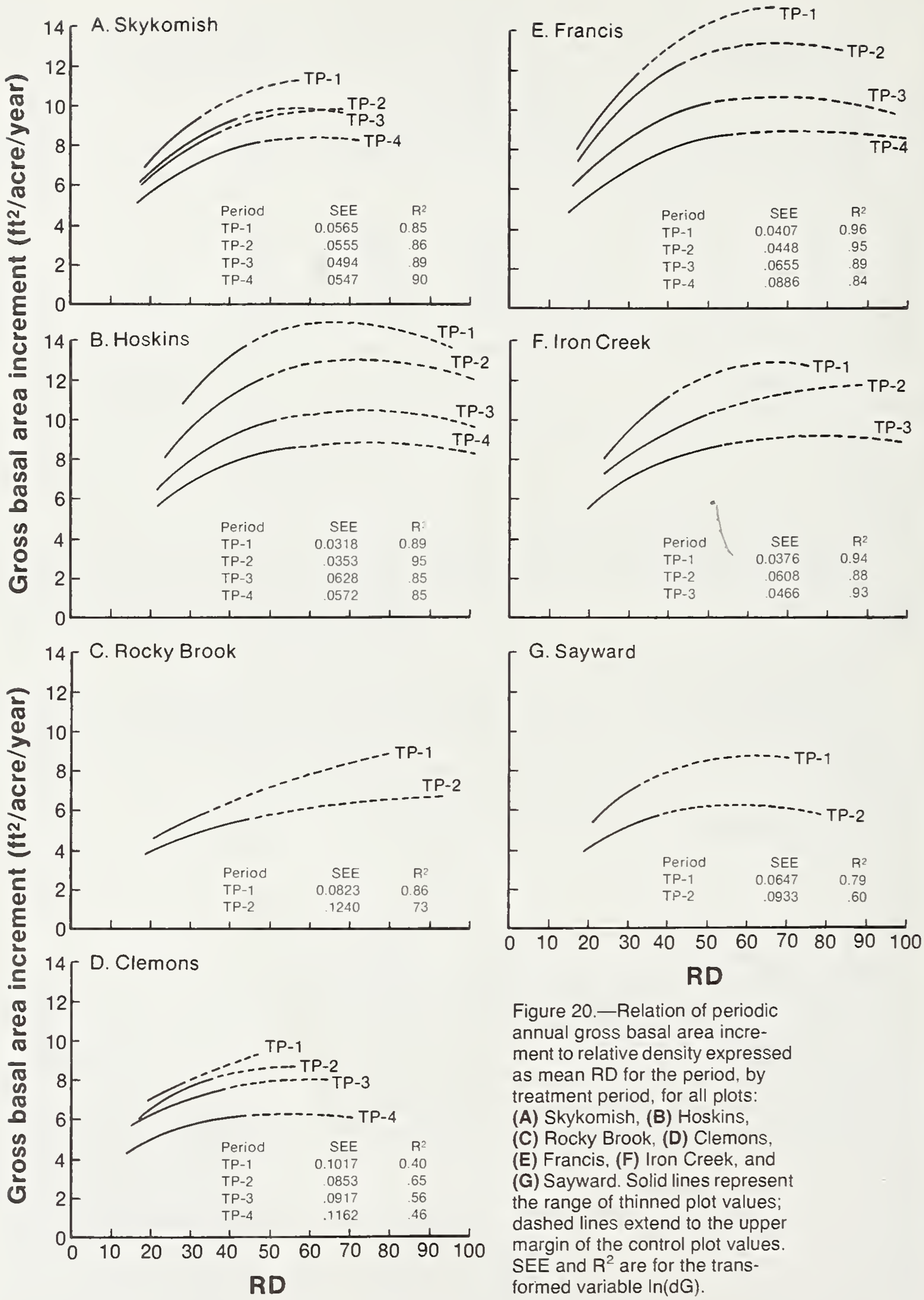


Figure 20.—Relation of periodic annual gross basal area increment to relative density expressed as mean RD for the period, by treatment period, for all plots: **(A)** Skykomish, **(B)** Hoskins, **(C)** Rocky Brook, **(D)** Clemons, **(E)** Francis, **(F)** Iron Creek, and **(G)** Sayward. Solid lines represent the range of thinned plot values; dashed lines extend to the upper margin of the control plot values. SEE and R^2 are for the transformed variable ln(dG).

Table 17—Comparison of residual mean squares for period regressions of the form, lnG = blnRD + cRD

Study	Treatment period	Degrees of freedom	Residual mean square	Significance 1/ of differences in mean squares between period	Pooled mean square, all periods
Skykomish	1	25	0.003197	Not significant	0.002926
	2	25	.003076		
	3	25	.002444		
	4	25	.002988		
Hoskins	1	24	.001011	$p < 0.01$	.002306
	2	24	.001246		
	3	2/ 23	.003936		
	4	24	.003274		
Rocky Brook	1	24	.006781	$p < 0.05$	.011083
	2	24	.015385		
Clemons	1	24	.010354	Not significant	.009886
	2	24	.007272		
	3	24	.008405		
	4	24	.013508		
Francis	1	24	.001656	$p < 0.01$	.003950
	2	24	.002008		
	3	24	.004291		
	4	24	.007844		
Iron Creek	1	24	.001407	Not significant	.002427
	2	24	.003704		
	3	24	.002170		
Sayward	1	24	.004182	Not significant	.006444
	2	24	.008708		

1/ F-test if number of periods is 2, Bartlett's test otherwise (Snedecor and Cochran 1980, p. 252).

2/ One highly aberrant plot value deleted.

The curves corresponding to these period regressions show a regular progression over time, with the one exception of treatment periods 2 and 3 at Skykomish. The sequence of curves for any one installation could be readily expressed as a function either of RD and H40 or of RD and age.

These curves show a general similarity, which strongly suggests that the family of curves representing any one installation could be represented by a system of proportional curves; that is, on logarithmic axes, by parallel curves differing only in elevation. This suggests that the family of curves can be represented by a general equation of the form:

$$\ln dG = a_1 + a_2P_2 + \ldots\ldots + a_iP_i + b\ln RD + cRD\ ;$$

where the P_i are dummy variables representing successive periods, and values of b and c are the same for all periods within an installation.

Installation regressions with common slopes.—Regressions of the above form were fitted to the pooled data for each installation. The hypothesis of common values of b and c for all periods was tested as shown in table 18. The F-test was nonsignificant in all cases. There is no evidence against the hypothesis that periods within each installation can be satisfactorily represented by proportional curves. On logarithmic scales, any additional terms expressing the effects of height or age would be additive.

Table 18—Test of hypothesis of common slopes b and c, by installation, in regressions, lndG = a + b lnRD + cRD

Study	Period regressions		One regression, common slopes		Due to separate slopes			Regression with common slopes
	SS 1/	df 2/	SS 1/	df 2/	SS 1/	df 2/	F-test 3/	SEE_{lndV} 4/
Skykomish	0.2926	100	0.2997	106	0.0071	6	0.40 ns 5/	0.0532
Hoskins	.2234	95	.2335	101	.0101	6	.72 ns	.0481
Rocky Brook	.5320	48	.5535	50	.0215	2	.97 ns	.1052
Clemons	.9489	96	.9667	102	.0178	6	.30 ns	.0974
Francis	.3792	96	.4046	102	.0254	6	1.07 ns	.0630
Iron Creek	.1748	72	.1989	76	.0241	4	2.49 ns	.0512
Sayward	.3094	48	.3246	50	.0152	2	1.18 ns	.0806

1/ SS = sum of squares.

2/ df = degrees of freedom.

3/ $F = \frac{(SS,\ separate\ slopes)/(df,\ separate\ slopes)}{(SS,\ period\ regressions)/(df,\ periods)} = \frac{MS,\ separate\ slopes}{MS,\ period\ regressions}$.

4/ SEE_{lndB} = standard error of estimate of lndG.

5/ ns = $p > 0.05$.

Comparisons among installation regressions.—Given these installation regressions of the form:

$$\ln dG = a + b\ln RD + cRD \ ;$$

in which a is a function of period, shapes of the installation curves can be graphically compared by adjusting the value of a so that all curves pass through a common point. This is done in figure 21 using an RD value of 50 (RD50 in the notation used hereafter) as the reference point. Each curve corresponds to an equation:

$$\ln Y = a \quad + b\ln RD + cRD \ ;$$

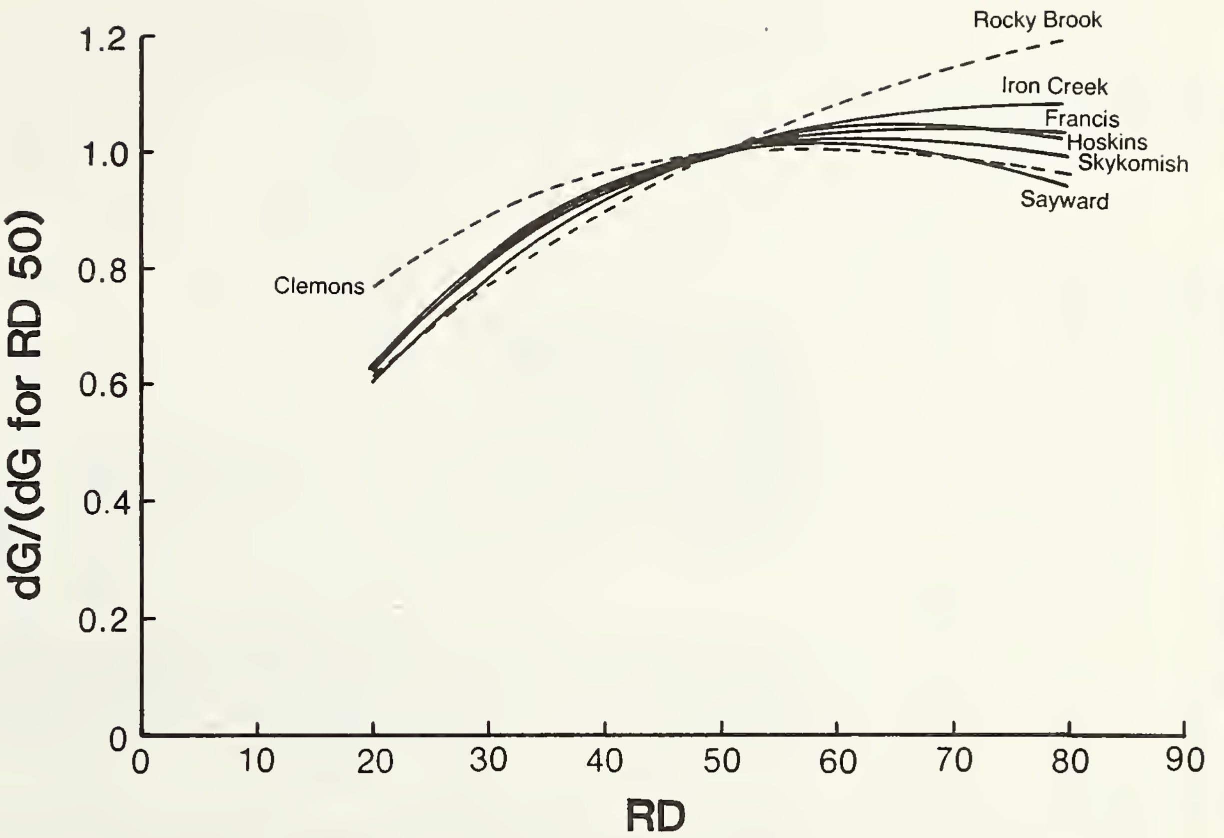
in which b and c are the estimates of common coefficients previously obtained and:

$$a \quad = \ln(1.0) - b\ln(50) - c(50) \ .$$

Y is then the ratio of estimated basal area growth rate to the rate expected when RD is 50. RD50 was chosen as the reference point because this is about the upper margin of the range in midperiod RD now present in the thinned plots. Beyond this, curves are determined by the control plots, which are more variable and differ considerably in characteristics among installations.

Figure 21 shows that these curves are very similar in shape within the range of RD of practical concern in thinning; that is, RD20 to RD60. The major exceptions are the Clemons study and, to a lesser extent, Rocky Brook. There are only two treatment periods available for Rocky Brook and as yet the thinned plots represent only a narrow range of densities; therefore, the shape of the curve is not well determined. Clemons appears distinctly different; one more of several indications that the Clemons study differs from others in some undetermined way.

Figure 21.—Comparison of shapes of installation curves ($\ln dG = a_i + b \ln RD + cRD$) fitted with common slopes for all periods within a single installation. Estimates expressed as ratios of estimated dG to expected dG for RD50.



A single regression for combined data.—A single regression with common b and c coefficients and with periods represented by dummy variables was fitted to all data exclusive of the Clemons and Rocky Brook studies. Standard error of estimate was 0.0592. The dashed line in figure 22 is derived from this regression, and has the equation:

$$Y = EXP[-3.11426 + 0.96139(\ln RD) - 0.013860(RD)] ;$$

where:

$$Y = dG/(dG_{est} \text{ for RD70}) .$$

Because variances are not homogeneous, significance of differences among individual installation curves cannot be tested. It seems clear, however, that this is a good average of the individual installation curves.

The solid line in figure 22 represents a similar curve derived from a regression fitted to all data, including Clemons and Rocky Brook. Although the Clemons and Rocky Brook curves diverge from the others and the differences for Clemons are probably real, inclusion of the additional data alters shape and position of the average curve only slightly, while it increases the standard error of estimate to 0.0791.

The solid curve in figure 22 has the equation:

$$Y = EXP[-2.71189 + 0.81768(\ln RD) - 0.010886(RD)] .$$

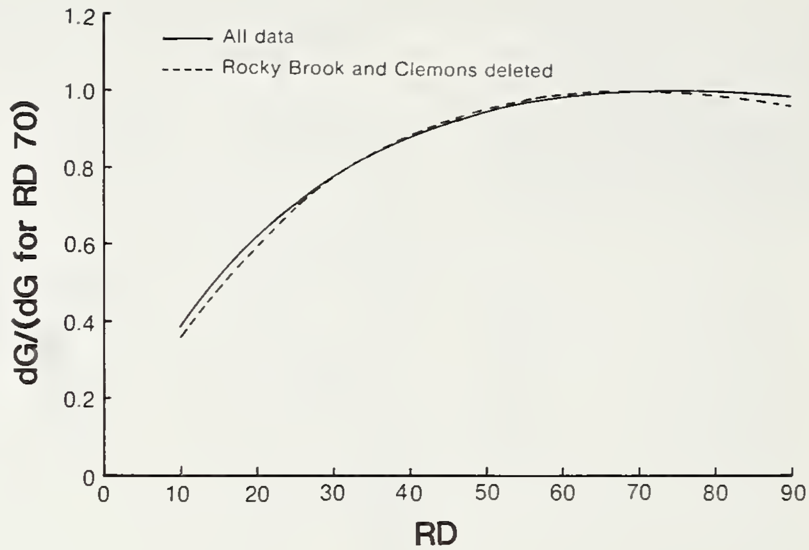


Figure 22.—Ratio of estimated dG to expected dG for RD70, based on the regression ($\ln dG = a_i + b \ln RD + cRD$) fitted to combined data under the assumption of common b and c coefficients for all installations and periods.

RD70 is used as the reference point in figure 22 rather than the RD50 from the preceding section, because RD70 corresponds to "normal" in the DFSIM yield tables (Curtis and others 1981). Those accustomed to thinking in terms of normality can convert the RD scale to a normality ratio by dividing by 70.

Because little mortality occurs below RD values of about 60, there is little difference between gross and net increment rates within the density range of concern in thinning.

These average curves are of interest from two standpoints: First, the curves are relatively flat topped and indicate a considerable range of densities within which there is relatively little difference in basal area growth. (This differs considerably from the behavior of volume increment, as will be shown later.) Second, for plots comparable in other respects, the average curves provide an estimate of the relative rates of basal area growth associated with different levels of stocking, as expressed by RD.

Volume Growth

Volume increment as a function of volume.—The equation:

$$\ln y = a + b \ln x + cx ;$$

previously used to express gross basal area increment as a function of basal area, also provided a satisfactory expression of the relationship between gross volume increment and volume of growing stock.

Curves corresponding to period regressions are shown in figure 23; standard errors of estimate are given in table 19 for comparison with alternate regressions. These standard errors of estimate are generally lower than are those obtained using alternate measures of growing stock or stand density. Trends over time, within an installation, resemble those for basal area growth. Slopes relative to growing stock are steeper, with growth increasing with growing stock to—in most cases—the upper limits of the data. The sequence of curves over time is somewhat less regular than for basal area. In particular, the curve for treatment period 3 at Hoskins is obviously inconsistent with the other curves for this installation; this suggests possible errors in the height estimates for this 2-year period.

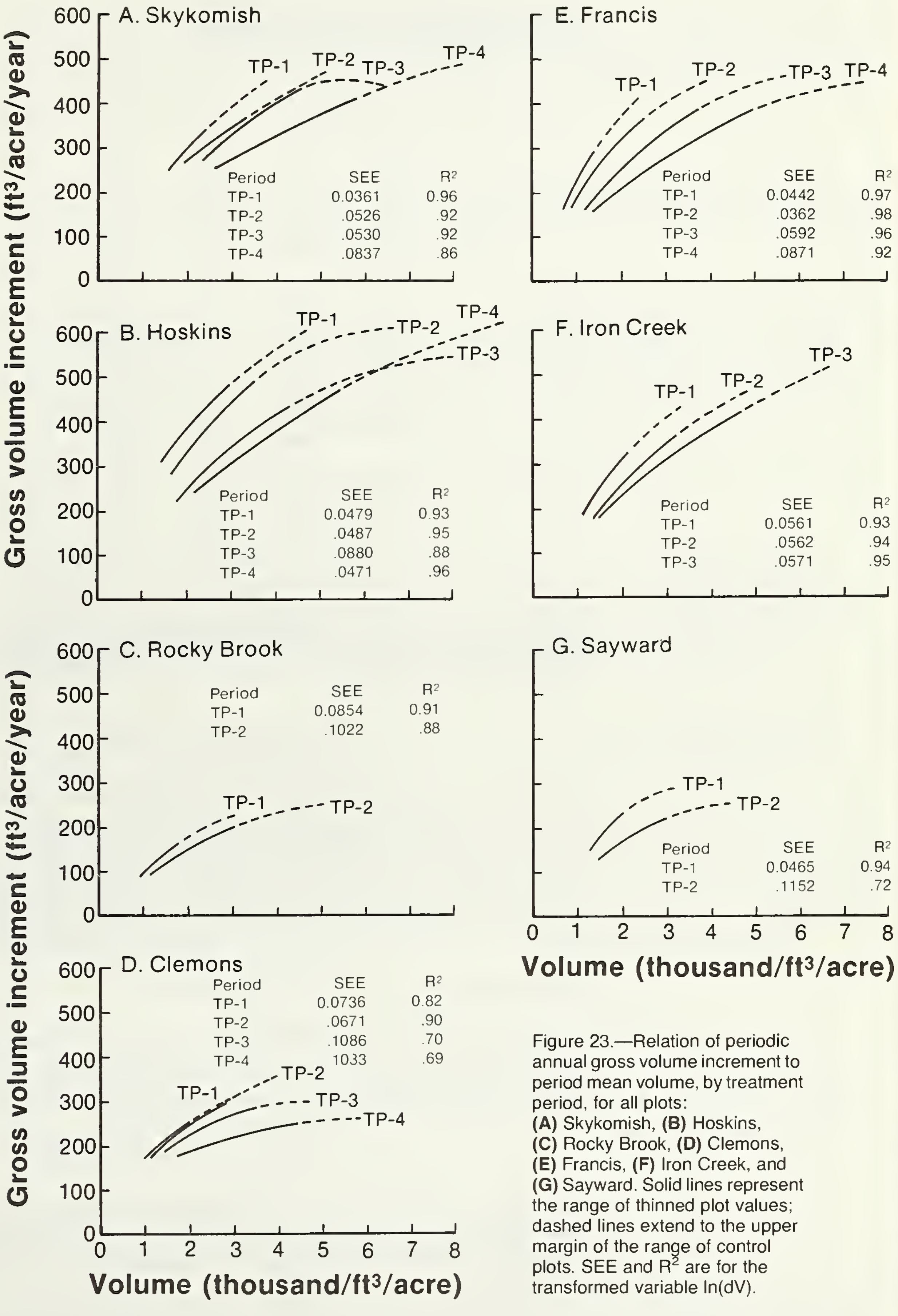


Figure 23.—Relation of periodic annual gross volume increment to period mean volume, by treatment period, for all plots: **(A)** Skykomish, **(B)** Hoskins, **(C)** Rocky Brook, **(D)** Clemons, **(E)** Francis, **(F)** Iron Creek, and **(G)** Sayward. Solid lines represent the range of thinned plot values; dashed lines extend to the upper margin of the range of control plots. SEE and R^2 are for the transformed variable ln(dV).

Table 19—Standard errors of estimate of some regressions, lndV = f(x_i), by periods

Study	Period	lndV = a+blnV+cV	lndV = a+blnG+cG	lndV = a+blnRO+cRO	lndV = a+blnRO+RO+ln(Hi/Hm)
Skykomish	1	0.0361	0.0434	0.0518	0.0417
	2	.0526	.0534	.0604	.0554
	3	.0530	.0475	.0457	.0456
	4	.0837	.0869	.0801	.0819
Hoskins	1	.0479	.0497	.0565	.0497
	2	.0487	.0522	.0603	.0533
	3	.0880	.0956	.1019	.0946
	4	.0471	.0438	.0434	.0440
Rocky Brook	1	.0854	.1489	.1705	.1146
	2	.1022	.1565	.1803	.1391
Clemons	1	.0736	.0845	.1017	.1011
	2	.0671	.0794	.0939	.0934
	3	.1086	.1165	.1240	.1247
	4	.1033	.0983	.1030	.1042
Francis	1	.0442	.0608	.0729	.0483
	2	.0365	.0540	.0730	.0597
	3	.0592	.0626	.0650	.0650
	4	.0871	.0810	.0775	.0778
Iron Creek	1	.0561	.0852	.0952	.0657
	2	.0562	.0597	.0716	.0605
	3	.0571	.0695	.0792	.0754
Sayward	1	.0465	.0648	.0862	.0566
	2	.1152	.1354	.1488	.1188

Volume increment as a function of basal area.—Periodic annual increments in gross volume (dV) were plotted against mean period basal areas, by periods. Corresponding regressions of the form:

$$\ln dV = a + b \ln G + cG ;$$

were fitted. There was generally a well-defined relationship within periods, although standard errors of estimate were larger for these regressions than for regressions using volume as the independent variable (table 19). The period curves (not shown) appeared more or less parallel within each installation. In a general way, curve elevations tended to decrease over time, although this trend was much more irregular than for the curves of basal area growth over basal area and of volume growth over volume.

Volume increment as a function of RD.—

Data plots and period regressions.—When volume growth was plotted over RD, the scatter diagrams (not shown) resembled those for dV over G, except for lateral shifts in position produced by the transformation of the horizontal axis. Regressions of the form:

$$\ln dV = a + b \ln RD + cRD ;$$

were fitted. In most cases standard errors of estimate (table 19) were slightly larger than those for the corresponding regressions that used basal area as the independent variable; this was markedly so for Sayward, Clemons, and Rocky Brook.

Differences in height among plots, which are associated with differences in site among plots, could have some effect on both the $dV = f(G)$ and the $dV = f(RD)$ relationships, and could contribute to unexplained variation. The $dV = f(RD)$ relationship may also be influenced through the probable association of height differences with differences in the diameter used as the divisor in RD.

An additional independent variable, $\ln(Hi/Hm)$, was included in the regressions to remove possible effects of plot differences in H40. Hi was individual plot estimated H40, and Hm was the installation mean of such estimates. For the average condition in an installation, the term, $\ln(Hi/Hm)$, becomes zero.

The resulting curves (fig. 24) were nearly identical with those previously obtained, but there was a marked reduction in standard errors of estimate, especially for Sayward and Rocky Brook (table 19). Estimates were not improved for Clemons; this may reflect the small height samples in this study, which required that height samples be pooled for all plots in a given treatment, and probably results in poor estimates of individual plot H40.

Very similar standard errors of estimate were obtained in parallel sets of regressions (not shown), which used basal area in combination with $\ln(Hi/Hm)$.

Comparison of variances.—Residual mean squares from the regressions, $\ln dV = a + b\ln RD + cRD + d\ln(Hi/Hm)$, were tested for homogeneity, within installations. Differences among period mean squares were significant for Sayward, Hoskins, and Skykomish, and nonsignificant for all other studies. Significance of differences for Hoskins is a result of treatment period 3; for Skykomish, treatment period 4.

Period residual sums of squares were then pooled to calculate installation mean squares. Differences among installations were highly significant. Rocky Brook and Clemons in particular had much higher variances than did other installations.

Installation regressions with common slopes.—Comparison of the curves, $dV = f(G)$, with corresponding curves, $dV = f(RD)$, for successive periods within installations suggested that the change to the variable RD tended to (1) shift curves into a more nearly coincident position, and (2) produce curves that appeared more nearly proportional to each other. This suggested that, as with basal area growth, the curves corresponding to the regressions:

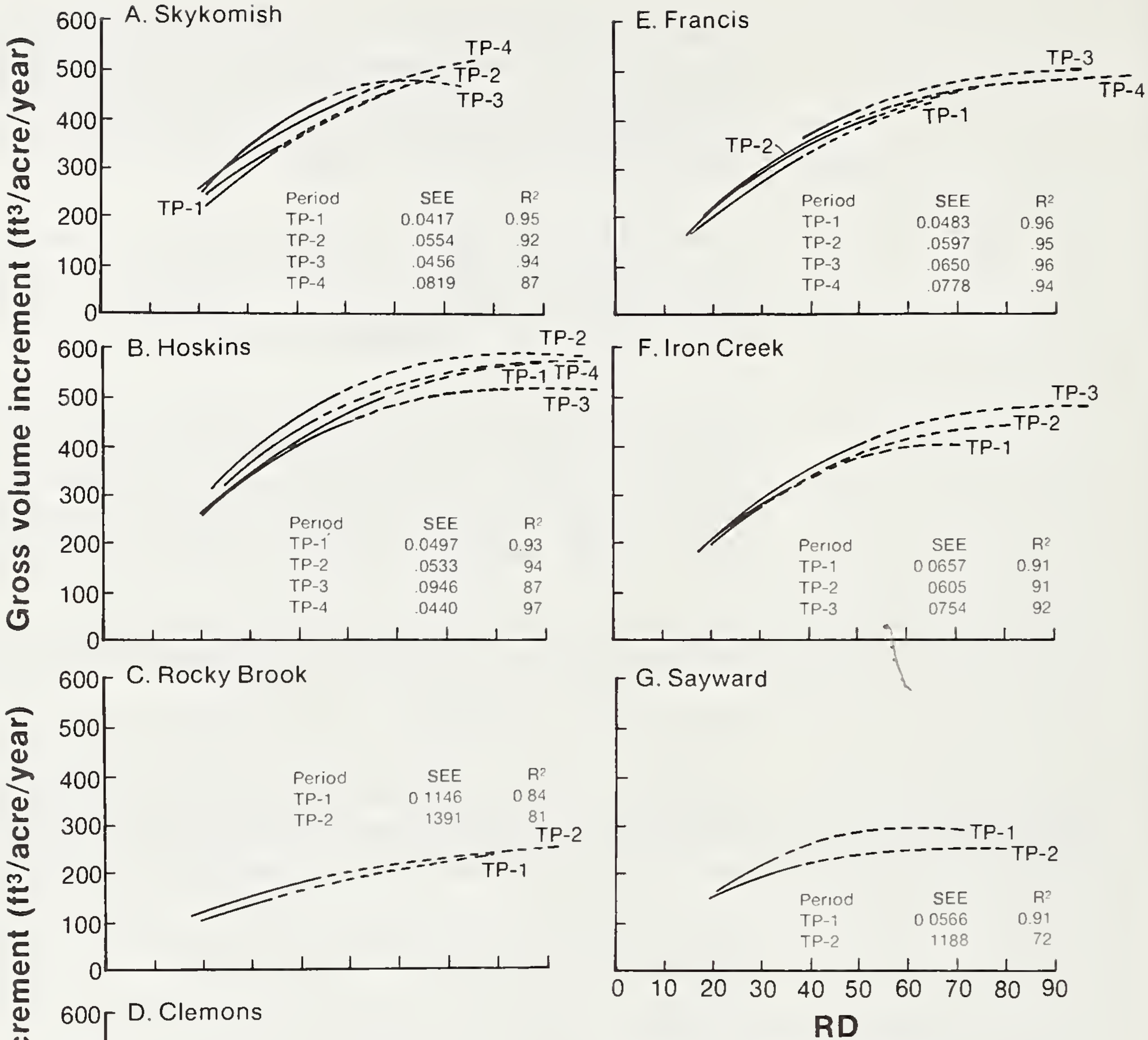
$$\ln dV = a + b \ln RD + cRD + d\ln(Hi/Hm) ;$$

can be regarded as a series of proportional curves, at least for the limited range of ages represented by these data. On logarithmic scales the elevation coefficient a varies among periods and among installations, while the other coefficients can be regarded as constants.

Regressions of the form:

$$\ln dV = a_1 + a_2P_2 + \ldots + a_1P_i + b\ln RD + cRD + d\ln(Hi/Hm) ;$$

were fitted to pooled data for installations. The P_i are dummy variables representing successive periods.



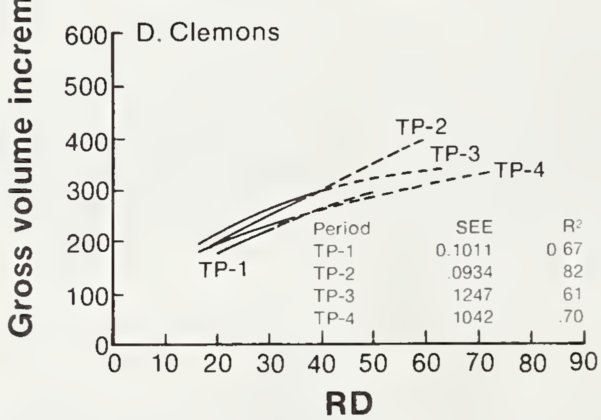


Figure 24.—Relation of periodic annual gross volume increment to relative density expressed by RD, by treatment period, for all plots: **(A)** Skykomish, **(B)** Hoskins, **(C)** Rocky Brook, **(D)** Clemons, **(E)** Francis, **(F)** Iron Creek, and **(G)** Sayward. Solid lines represent the range of thinned plot values; dashed lines extend to the upper margin of the range of control plots. SEE and R^2 are for the transformed variable ln(dV).

Table 20—Test of hypothesis of common slopes, b, c, and d, by installation, in regressions, $\ln dV = a + b\ln RD + cRD + d\ln(H_i/H_m)$

	Period regressions		One regression, common slopes		Separate slopes			Regression with common slopes
Study	SS 1/	df 2/	SS 1/	df 2/	SS 1/	df 2/	F-test 3/ 4/	$SEE_{\ln dV}$ 5/
Skykomish	0.326329	96	0.424567	105	0.098239	9	3.21 **	0.0636
Hoskins	.363544	91	.398470	100	.034926	9	.97 ns	.0631
Rocky Brook	.707564	46	.728500	49	.020933	3	.45 ns	.1219
Clemons	1.043124	92	1.164920	101	.121795	9	1.19 ns	.1074
Francis	.364075	92	.398296	101	.034221	9	.96 ns	.0628
Iron Creek	.346620	69	.378826	75	.032206	6	1.07 ns	.0711
Sayward	.396480	46	.412110	49	.015629	3	.65 ns	.0917

1/ SS = sum of squares.

2/ df = degrees of freedom.

3/ $F = \frac{\text{(SS, separate slopes)/(df, separate slopes)}}{\text{(SS, period regressions)/(df, periods)}} = \frac{\text{MS, separate slopes}}{\text{MS, period regressions}}$.

4/ ns = $p > 0.05$; ** = $p < 0.01$.

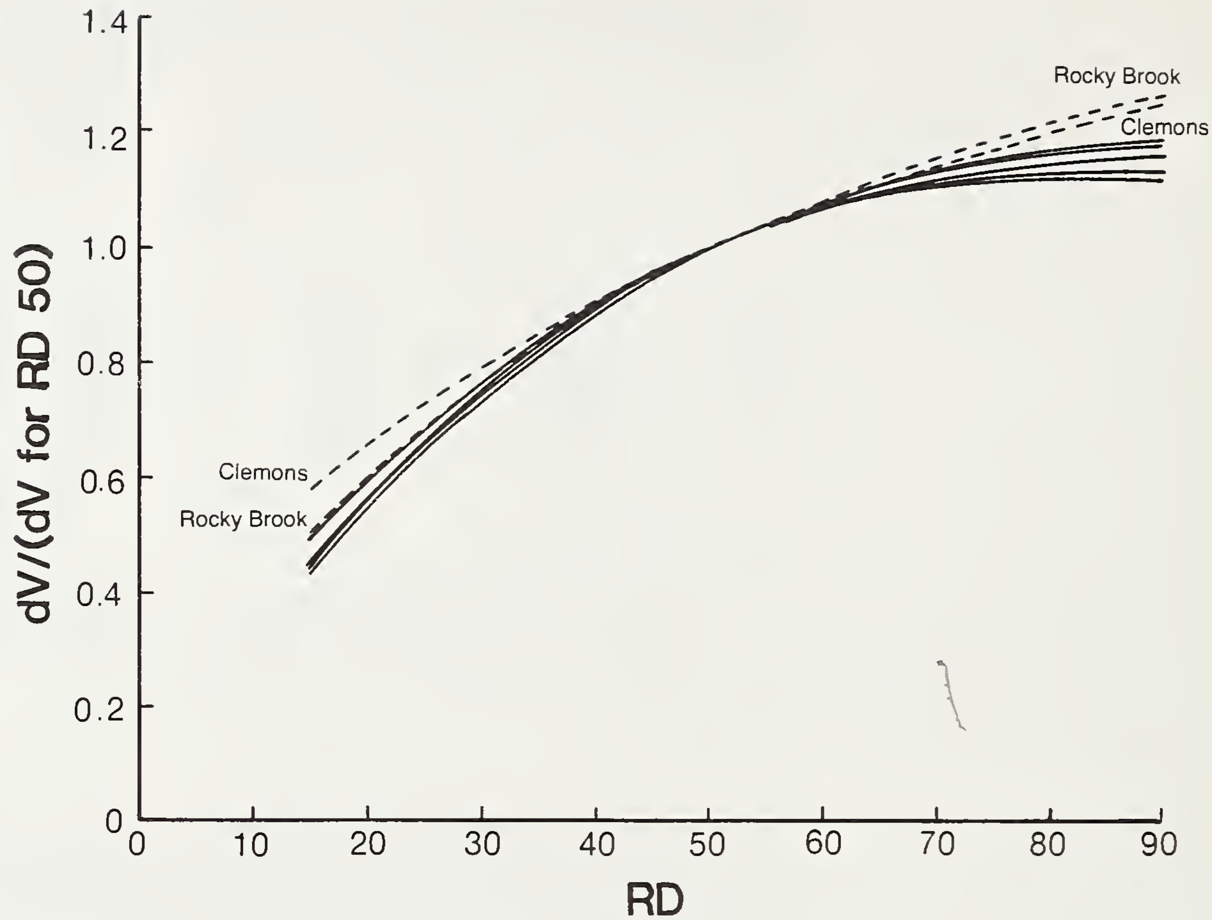
5/ $SEE_{\ln dV}$ = standard error of estimate of lndV.

The hypothesis of common slopes was tested as shown in table 20. Differences in slopes among periods within an installation were nonsignificant for all installations except Skykomish. The period curves show clearly that the significant result for Skykomish arose from treatment period 3, for which the curve is odd in both shape and elevation.

Comparisons among installation regressions.—The resulting installation regressions were transformed and graphed as shown in figure 25, in which the y-variable is ratio of predicted dV for a given RD, to the dV predicted for RD50. This transformation, which causes all curves to pass through a common point, y = 1.0 at RD50, allows a visual comparison of curve shapes. As before, the reference value RD = 50 approximates the upper margin of the range in midperiod RD now present in the thinned plot data.

Because variances were not homogeneous, differences among installation curves could not be tested statistically. It seemed clear, however, that curves for all installations except Rocky Brook and Clemons could reasonably be represented by a single curve, as done previously for basal area growth; and that even inclusion of Rocky Brook and Clemons in the calculation of such a curve would not materially alter the results.

Figure 25.—Comparison of shapes of installation curves ($\ln dV = a_i + b\ln RD + cRD + d\ln(Hi/Hm)$) fitted with common slopes for periods within a single installation. Estimates expressed as ratios of estimated dV to expected dV for RD50.



A single regression for combined data.—A regression:

$$\ln dV = a_1 + a_2P_2 \ldots + a_iP_i + b\ln RD + cRD + d\ln(Hi/Hm) \;;$$

in which the P_i represent periods, was fitted to the combined data for all installations. The resulting equation (standard error of estimate 0.0888) can be transformed and plotted as shown in figure 26, in which form the curve passes through the point y = 1.0 at RD70 (value of 70 was selected because this represents "normal," traditionally a widely used reference point). The equation corresponding to the curve in figure 26 is:

$$y = EXP(-3.029434 + 0.837763 \ln RD - 0.00756852\ RD)\,.$$

When expressed in this form, the curve provides an estimate of periodic annual increment in gross volume for a given RD, expressed as a fraction of that expected for RD70.

The corresponding, previously derived curve for basal area is shown as the dashed curve in figure 26 (for use in later comparisons).

Diameter Growth, Basal Area, and RD

Net periodic annual increment in quadratic mean diameter of all trees (dD), is the net change from the start of the period (after thinning) to the end of the period (before thinning). Change due to removal of trees is excluded, but change due to mortality is not. The latter is negligible on most thinned plots.

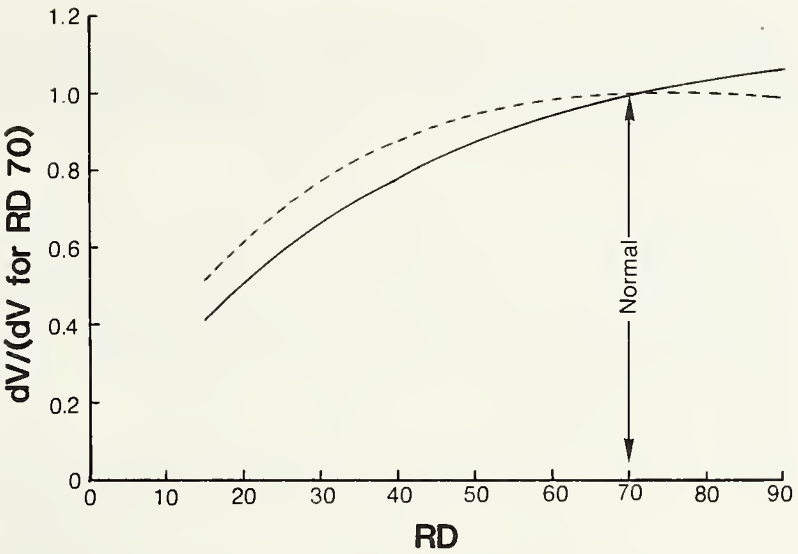


Figure 26.—Ratio of estimated periodic annual increment in gross volume (dV) to dV expected for RD70, based on the regression (lndV = a, + blnRD + cRD + dln(Hi/Hm)) fitted to combined data, assuming common slopes for all installations and periods. Dashed line represents similar curve for gross basal area increment.

Diameter increment in relation to basal area.—

Data plots.—Values of dD were plotted over period mean basal area by periods. In many but not all cases, the relationship appeared approximately linear. The curvilinearity apparent in some instances arose mainly from the control plots. The scatter diagrams (not shown) suggested that, if only thinned plots were considered, the relationship might be satisfactorily approximated by straight lines; this would be expected from the previous ANOVA results.

Period regressions.—Regressions of the form:

$$dD = a + bG + cG^2 ;$$

were fitted to all plots by periods. The squared term was significant ($p \leq 0.05$) in 7 out of 23 periods, which indicated that it should not be omitted.

The corresponding curves (not shown) gave an impression that if only thinned plots were included, relationships could be represented by a series of parallel lines. There seemed to be no consistent order of elevations by periods, however; and the portions of the curves that included the control plots were irregular in shape and position.

Diameter increment as a function of RD.—

Data plots.—Scatter diagrams of dD over RD (not shown) indicated a strongly curvilinear relationship, which was linearized by transformation of dD to lndD.

Period regressions.—An appropriate equation form appeared to be:

$$\ln dD = a + bRD + c\ln(Hi/Hm) .$$

The square of RD was significant in only 3 of 23 periods and in no more than 1 period in any one installation; it was therefore omitted. ln(Hi/Hm) was significant in 7 of 23 periods, including all periods at Sayward and Rocky Brook, and has therefore been included.

Regressions of this form were fitted for each period, and corresponding curves are shown in figure 27. As with previous curves for basal area growth and for volume growth, these curves suggest that—at least within the limited range of ages and heights represented—curves for successive periods can be regarded as proportional.

Installation regressions with common slopes.—A test of the hypothesis of common slopes (table 21) showed no significant difference among periods for six of the seven installations. The one exception was Rocky Brook, for which only two periods are available. It therefore appears that the relationships within each installation can be represented by logarithmic curves differing only in elevation (proportional curves on untransformed scales).

A single regression was fitted to all periods, within each installation, of the form:

$$\ln dD = a_1 + a_2P_2 + \dots + a_iP_i + bRD + c\ln(Hi/Hm) ;$$

in which the P_i are dummy variables representing individual periods within the installation.

Comparisons among installation regressions.—Shapes of the curves corresponding to these installation regressions are compared in figure 28, where the ordinate is the ratio of estimated dD for a given RD to the corresponding dD estimate for RD50. Shapes of installation curves appear very similar. It seems reasonable to generalize the relationship by combining these installation curves into one average curve.

A single regression for combined data.—A single regression of the same general form was fitted to all data combined, with periods and installations represented by dummy variables. The curve corresponding to this regression (standard error of estimate of regression = 0.1022), after transformation, is shown in figure 29. This is scaled relative to RD70, which—as the "normal" of Curtis and others (1981)—provides a convenient reference point. The equation of this transformed curve is:

$$y = EXP(1.46650 - 0.020950\ RD) ;$$

where:

$$y = dD/(dD_{est}\ \text{for RD70}) .$$

This curve provides an estimate of the expected diameter growth rate of such thinned stands relative to unthinned "normal" stands that are comparable in origin, age, and height. Thus, a thinned stand at an average density of RD50 is expected to grow about 50 percent faster in diameter than the normal stand; one at RD35 will grow about twice as fast as the normal stand. There must be a maximum diameter growth rate attained at very low stand densities, where trees are growing essentially without competition, and this curve (fig. 29) should not be extrapolated to densities below about RD20.

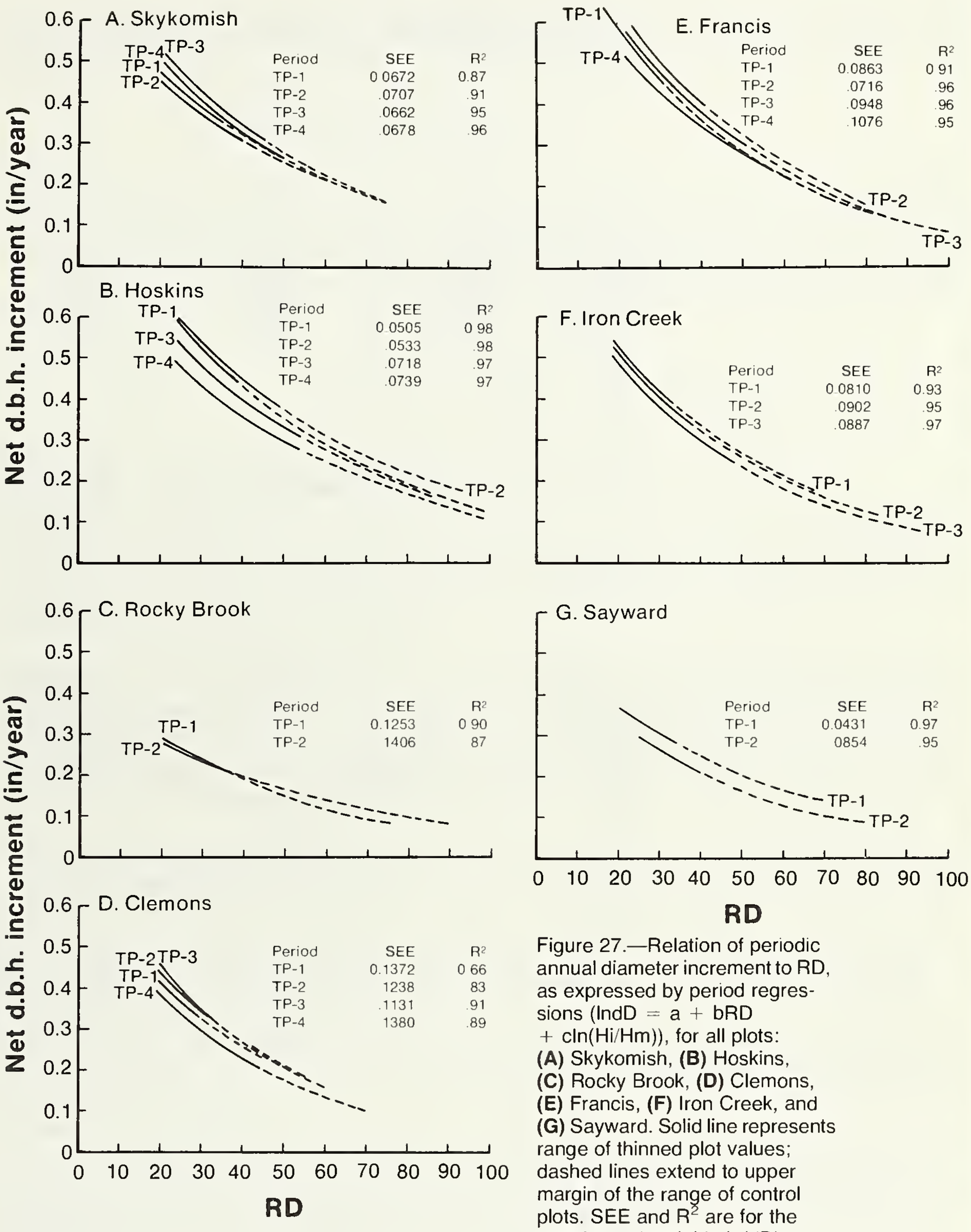


Figure 27.—Relation of periodic annual diameter increment to RD, as expressed by period regressions ($\ln dD = a + bRD + c\ln(Hi/Hm)$), for all plots: **(A)** Skykomish, **(B)** Hoskins, **(C)** Rocky Brook, **(D)** Clemons, **(E)** Francis, **(F)** Iron Creek, and **(G)** Sayward. Solid line represents range of thinned plot values; dashed lines extend to upper margin of the range of control plots. SEE and R^2 are for the transformed variable ln(dD).

Table 21—Test of hypothesis of common slopes, b and c, by installation, in regressions, lndD = a + bRD + cln(Hi/Hm)

	Period regressions		One regression, common slopes		Separate slope			Regression with common slopes
Study	SS 1/	df 2/	SS 1/	df 2/	SS 1/	df 2/	F-test 3/ 4/	SEE_{lndD}
Skykomish	0.462413	100	0.501773	106	0.039356	6	1.4 ns	0.0688
Hoskins	.379595	95	.396767	101	.017172	6	.7 ns	.0627
Rocky Brook	.851142	48	1.076919	50	.225776	2	6.4 **	.1468
Clemons	1.582961	96	1.645569	102	.062608	6	.6 ns	.1270
Francis	.795141	96	.841666	102	.046525	6	.9 ns	.0908
Iron Creek	.541484	72	.582634	76	.041151	4	1.4 ns	.0876
Sayward	.219347	48	.241476	50	.022129	2	2.4 ns	.0695

1/ SS = sum of squares.

2/ df = degrees of freedom.

3/ $F = \frac{(SS,\ separate\ slopes)/(df,\ separate\ slopes)}{(SS,\ period\ regressions)/(d.f.,\ periods)} = \frac{MS,\ separate\ slopes}{MS,\ period\ regressions}$.

4/ ns = $p > 0.05$; ** = $p < 0.01$.

5/ SEE_{lndD} = standard error of lndD.

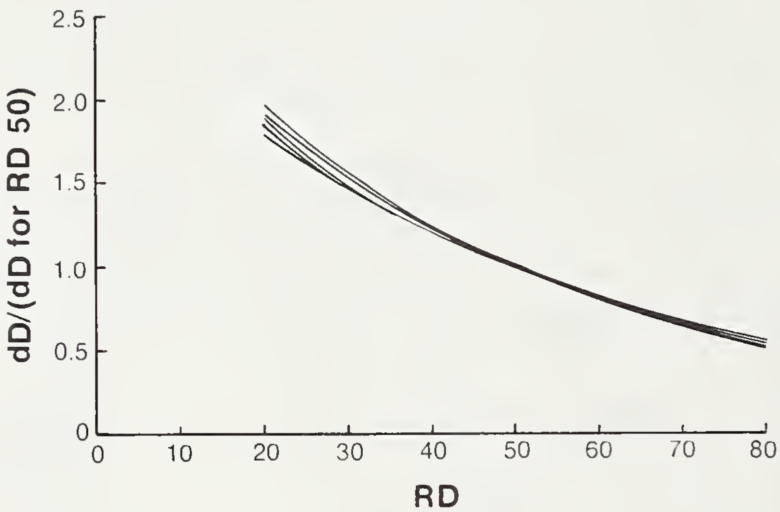


Figure 28.—Comparison of shapes of installation curves ($\ln dD = a_i + bRD + c\ln(Hi/Hm)$) fitted with common slopes for all periods within a single installation. Estimates expressed as ratios of estimated dD to expected dD for RD50.

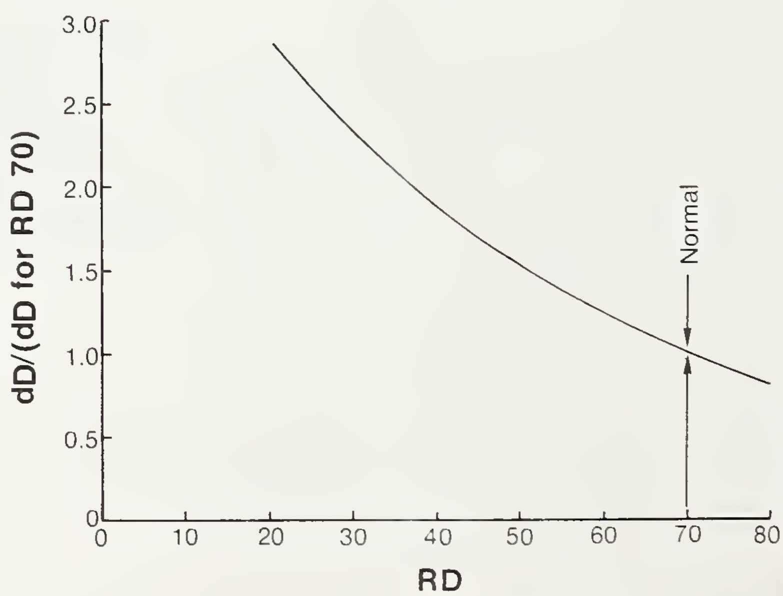


Figure 29.—Ratio of estimated periodic annual increment in diameter (dD) to expected dD for RD70, based on the regression ($\ln dD = a_i + bRD + c\ln(Hi/Hm)$) fitted to combined data assuming common slopes for all installations and periods.

Growth, Height, and Height Increment

It has been shown that growth for individual periods can be expressed as functions of growing stock:

$$\ln dV = a + b\ln V + cV, \text{ and}$$
$$\ln dG = a + b\ln G + cG.$$

Within any given installation, these curves form a progression over time (and height) that could be represented by similar functions in which the coefficients are functions of height. It seemed plausible that a common relationship, allowing generalization across installations and sites, might be obtained by expressing growth as increment per unit of height growth, rather than per unit of time; that is:

$$\ln(dV/dH) = a + b\ln V + cV, \text{ and}$$
$$\ln(dG/dH) = a + b\ln G + cG;$$

where one or more of the coefficients, a, b, or c, are functions of height.

Estimates of individual plot dH were clearly too erratic to be useful. In the following comparisons we used smoothed estimates, obtained by differentiating equations $H = a + b(\text{Age}) + c(\text{Age})^2$, which had been fitted to means of H40 and age for successive periods, separately for each installation.

Regressions having ln(dV/dH) and ln(dG/dH) as dependent variables and with coefficients expressed as functions of H40, were fitted to the combined measurements for (1) the five site II installations; (2) Skykomish, Hoskins, Francis, and Iron Creek only; and (3) all seven installations. Resulting estimates were graphed in the same manner as the previous regressions for individual periods.

Comparisons with the individual period curves (figs. 19 and 23) for volume growth and for basal area growth showed that:

1. Regressions fitted to combined data for the five site II installations provided a good representation for Skykomish, Hoskins, Francis, and Iron Creek. Growth rates were seriously overestimated for Clemons.
2. Regressions fitted to the four site II installations other than Clemons provided an excellent approximation to the individual period curves for these installations, aside from occasional anomalies in individual period curves (which could not be well represented by any overall equation).
3. When regressions were fitted to combined data for all seven installations, the Rocky Brook and Sayward data, as well as those for Clemons, differed considerably from estimates. There were, however, only two treatment periods available at Rocky Brook and Sayward, a very weak basis for conclusions.

This approach seems attractive as a possible means of generalizing results and is well suited to future applications of growth functions. Results of these trials are inconclusive. The procedure worked well for four of five site II installations. Although it did not work well for Clemons, other analyses also indicate that Clemons is in some way different. There are too little data now available from the poorer sites to draw any conclusion about the applicability of the procedure across a range of sites. This approach should be further examined when more data are available from the installations on the poorer sites.

Comparisons of Diameter Growth by Stand Components

It has been shown previously that increment in quadratic mean diameter of all trees is strongly related to growing stock (treatment). Because those treatments with higher stocking levels also retain more of the initially smaller trees, one may ask whether effects of treatment and stocking level on growth of a fixed number of largest trees, or on growth of crop trees, are similar to the effects on growth of all trees.

Comparisons in this section are limited to the four installations for which data are available through the fourth treatment period—Skykomish, Hoskins, Clemons, and Francis.

Periodic diameter increments of the largest 40 trees per acre, of crop trees, and of all trees, were summed over all periods (calibration plus four treatment periods) to give the results shown in figure 30. This computation excludes changes in average diameter caused by removal of small trees in thinning and is not the same as the difference between average diameters of the specified grouping of trees at the beginning of the calibration period and the end of the fourth treatment period. The diameter increments shown represent real growth, except for changes caused by mortality (negligible except for the "all trees" component in the controls).

Figure 30 shows generally consistent trends across treatments. In the fixed percentage treatments, the general ranking is 1 is greater than 3 is greater than 5 is greater than 7; in the increasing percentage treatments, 2 is greater than 4; in the decreasing percentage treatments, 6 is greater than 8. Trends for all three stand components appear similar. Results for Skykomish are inconsistent with the other three installations in that the positions of treatment 7 vs. 5 and of 4 vs. 2 are reversed. Differences among treatments are also less than in the other three installations. The explanation is unknown, although difference in species composition is a possible factor.

Because treatments 1 through 8 are identical through the calibration period and differences in growing stock develop gradually thereafter, differences in diameter growth are small at first and increase in later periods. Figure 31 shows diameter growth during the fourth treatment period for the largest 40 trees per acre, for crop trees, and for all surviving trees. Differences are much more striking than in the cumulative totals of the previous figures, and the ranking of treatments at Skykomish is consistent with the other installations even though differences are less. It is apparent that differences among treatments are increasing rapidly as the stands develop, and that even the largest trees are being strongly influenced by thinning treatments.

Comparisons of Yields

We made graphic comparisons of treatment means among installations and treatments. Rocky Brook and Sayward were omitted because these studies are not yet far enough into the thinning sequence to provide results that can be readily compared with those from the more advanced studies. Although Iron Creek was included, this study extends only through the third treatment period; data through the fourth treatment period were available for the other four studies.

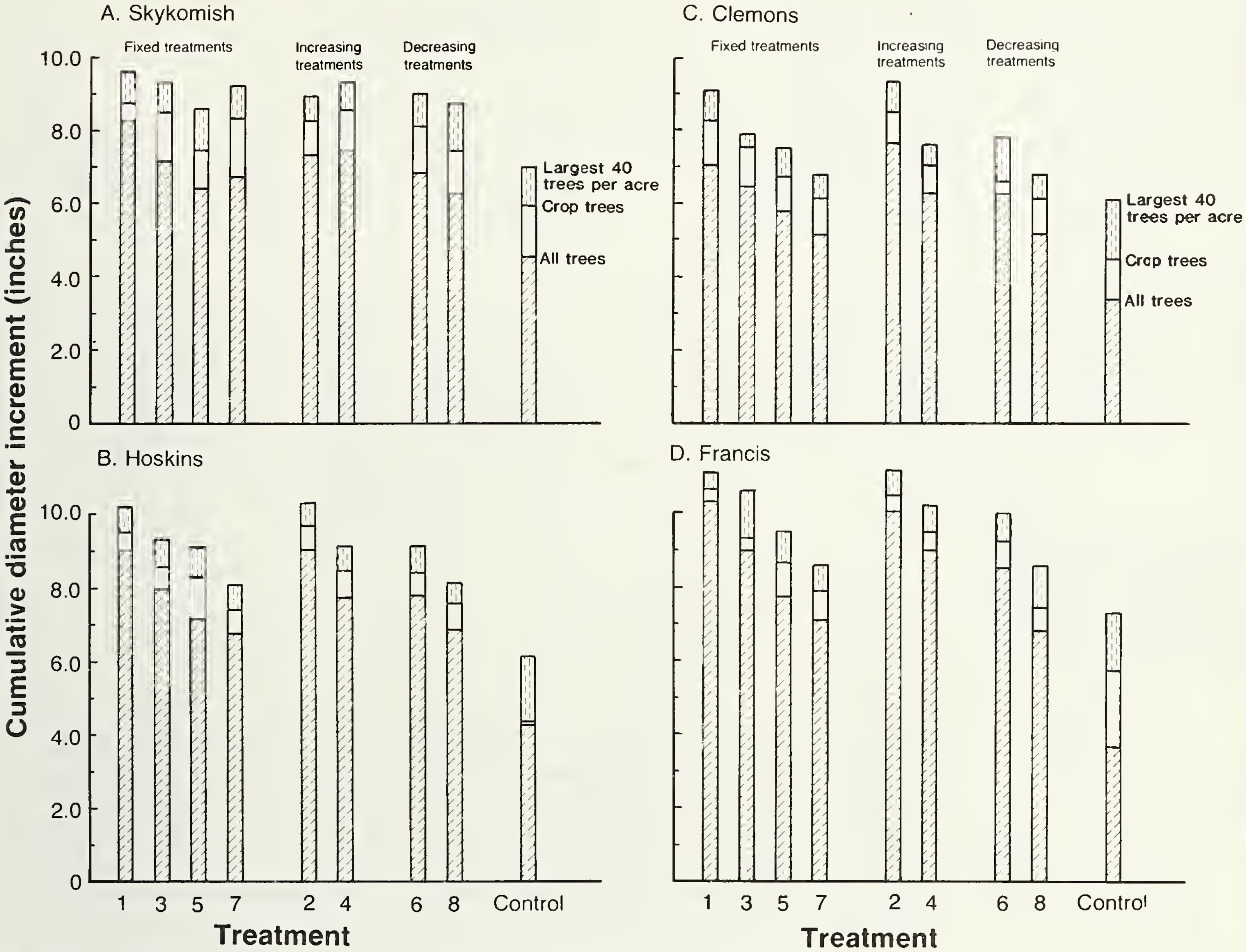


Figure 30.—Cumulative diameter increment, from study establishment to end of fourth treatment period, of largest 40 trees per acre, crop trees, and all trees, by treatment: **(A)** Skykomish, **(B)** Hoskins, **(C)** Clemons, and **(D)** Francis.

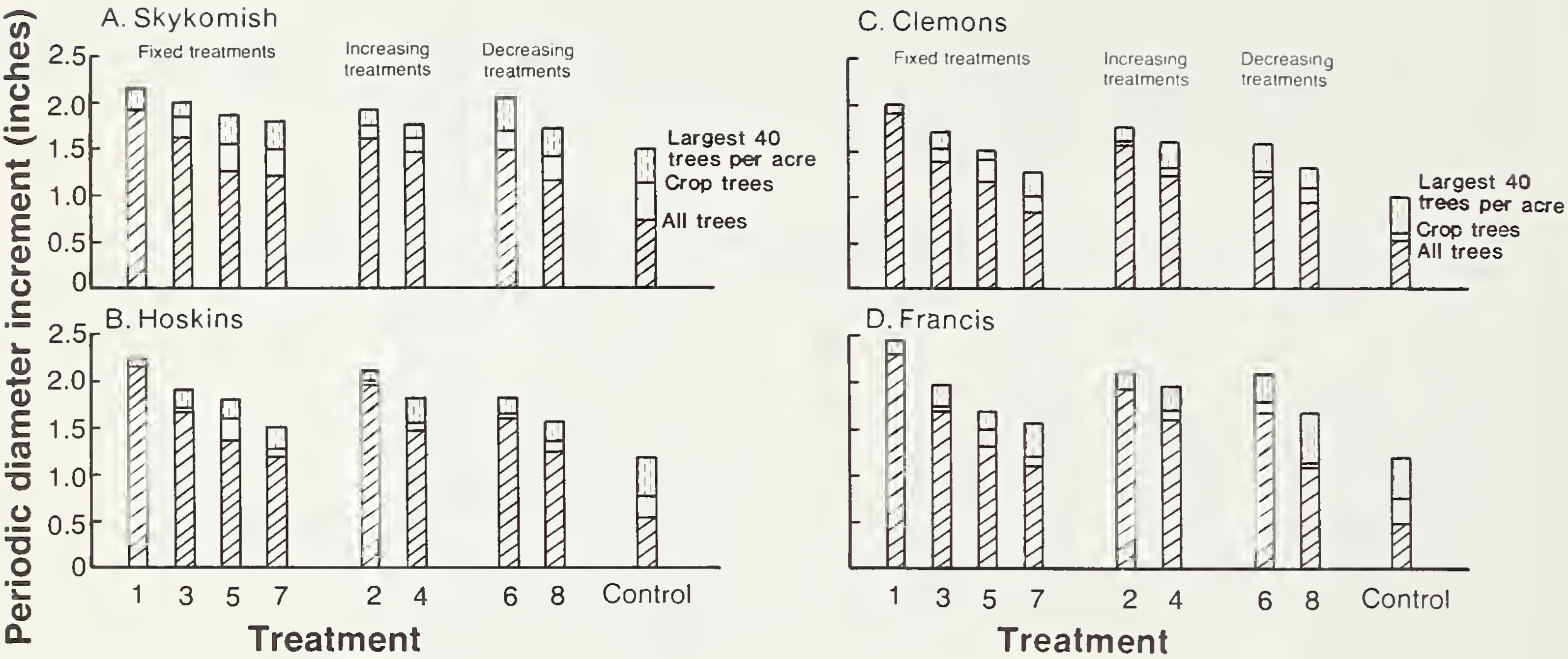


Figure 31.—Periodic diameter increment of the largest 40 trees per acre, crop trees, and all surviving trees, for fourth treatment period: **(A)** Skykomish, **(B)** Hoskins, **(C)** Clemons, and **(D)** Francis.

Gross volume yields.— Gross cubic volume yields (including mortality) for all trees 1.6 inches d.b.h. and larger are given in table 46 (appendix). Material removed in the calibration cut has been omitted. Relation of these gross yields to attained H40 is shown in figure 32 for the fixed treatments (1, 3, 5, and 7). Trends are generally similar among installations, with gross yields by treatments diverging sharply in the later treatment periods. Clemons differs from the other installations in that gross yields for a given H40 are lower, and differences in gross yield among thinning treatments are smaller, both absolutely and relatively, and not entirely consistent.

Quadratic mean diameters.—Quadratic mean diameters (values after thinning) are shown in table 47(appendix), by installation age, H40, and thinning regime. The relation of these values to H40 is shown for the fixed treatments (1, 3, 5, and 7) in figure 33. Again there are clearly defined differences among treatments; these differences increase sharply in the third and fourth treatment periods. Attained diameters for a given H40 and treatment are considerably less at Clemons than in the other installations. The crossing of trends for treatments 5 and 7 at Skykomish is probably associated with variations in species composition. Skykomish has a high percentage of hemlock, which is smaller in average diameter than the Douglas-fir component (table 47, appendix).

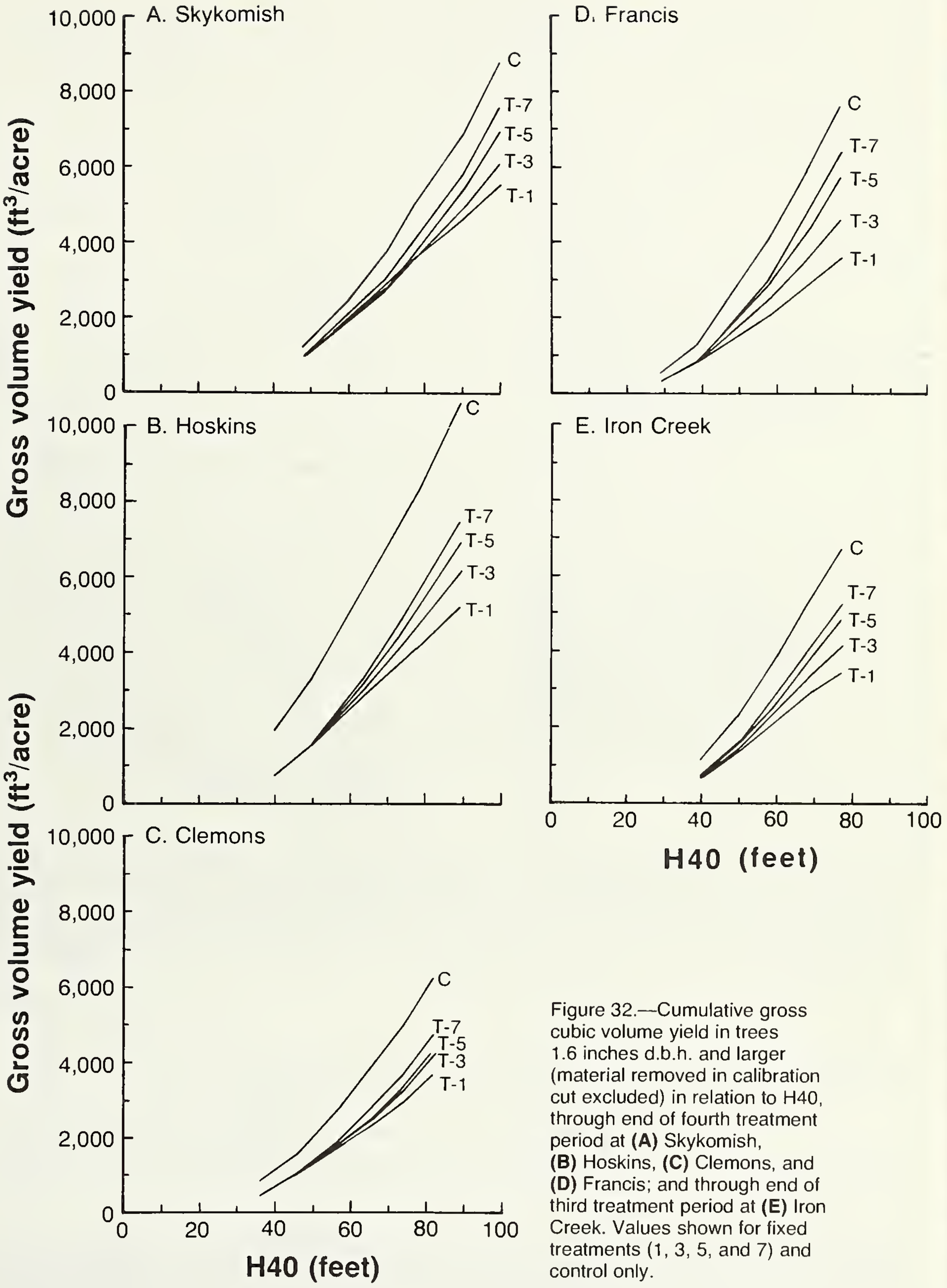


Figure 32.—Cumulative gross cubic volume yield in trees 1.6 inches d.b.h. and larger (material removed in calibration cut excluded) in relation to H40, through end of fourth treatment period at **(A)** Skykomish, **(B)** Hoskins, **(C)** Clemons, and **(D)** Francis; and through end of third treatment period at **(E)** Iron Creek. Values shown for fixed treatments (1, 3, 5, and 7) and control only.

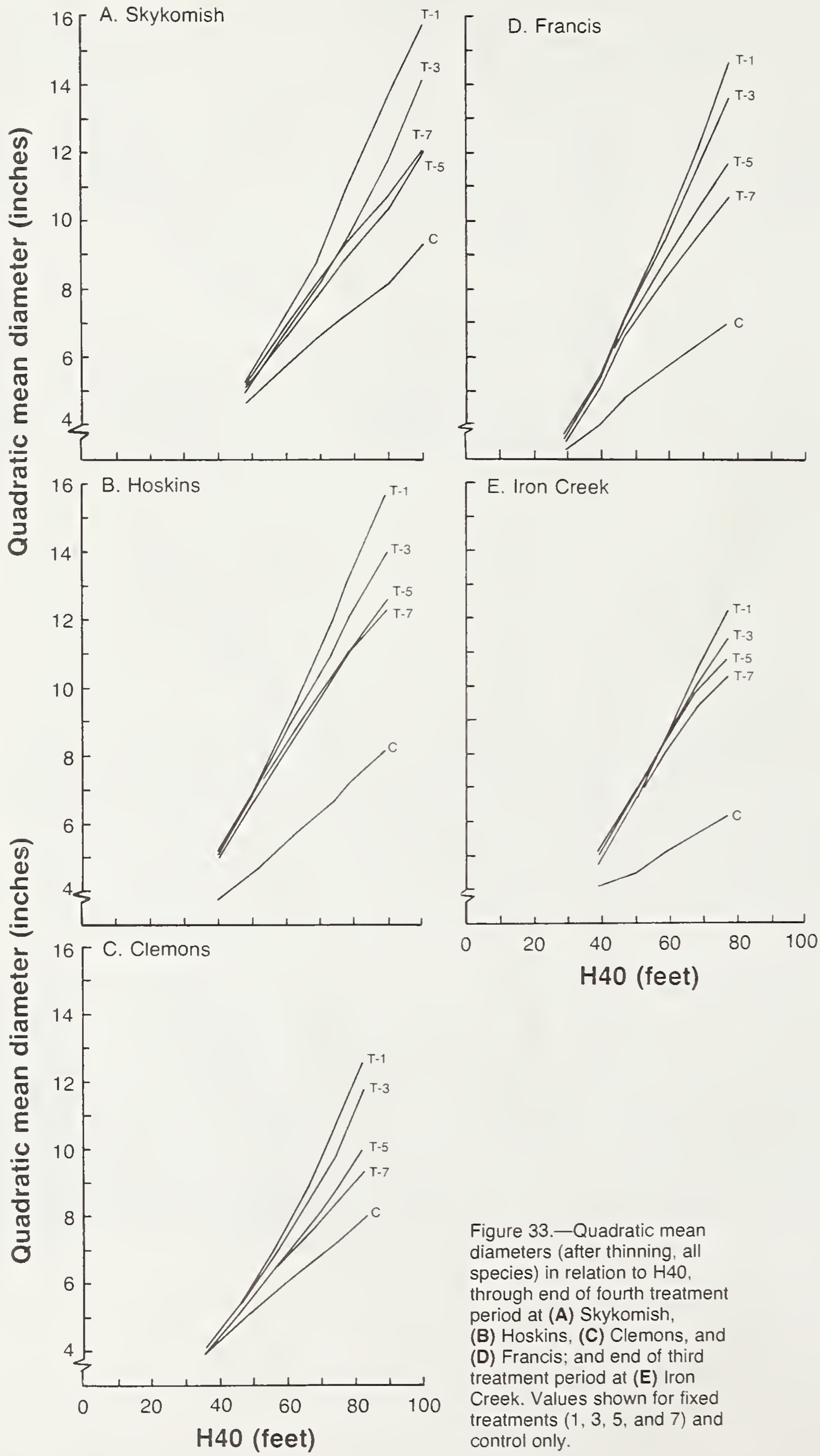


Figure 33.—Quadratic mean diameters (after thinning, all species) in relation to H40, through end of fourth treatment period at **(A)** Skykomish, **(B)** Hoskins, **(C)** Clemons, and **(D)** Francis; and end of third treatment period at **(E)** Iron Creek. Values shown for fixed treatments (1, 3, 5, and 7) and control only.

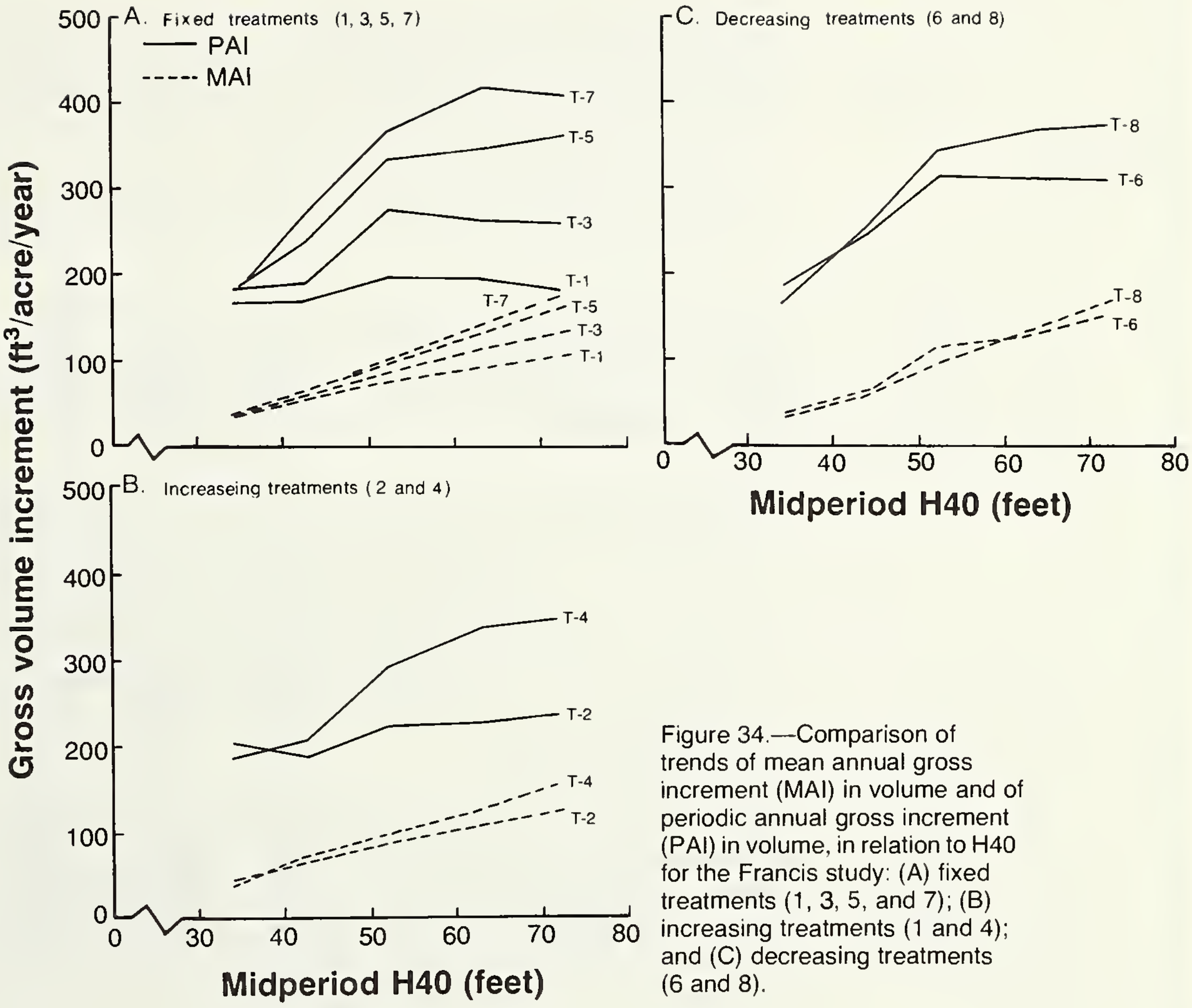


Figure 34.—Comparison of trends of mean annual gross increment (MAI) in volume and of periodic annual gross increment (PAI) in volume, in relation to H40 for the Francis study: (A) fixed treatments (1, 3, 5, and 7); (B) increasing treatments (1 and 4); and (C) decreasing treatments (6 and 8).

Mean annual increments.—PAI and MAI in gross volume, for all trees 1.6 inches d.b.h. and larger, are shown in tables 48 and 49 (appendix). Trends of MAI and PAI in relation to H40 are illustrated, for the Francis study, in figure 34. Trends for other installations are similar.

These trends show that:

1. After increasing in early periods, PAI appears to have more or less stabilized in the third and fourth treatment periods.
2. MAI has been and still is increasing sharply over successive periods.
3. By the fourth treatment period, MAI is still only about one-half the value of PAI for the period.

The fact that PAI is still roughly twice MAI clearly shows that these stands are still far short of any biologically reasonable rotation age. Differences between treatments are increasing rapidly, and even the end of the fifth treatment period will not provide a full evaluation of the potential differences in final results of these thinning regimes.

Volume production by tree size classes.—Cumulative volume production in trees larger than 1.6, 7.6, 9.6, 11.6, and 13.6 inches d.b.h., at the end of the fourth treatment period, is shown in tables 50 and 51 (appendix) for Skykomish, Hoskins, Clemons, and Francis. Values shown are the volume of live stand at the end of the fourth treatment period plus volume of material removed in previous thinnings, exclusive of the calibration thinning. (Material removed in the calibration thinning ranged from 216 ft^3/acre at Francis to 1,238 ft^3/acre at Hoskins, virtually all of it in the 1.6-7.5-inch d.b.h. class.)

The above values are compared in figure 35. Patterns are generally similar for Skykomish, Hoskins, and Francis, although absolute volumes produced differ considerably. Iron Creek was not included in these graphs, but trends at Iron Creek up to the end of the third treatment period are similar to Skykomish, Hoskins, and Francis.

The lowest levels of growing stock (regimes 1, 2, and 3) have generally resulted in major reductions in both total volume production and production of smaller merchantable material (7.6-11.5 inches d.b.h.) without corresponding gains in volume of larger material. The higher levels of growing stock in regimes 5, 7, 4, and 8 have produced volumes in trees 7.6 inches and larger more or less equal to those of the controls; volumes in trees 11.6 inches and larger and in trees 13.6 inches and larger are far greater than the controls, and equal to or greater than the volumes produced in the low-density regimes.

Clemons is again different. Not only is total production less at Clemons than at the other three installations shown, but there has been little apparent volume growth response to differences among thinning treatments. The control has a volume in trees 13.6 inches and larger equal to or greater than all but one of the thinning treatments, and a volume in trees 9.6 inches and larger about the same as in the thinning treatments. This represents, in part, a lack of response to thinning—as is evident when one compares results of treatments 1, 3, 5, and 7. It is probably also another indication (consistent with differences in diameter distributions and H40 for control vs. thinned, as noted previously) that the calibration thinning at Clemons removed more of the larger trees than was the case in other studies.

Comparisons Among Installations

Differences among installations for a given thinning regime can be illustrated by graphs showing, on the same axes, results of a specified treatment at several installations. Such graphs are shown for the five site II installations, extending through the fourth treatment period at Skykomish, Hoskins, Clemons, and Francis, and through the third treatment period at Iron Creek (figs. 36, 37, and 38).

Gross volume yield by installation within thinning regime.—Figure 36 shows the relation of gross volume yield to H40, by installation, separately for treatments 1, 3, 5, and 7. This corresponds to the relation for the controls given in figure 12. Relative ranking of installations is generally similar to that for the controls, with Clemons and Skykomish having considerably lower volume production than Hoskins, Francis, and Iron Creek.

Attained diameter by installation within thinning regime.—Figure 37 shows the relationship of quadratic mean diameter to H40, by installation, separately for treatments 1, 3, 5, and 7. This corresponds to the relation for the controls in figure 9. Diameters shown are values before thinning, except the first measurement which is the value after the calibration thinning. Again, the ranking of installations is generally similar to that for the controls.

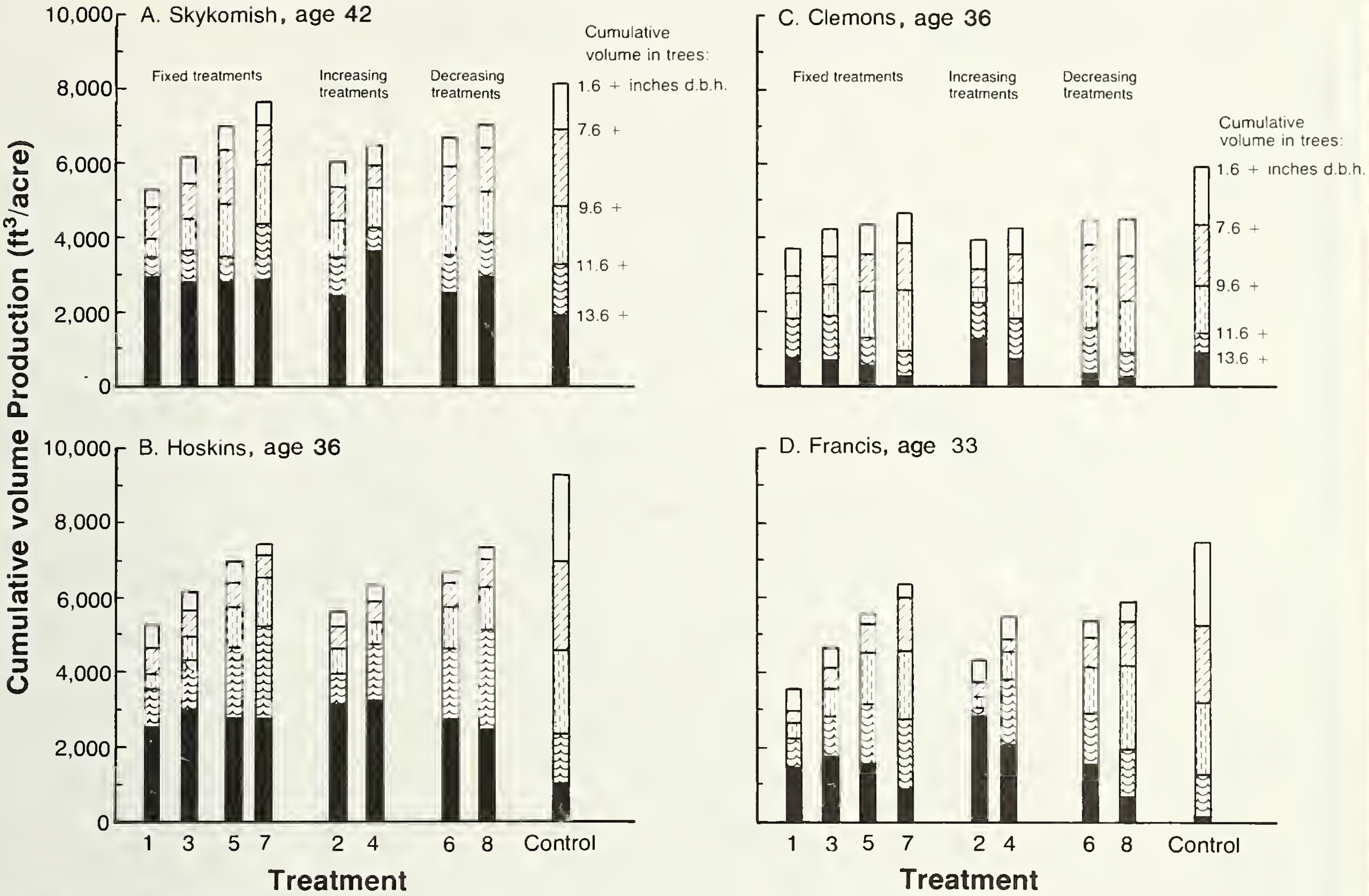


Figure 35.—Volume production to end of fourth treatment period, by tree size classes: **(A)** Skykomish, age 42; **(B)** Hoskins, age 36; **(C)** Clemons, age 36; and **(D)** Francis, age 33. Values are sums of live stand at end of fourth treatment period plus previous thinnings (calibration cut excluded).

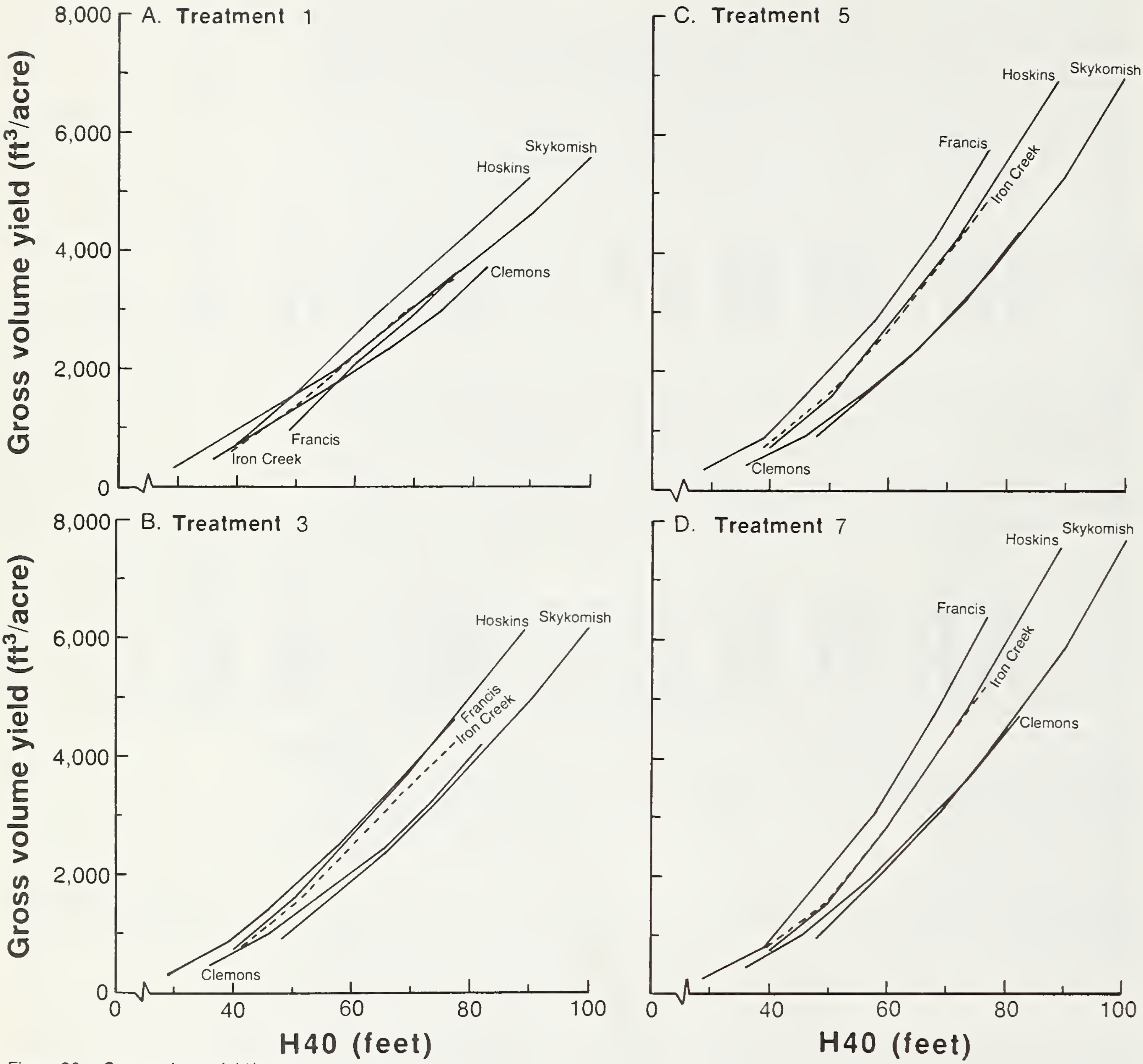


Figure 36.—Gross volume yield in relation to H40, by treatment, through fourth treatment period at Skykomish, Hoskins, Clemons, and Francis, and through third treatment period at Iron Creek: (**A**) treatment 1, (**B**) treatment 3, (**C**) treatment 5, and (**D**) treatment 7.

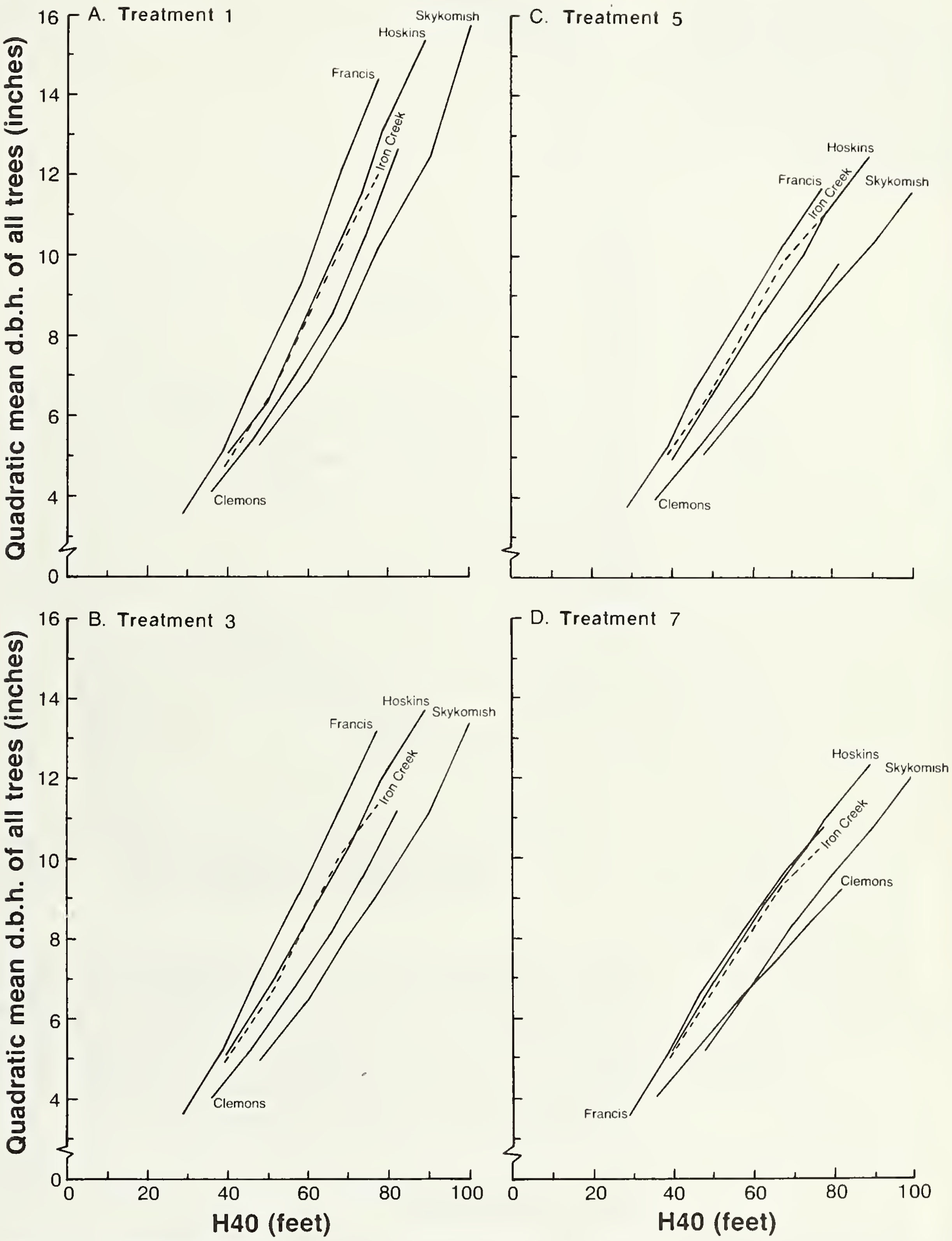
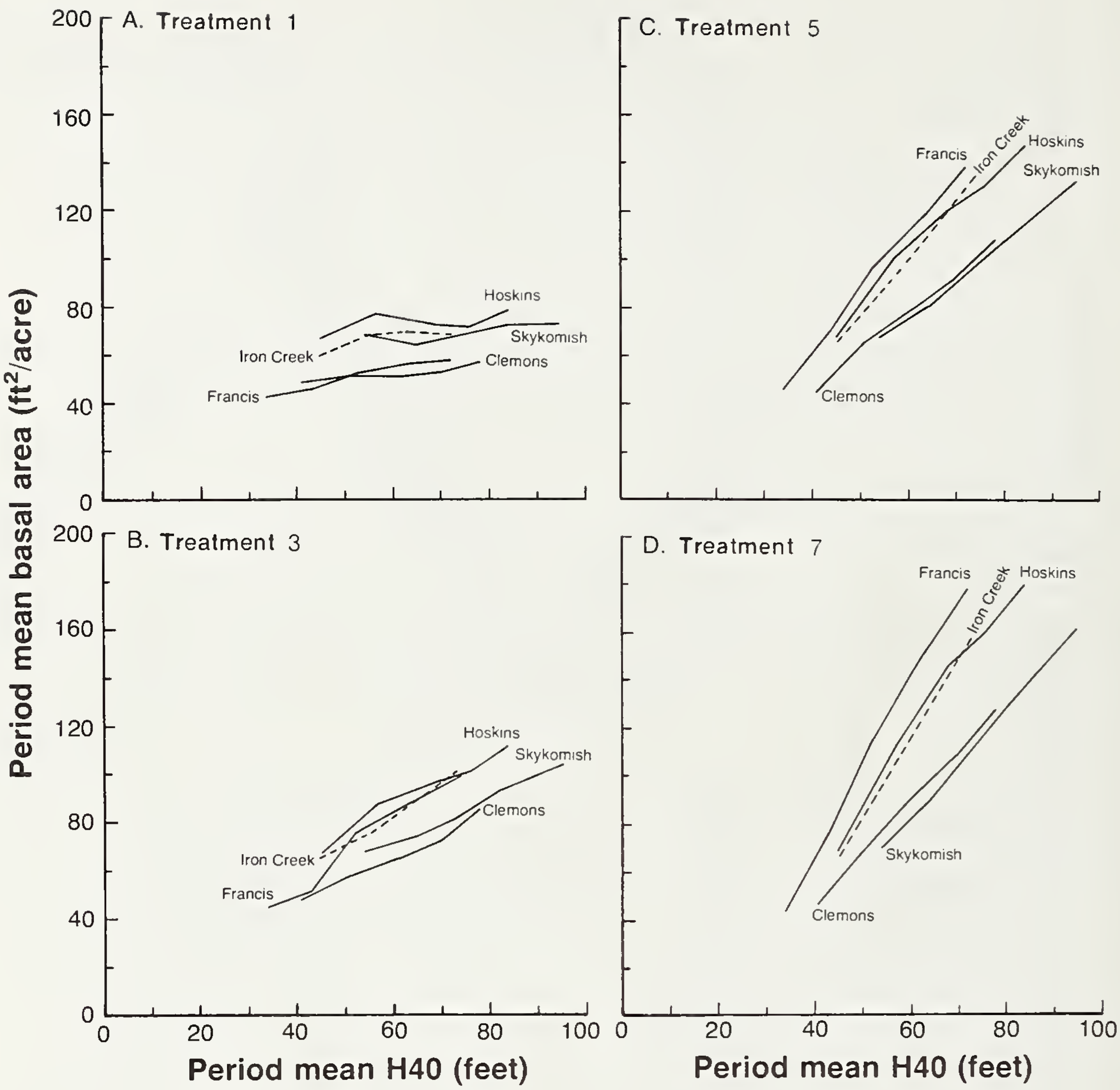


Figure 37.—Quadratic mean diameter (all trees) in relation to H40, by treatment, through fourth treatment period at Skykomish, Hoskins, Clemons and Francis, and through third treatment period at Iron Creek: **(A)** treatment 1, **(B)** treatment 3, **(C)** treatment 5, and **(D)** treatment 7. Diameters are before cut, except for the first measurement which is after the calibration cut.

Figure 38.—Relation of period means of basal area to period means of H40, by treatment, through fourth treatment period at Skykomish, Hoskins, Clemons and Francis, and through third treatment period at Iron Creek: **(A)** treatment 1, **(B)** treatment 3, **(C)** treatment 5, and **(D)** treatment 7.



Mean period basal area by installation within thinning regime.—Figure 38 shows the relationship of mean period basal area to H40, by installation, separately for treatments 1, 3, 5, and 7. Line segments connect points that represent means of basal area at start of period (after thinning) and end of the period (before the next thinning); these points represent the periodic average growing stock which produced the observed periodic growth. The figure is analogous to figure 10 for the controls.

Figures 36, 37, and 38 show that there are consistent differences among installations for any given treatment.

Distribution of Volume

Percentage distributions of volumes by tree size classes at the end of the fourth treatment period are shown for Skykomish, Hoskins, Clemons, and Francis in figure 39. The patterns are generally similar, although differences among treatments are smaller and less consistent at Clemons than in the other three studies. In particular, the curve for the control at Clemons is inconsistent with those for the thinning treatments, probably reflecting the atypical calibration thinning on this study (noted earlier).

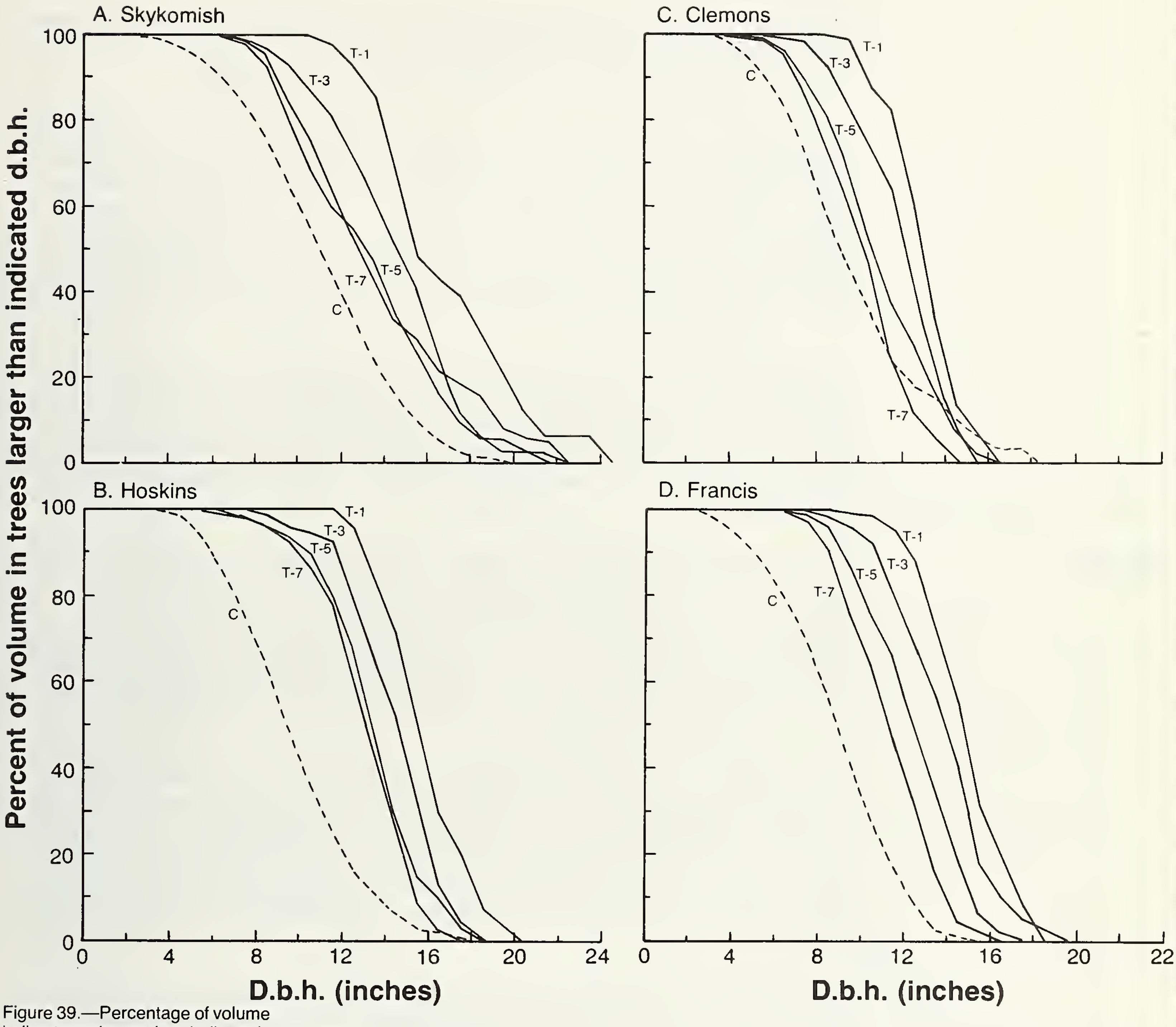


Figure 39.—Percentage of volume in live trees larger than indicated diameters, at end of fourth treatment period: **(A)** Skykomish, age 42; **(B)** Hoskins, age 36; **(C)** Clemons, age 36; and **(D)** Francis, age 33. Values shown for fixed treatments (1, 3, 6, and 7) and control only.

Distribution of cumulative volume production by tree size classes, through the end of the fourth treatment period, is shown in figure 40. Volume distribution curves at the end of the fourth treatment period show a similar pattern for the live stand.

Total volume produced on the controls is greater than that produced on the thinned plots at all installations. The thinned plots at Hoskins and Francis have, however, produced much more volume in merchantable-size material, 7.6 inches and larger (for treatments 5 and 7, approximately twice as much as on the controls). Iron Creek (not shown) appears to be developing similarly. Current trends in net growth suggest that this advantage for the thinned plots will be maintained or even increased in the next growth period. Differences at Skykomish are similar but are smaller in magnitude, possibly in part because of the later start of thinning.

Clemons is different; it shows little or no gain of thinning treatments over control in merchantable as well as total volume production. This is associated with the unexplained poor response to thinning in this installation, plus the continuing effect of the initial removal of large trees in the calibration cut. The initial advantage of the control in large trees (table 5) has not been overcome by the modest increase in diameter increment on the thinned plots.

Mortality

Overall, mortality on thinned plots in the five site II installations has been minor. Since study establishment, volume of mortality on thinned plots has been, on average, less than 1 percent of gross growth at Hoskins and Francis, 2 percent at Skykomish, 3 percent at Clemons, and 5 percent at Iron Creek. The higher mortality at Iron Creek was the result of a combination of root rot and early damage by bear. Some individual plots had substantial mortality, that is not evident in these averages. Mortality had no relation to thinning treatment or to time (except the early damage by bear at Iron Creek).

Total mortality on the controls, expressed as percentages of total gross growth since establishment, ranges from 3 percent at Francis to 15 percent at Hoskins. This mortality was mainly due to suppression, and has been increasing rapidly over successive growth periods as the controls approach maximum density. In the third and fourth treatment periods, mortality has become a substantial fraction of periodic gross growth at Iron Creek, Hoskins, Skykomish, and Clemons. The density trends (fig. 13) suggest that this will soon also be true at Francis.

The two poorer site installations, Sayward and Rocky Brook, appear to be following similar trends. Through the end of the second treatment period, the thinned plots at Sayward had almost no mortality. Rocky Brook has lost about 3 percent of total gross growth overall since establishment; much more on some individual plots. The Rocky Brook mortality has been mainly from root rot, plus some snowbreakage. At both installations, the controls are now developing substantial suppression mortality.

Secondary Vegetation

It is evident from casual inspection that differences exist in species composition and vigor of the secondary vegetation, both among areas and among treatments within individual areas. To date, there have been no quantitative measurements of composition and development of the secondary vegetation.

The study areas should be examined and classified by plant association; quantitative descriptions of species composition and development of the secondary vegetation should be made for a selected set of contrasting treatments.

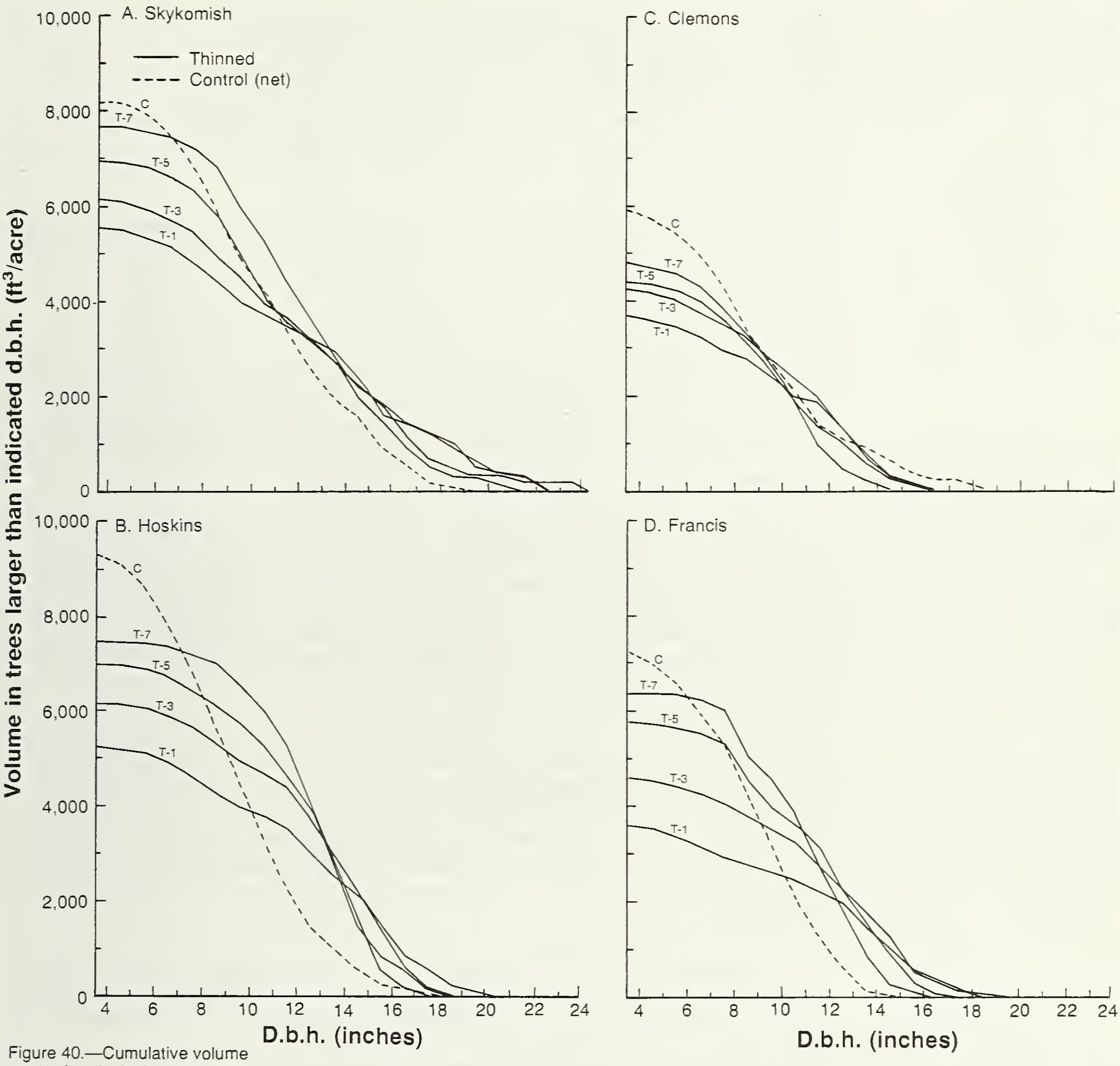


Figure 40.—Cumulative volume production (including thinnings) in trees larger than indicated diameters, to end of fourth treatment period: **(A)** Skykomish, to age 42; **(B)** Hoskins, to age 36; **(C)** Clemons, to age 36; and **(D)** Francis, to age 33. Material removed in calibration cut omitted. Values shown for fixed treatments (1, 3, 5, and 7) and control only.

Discussion

Differences in Productivity

Volume and basal area production and diameters of trees at individual installations are expected to differ with differences in age and site index. These differences should be largely removed when height (H40) rather than age is used as the basis for comparison. The most advanced studies in the LOGS series—Skykomish, Hoskins, Clemons, Francis, and Iron Creek—are similar in site index; the most recent SI_{50} estimates are 128, 132, 122, 125, and 125, respectively. These installations could, therefore, be expected to behave similarly in relation to H40 development.

Considerable differences do exist. The Skykomish and Clemons installations are clearly producing less volume, less basal area, and less diameter growth than expected for their site indexes and attained H40 values.

Evidence for differences.—

Controls.—The graphs of basal area, cumulative basal area production, cumulative volume production, and relative density in relation to H40 (figs. 10 through 13) all show much lower production for the Skykomish and Clemons controls than for controls in the other five installations compared. RD values do not appear to be approaching the same upper limit.

Clemons has produced much less basal area and volume for a given H40 than have the other installations (except Skykomish), even though the site index and initial height at Clemons were comparable to Hoskins, Francis, and Iron Creek. By the time the stands reached 90 feet in height, diameter of the Hoskins control exceeded that at Clemons despite the fact that Hoskins had nearly twice as many trees per acre (figs. 7, 8, 9, and 10). The Skykomish control has also produced much less basal area and volume for its H40 than did Hoskins, Francis, and Iron Creek, which have similar site indexes.

Thinning treatments.—Graphs of periodic annual increment in basal area and volume in relation to basal area, treatment, and period (figs. 15 and 16) show relationships that are qualitatively similar but quantitatively different. Clemons in particular has much less growth than the other site II installations. Cumulative production curves (fig. 32) show similar patterns, but with much less total production at Clemons. The same is true for attained diameters (fig. 33). The various curves relating periodic annual increment in basal area, volume, and diameter to measures of growing stock are likewise lower for Clemons.

Graphs comparing gross volume yields and attained diameters among installations by individual treatments (figs. 36 and 37) show differences similar to those for the controls; curves for Clemons and Skykomish are markedly lower than those for other installations.

Stands differed somewhat in height, average diameter, number of trees, and basal area at the start of the individual experiments, and it is not surprising that subsequent development has not been identical. To the extent that these initial differences have influenced subsequent basal area growth of controls, they must have influenced the definition of thinning treatments. Basal area levels for a given treatment do differ considerably among installations (fig. 38). Differences in initial condition do not seem a sufficient explanation of the observed differences, however.

Possible causes of differences.—

Skykomish.—This installation differs from others in that it was somewhat taller and had the most volume at the start of the experiment, the stand was and is about 50 percent hemlock by basal area, and trees on the control that were less than one-half the average diameter of crop trees were cut in the calibration thinning, unlike the procedure on other studies. The slightly later start of treatments could be a factor in the lower basal area growth and must affect comparisons of development in relation to H40. Removal of small trees from the control plots may have had some slight effect on subsequent development of the control plots and hence on treatment basal area levels. The major apparent difference from the other studies is species composition. The hemlock component has a substantially lower diameter growth rate and less height and average diameter (table 47) than did the Douglas-fir component which is used as the basis for site index and H40 estimates. Each of these factors probably contributes to observed differences, although they do not necessarily provide a complete explanation.

Clemons.—Initial stand values at Clemons were well within the range of those for Hoskins, Francis, and Iron Creek (table 2). Clemons had the smallest initial number of trees, was closely comparable to Hoskins and Iron Creek in initial H40, and was in between Hoskins and Iron Creek in average diameter (Francis had considerably smaller initial H40 and average diameter). The principal difference when compared to Hoskins and Iron Creek was lower initial basal area at Clemons (Francis had a still lower initial basal area, associated with smaller average diameter and lesser initial H40). This difference continued throughout subsequent development of control plots (fig. 10) and corresponding differences are evident for thinning treatments (figs. 36 through 38). The poor subsequent diameter and basal area growth, when compared to more heavily stocked and otherwise comparable installations, indicate that the difference in basal area is not a cause but a result of some inherent difference in stand productivity.

The original stand had considerable animal and freeze damage and many damaged trees were removed in the calibration thinning. The diameter distribution after calibration (table 5) suggests that more of the larger trees were removed than in the other studies; the 6-foot difference between mean H40 of controls and that for thinned plots suggest the same. Also, d/D at the second treatment thinning was unusually high (fig. 14), for reasons unknown (also true at Skykomish), and may have accentuated differences. These differences were still present at the end of the fourth treatment period, as shown by the volume distribution curves of figure 39 and the 10-foot difference in estimated site index of control plots vs. treated plots (table 8).

Several observers have commented that trees at Clemons appear less vigorous than those in other installations; the trees have a slight yellowish cast to the foliage and relatively thin crowns. Possible causes that have been suggested for this appearance and for differences in performance from the other site II installations include an unknown and possibly off-site seed source, some unrecognized nutritional problem, effects of a severe burn in the early 1940's, and heavy initial brush competition.

There is considerable evidence, much of it from Europe (Assmann 1970, Bradley and others 1966) that differences in stand productivity and stockability exist which are not fully accounted for by height growth or site index and which are often related to differences in soils or regional climate. Although such differences could be involved here, we have no reason to expect them for the soils and locations concerned. Differences in early damage and initial treatment, a possibly unadapted seed source (Clemons), and species composition (Skykomish) seem more likely explanations.

Definition of Thinning Regimes

Staebler's use of control plot growth to define residual stocking for the thinning regimes in the LOGS studies was based on the beliefs that local productivity differences exist and that definition of thinning regimes in relation to productivity of the individual stand, rather than in relation to regional averages, would be biologically meaningful. The differences discussed above appear to confirm the hypothesis of local productivity differences. It is arguable whether the attempt to define thinning regimes in relation to productivity of the individual stand has really simplified analysis and interpretation of the experiments.

The method used to define regimes has probably not achieved complete comparability of thinning regimes among installations. Basal area increment culminates early in dense stands, and time of culmination is influenced by initial density (Pienaar and Turnbull 1973). Installations differed considerably in initial number of stems, basal area, and height at the time the study was established, and such differences may well have introduced inconsistencies in defining thinning treatments.

The numerous small stems of associated species that are present in some installations distort summary values and growth trends for the number of trees and average diameter and introduce some confusion in comparisons among installations. In retrospect, it would have been preferable to have removed the small trees at the time of study establishment, as was done at Skykomish but not in the other installations. Alternatively, more nearly equal initial conditions might have been provided by thinning all controls to a fixed number of trees—a number large enough to allow early crown closure—at the time of study establishment.

Analyses of Variance

Differences among treatments.—The analyses of variance (tables 11-14) show no significant differences between averages of the fixed and variable treatments, which always have the same average amount of retained growing stock. Gross basal area growth and gross volume growth increased with growing stock; growth percents decreased with growing stock. Basal area growth, and basal area and volume growth percent have decreased over successive treatment periods. Diameter growth (both PAI and growth percent) has decreased with increasing growing stock and has shown decreases over successive periods except for PAI at the lowest level of growing stock.

So far, basal area and volume PAI have been greater for the decreasing treatments than for the increasing treatments. At the end of the fourth treatment period, the average percentage of control plot growth retained is 35 percent for the increasing treatments and 45 percent for the decreasing treatments. Average growing stock level of the latter is higher and would be expected to produce more growth. The experiment will not be completely developed until the end of the fifth treatment period, when the same average growing stock levels are expected for both increasing and decreasing treatments. Even though increasing and decreasing treatments differ at present, we cannot now conclude that they will be different at the end of the fifth treatment period.

Results for the contrasts between increasing treatments (D) and between decreasing treatments (E) (table 9) vary among installations. Where significant differences occur, they are consistent with results of the fixed percentage comparisons. Treatments 4 and 8 tend to have greater basal area and volume PAI in the increasing and decreasing groups, respectively. These retain more growing stock than the alternative treatments, 2 and 6. The opposite is true of growth percent, with treatments 2 and 6 having greater growth percents when there is a significant difference because growth is on fewer and larger trees. For quadratic mean diameter, treatments 2 and 6 have larger PAI and growth percents because of the greater radial growth response associated with less growing stock in these treatments.

The error mean squares (tables 10 through 15) show that Clemons has much higher variability than the other three installations discussed. Nonsignificance of most interactions at Clemons probably reflects less sensitivity associated with this greater variability.

Differences among installations.—The graphs of means for the fixed percentage treatments (figs. 15 through 18) show that trends are qualitatively similar among the four installations compared, but that there are considerable differences in productivity, as noted previously.

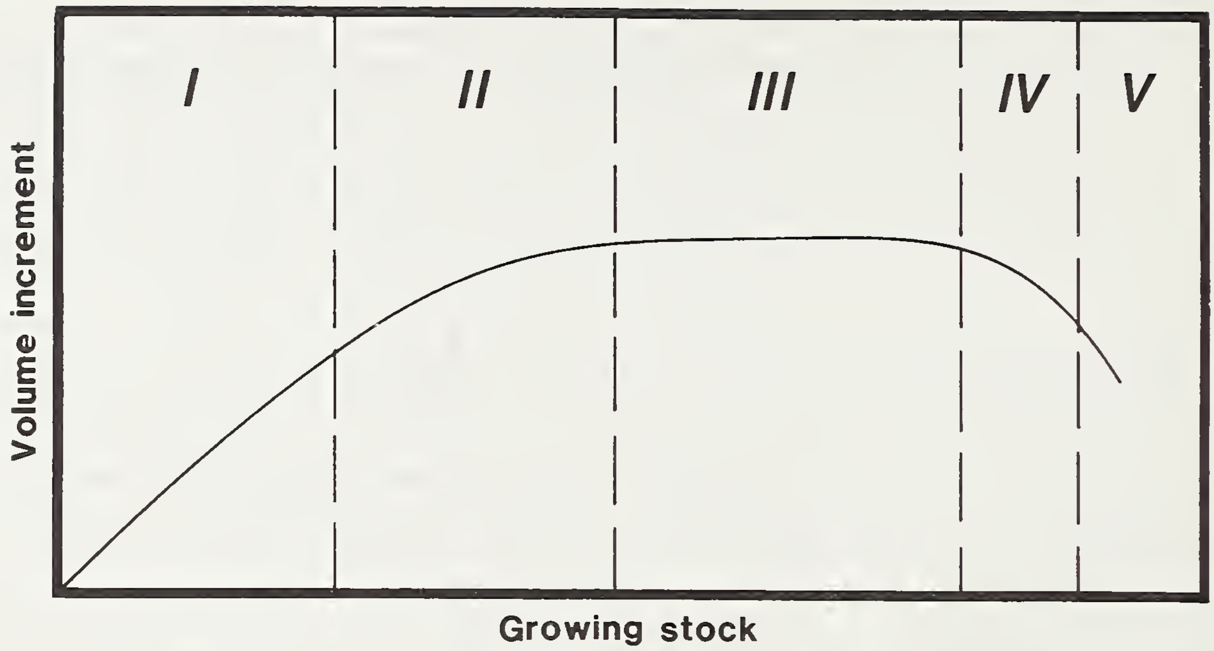
Relationships Between Growth and Growing Stock

Past observations and the Langsaeter curve.—Thinking at the time the LOGS studies were established was strongly influenced by the so-called Langsaeter curve (fig. 41), which portrayed a generalized relationship of growth to growing stock (Braathe 1957, Langsaeter 1941). The possible range of growing stock was subdivided into a free-growth zone (I) not influenced by competition, a transition zone (II), a zone (III) within which growth is nearly constant over a wide range of growing stock, and a zone (IV) in which growth is reduced by excessive competition. One purpose of the LOGS studies was to provide a quantitative definition of the rising portion of this curve, particularly zone II.

Subsequent to the widely quoted publications by Braathe (1957) and Mar:Moller (1954), the generalization has been frequently made that essentially the same total cubic volume production can be obtained over a wide range of stand densities. A considerable number of thinning studies in several species have seemed to support this, and Staebler (1960) based his theoretical thinning regime on the assumption that the same gross increment may be produced with widely differing combinations of growing stock and tree size.

There is considerable information for Douglas-fir that does not agree with the concept of constant gross growth over a wide range of densities. Curtis (1967) found that in untreated natural stands, gross increment in both basal area and volume increases with increasing stand density; there was no indication of a maximum within the range of his data. Reukema (1972) and Reukema and Bruce (1977) found, as did Curtis and others (1982), that thinning reduced gross volume increment. This is stem volume only, and mortality in unthinned stands may partially or completely offset this reduction in terms of recoverable volume. Also, the studies cited involve uncertainties arising from use of heterogeneous samples in regression and thinning practices that were influenced by merchantability considerations.

Figure 41.—Relation between volume increment and growing stock, as hypothesized by Langsaeter (adapted from Braathe 1957). Roman numerals denote Langsaeter's "density types."



The LOGS study results.—The LOGS studies constitute the most closely controlled and extensive series of thinning experiments in existence for young stands of Douglas-fir. In time, they should define the relationship of gross growth to growing stock in young stands that have been reduced to low stocking at an early age which was followed by consistent thinning to maintain a series of growing stock levels. Few data are yet available from the installations on poor sites, so we can say little about these; but relationships now seem fairly well established for the better sites.

We do not imply that the quantitative results would necessarily hold for thinnings begun at a later stage in stand development or for regimes that produce radically different stand structures. The close relationships of growth to growing stock found in the LOGS studies, in contrast to the results of the somewhat similar study reported by Oliver and Murray (1983), probably reflect the close control of initial conditions and kind of thinning that are a major feature of the LOGS studies. These specifications in turn imply development of a particular stand structure over time.

Gross growth.—Within the range of the thinned stands, gross growth in both basal area and volume increases with an increase in growing stock (figs. 19 and 23). For basal area growth, some of the curves suggest a possible maximum between the upper margin of the range of the thinned plots and the controls, with a zone of nearly constant growth in later periods. The volume growth curves appear much steeper and show little indication of any maximum or of any zone of constant growth.

Similar curves (figs. 20 and 24) with RD on the horizontal axis suggest that on these axes the curves are approximately proportional (and, therefore, parallel when transformed to logarithmic scales). Statistical and graphic comparisons indicated that curves for successive periods within an installation could be regarded as proportional and that this is also at least approximately true across installations (with the possible exceptions of Clemons and Rocky Brook).

These statements do not imply any theoretical basis for proportionality, nor do the statements necessarily hold over a wider range of ages and heights. For the limited range under consideration, proportional curves appear to be a sufficiently close approximation to reality to allow their use in summarizing relationships in an easily interpretable form.

Assuming such proportionality, relationships between growth and growing stock can be generalized as shown in figure 26 where the variable on the vertical axis is the ratio of growth rate to the growth rate expected at the "normal" density of RD70. The variable on the horizontal axis is the relative density expression, RD. For RD30, for example, about 66 percent of "normal" volume growth and about 77 percent of "normal" basal area growth would be expected.

The curves for individual periods (figs. 23 and 24) and the generalized curve in figure 26 do not support the idea that gross volume growth is the same over a wide range of stocking. The thinned stands in the LOGS study are clearly on the ascending portion of the Langsaeter curve (fig. 41) in Langsaeter's zones I and II. There is little indication of any plateau of gross growth.

Net growth.—Mortality on thinned plots was generally minor and, within the range of the thinning treatments, relationships between net growth and growing stock differ little from those for gross growth. Net growth increases with an increase in growing stock.

Suppression mortality is now substantial on the controls, and net growth of controls is considerably less than gross growth. The observed values, though erratic, indicate that by the third and fourth treatment periods net growth is about the same for the control and for treatment 7 (table 48, appendix). The accelerating suppression mortality on the control plots suggests that in the very near future net growth of the more heavily stocked thinning treatments is likely to exceed that of the controls.

Differences between basal area and volume increment curves.—The gross volume increment curves appear steeper than the basal area increment curves and, unlike the latter, show no indication of a maximum within the range of the data (fig. 26). The curve for gross basal area growth is much closer to the Langsaeter-Møller concept of near-constant growth over a wide range of densities than is the curve for volume growth.

Douglas-fir characteristically has rapid height growth that is sustained over long periods of time. In this respect it differs markedly from many eastern and southern species. This rapid and sustained height growth is the probable explanation for the difference in shape of the basal area and volume growth curves and is a characteristic that has important implications for management of the species.

Height growth as a factor in volume increment and density control.—A generally applicable equation for stand volume is:

$$V = FGH;$$

in which:

V = cubic volume per unit area,

F = form factor,

G = basal area per unit area, and

H = stand height.

We used H40 as stand height and calculated the corresponding form factor as:

$$F = V/(G\ H).$$

Differentiating the volume equation with respect to time (t), we have (Hegyi 1969):

$$dV/dt = FG(dH/dt) + FH(dG/dt) + GH(dF/dt)\ ;$$

in which dV/dt, dH/dt, dG/dt, and dF/dt are the net rates of change in volume, height, basal area, and form factor; all can be approximated by the corresponding periodic annual net increments. Values of F, G, and H corresponding to these rates are approximated by the period means of these quantities. This relationship can also be expressed as a difference equation (Evert 1964).

As a numerical illustration, we take values from the Hoskins study, treatment 5, fourth treatment period. These values are:

Period means	Growth rates
	dV/dt = 416 ft^3/acre/yr
F = 0.3770	dF/dt = −0.0013 per year
G = 147.4 ft^2/acre	dG/dt = 8.475 ft^2/acre/yr
H = 83 ft	dH/dt = 3.0 ft/yr

Substituting these values into the above equation for the derivative dV/dt:

$$dV/dt = 167 + 265 - 16 = 416\ ;$$

which agrees with the observed periodic annual increment.

The third term in the equation, GH(dF/dt), makes only a minor contribution to total volume growth. The contribution of the second term, FH(dG/dt), is directly proportional to basal area growth rate. The first term, FG(dH/dt), involves the product of basal area and height growth rate. The greater the rate of height growth, the greater the importance of this term. Differences in basal area levels will have a greater effect on the magnitude of the FG(dH/dt) term—and on volume growth rate—in stands that are growing rapidly in height than in stands which are growing slowly in height.

Volume growth will be more closely related to basal area stocking in a species such as Douglas-fir, which characteristically maintains rapid height growth over long periods of time, than in species that do not have this height growth pattern. In the latter, the principal contribution to volume growth is from the second term, FH(dG/dt), which includes basal area only indirectly through its effect on basal area growth rate, dG/dt.

It is thus not surprising that the growth over growing stock curves for basal area and for volume differ in shape, and that the volume growth curves show growth increasing with growing stock up to fairly high levels of stocking. The importance of height growth also suggests the possibility of different patterns on poor sites and in older stands as compared to the young stands on good sites discussed here.

Staebler's Assumptions

Staebler (1960) based his method for calculating thinning schedules on three assumptions:

1. Gross yield in cubic feet of a normal (fully stocked), unmanaged stand represents the maximum production of which the site is capable.
2. Periodic gross increment for any age period in the life of a normal stand represents full capacity of the site to produce wood in a stand of the chosen age.
3. Approximately full increment may be produced with widely differing combinations of growing stock, tree size, and radial increment.

These concepts played an important role in planning the LOGS studies. In view of the results obtained to date, what can now be said? First, although the LOGS studies do not provide a clear test of assumptions (1) and (2), results to date do not conflict with them. Second, assumption (3) is contradicted by the LOGS study results. For the stand conditions and treatments represented, gross volume increment is different for the different observed combinations of growing stock, tree size, and radial increment.

Time Trends and Their Implications

Because all treatments start from a common base at the end of the calibration period, differences among growing stock levels and resulting differences in response develop gradually.

Yield curves (fig. 32) differ little in early growth periods, but diverge sharply in later periods. The same is true of diameters and diameter growth rates (fig. 33). The differences among treatments discussed here extend only to the end of the fourth treatment period for the four most advanced installations. We can expect these differences to become more striking by the planned completion of the experiment at the end of the fifth treatment period.

Comparison of periodic annual volume increments and mean annual volume increments (tables 48 and 49 (appendix); fig. 34) show that periodic annual volume increment has more or less stabilized in the third and fourth treatment periods. Mean annual volume increment is increasing rapidly, although by the fourth treatment period it is still only about one-half the value of the periodic annual increment. This pattern is mainly a consequence of the rapid and sustained height growth characteristic of the species and is accentuated by the low stocking level and resulting reduced volume growth in the early periods.

Comparison of periodic annual increment and mean annual increment shows that these stands are still far short of culmination of mean annual increment. This, plus the rapidly developing divergence of the yield curves and the increased values associated with large tree sizes, indicates that even the end of the fifth treatment period will not provide a full evaluation of the potential effects of the thinning treatments. Realization of the full gains attainable from thinning will clearly require rotations considerably longer than the ages represented by the LOGS studies.

Comparison of Thinning Treatments

Volume production by tree size classes.—Total cumulative production by tree size classes, as of the end of the fourth treatment period, has been summarized in tables 50 and 51 (appendix) and figures 35 and 40 for the Skykomish, Hoskins, Clemons, and Francis studies. Generally, the lowest levels of growing stock (regimes 1, 2, and 3) have resulted in major reductions in both total volume production and production of the smaller merchantable material (7.6-11.5 inches d.b.h.), without corresponding gains in volume of large trees. The higher levels of growing stock in treatments 4, 5, 7, and 8 have produced volumes in trees 7.6 inches and larger that are more or less equal to those of the controls; volumes in trees 11.6 inches and larger are far greater than the controls and equal to or greater than those produced in the low-density treatments. Present trends leave little doubt that this superiority in net usable production will continue and will probably increase over time.

Again, Clemons is different. Not only is total production less than at the other three installations shown, but there has been less apparent response in volume growth to differences among thinning treatments (fig. 35). Figure 31 shows that there has, however, been a response in diameter growth. This seeming contradiction may be explained by the lower basal areas and the narrower range in basal areas in this installation, which are consequences of less basal area growth on the control. The fact that the Clemons control contains more large trees than do some of the thinning treatments probably reflects excessive removal of large trees in the calibration thinning.

Trends of basal area and RD in relation to H40.—Trends of basal area and of RD in relation to H40 and to age are shown in figures 42 and 43, for fixed treatments only, for Skykomish, Hoskins, Clemons, and Francis. Application of the study plan thinning specifications has resulted in much lower levels of basal area and RD, as well as volume growth, at Clemons. Differences among the other installations are smaller and probably attributable in part to associated differences in initial H40.

Quality.—To date, no comparisons of timber quality characteristics have been made in the LOGS studies. In none of the treatments have trees developed excessively large branches, even at the lowest density levels. Even treatment 1 contains fine looking trees. However, even if this impression of acceptable branch size were borne out by quantitative measurements, results would not necessarily extend to other stands established with initial numbers of trees comparable to those left in the calibration thinning; and certainly not to stands established with less trees. Although competition was not severe at the time the LOGS studies were established, crowns were in contact and lower branches were beginning to die. This has undoubtedly influenced later branch development.

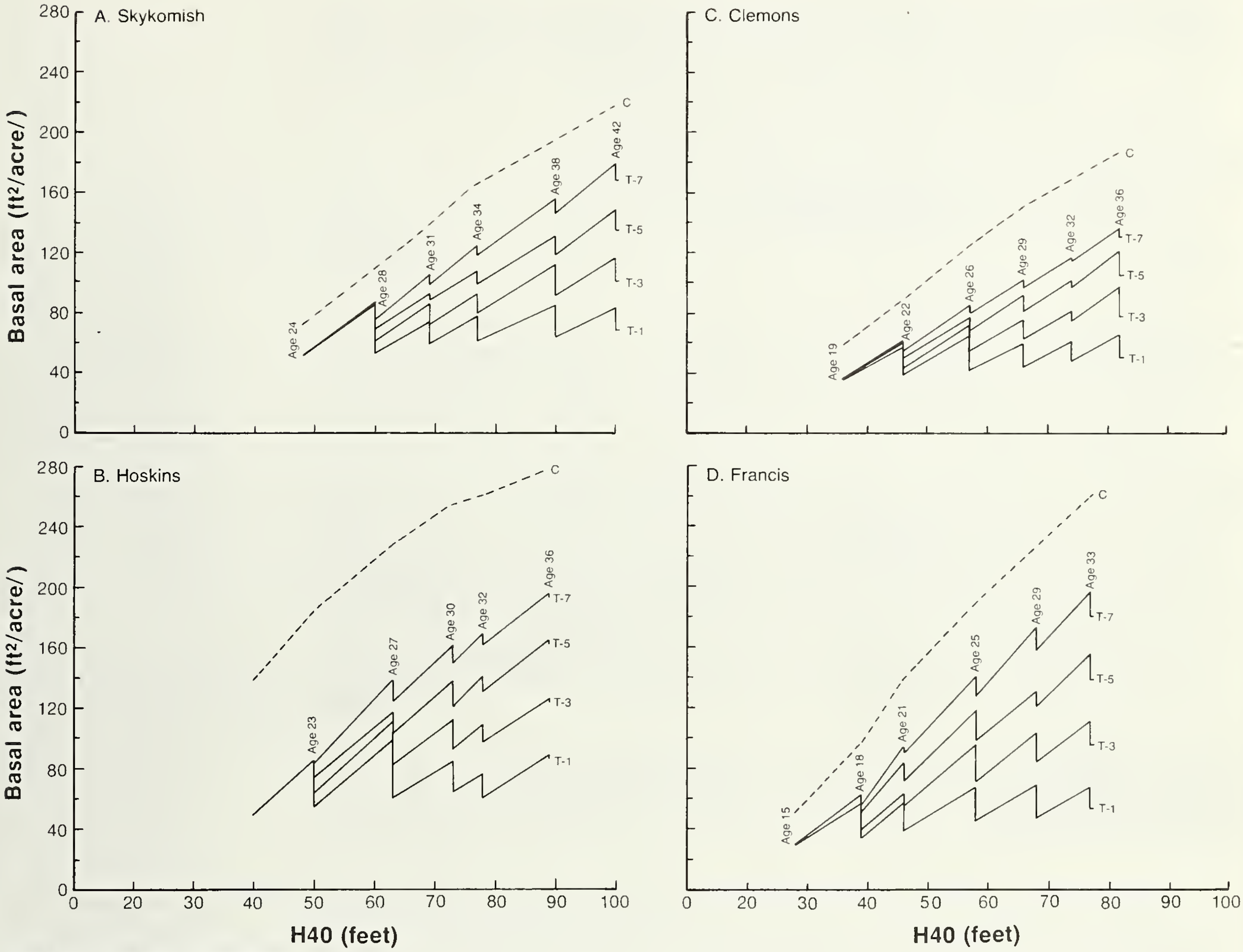


Figure 42.—Trends of basal area over H40, for fixed treatments (1, 3, 5, and 7) and control at: **(A)** Skykomish, **(B)** Hoskins, **(C)** Clemons, and **(D)** Francis.

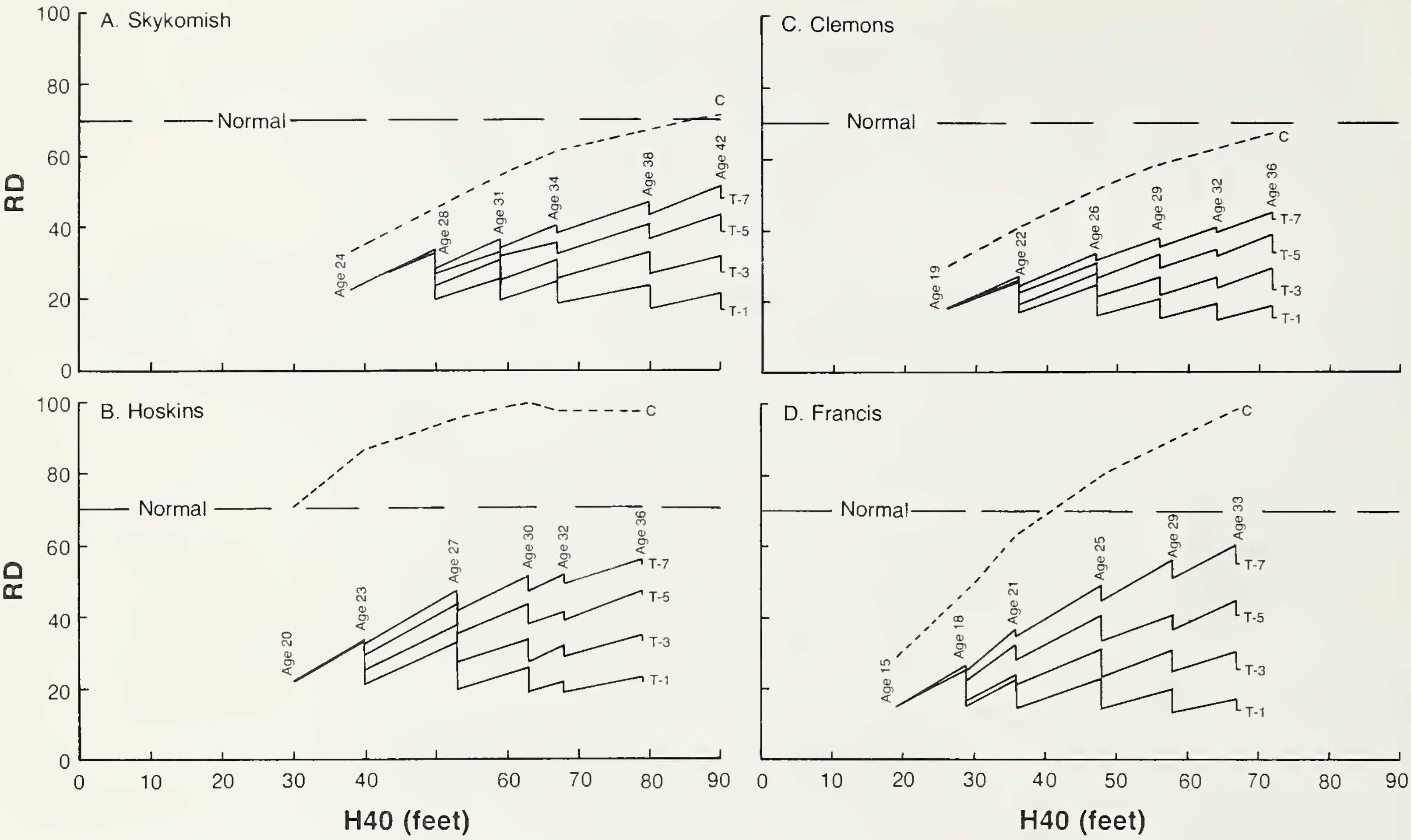


Figure 43.—Trends of RD over H40, for fixed treatments (1, 3, 5, and 7) and control at: **(A)** Skykomish, **(B)** Hoskins, **(C)** Clemons, and **(D)** Francis.

Value.—Although the thinning treatments have reduced total volume production, they have also sharply increased diameters. A ranking of treatments on the basis of value produced would differ considerably from a ranking by volume production.

Any value comparisons should ideally be made for some reasonable rotation age or range of rotation ages. These stands are still far short of such an age. Because the LOGS studies cannot be continued to rotation age, the appropriate point for a value comparison would seem to be the end of the fifth treatment period—the planned completion of the experiment. We have therefore made no attempt to include financial comparisons in this report.

Practical implications of LOGS results.—None of the LOGS studies is complete as of 1983, and little data are as yet available from the poorer sites. The LOGS studies were not designed as comparisons of operationally feasible regimes. Direct applications of current LOGS results to operational stand management are therefore limited.

The short thinning cycle used in the LOGS studies is not operationally realistic and should not be taken as an operational recommendation. There is, however, considerable evidence that for regimes with comparable average periodic growing stock or comparable initial conditions and thinning intensity (annual removal rate), moderate differences in thinning cycle have little effect on growth (Braathe 1957, Bradley 1963, Reukema 1972). Results generally similar to those of the LOGS regimes could probably be obtained with considerably longer cycles, provided trends of periodic mean growing stock and stand density over H40 correspond to those of the LOGS treatments (figs. 42 and 43).

It has been shown that volume increment is strongly related to growing stock for the conditions represented in the LOGS studies. Relatively high stand density is required for high cubic volume production. Conversely, diameter increment declines with increasing stand density.

Choice of any thinning regime is a compromise among conflicting desires for high volume production, large diameters, and relatively few thinning entries. Relative importance of volume growth and diameter growth varies with stage of stand development. Volume growth is a minor consideration when trees are small; the objective then is to get trees to merchantable size as rapidly as possible, consistent with acceptable stem quality. Once merchantable size is reached, volume growth becomes important. Timing of the change in emphasis depends on the diameters selected for beginning of commercial thinning or for harvest. The silviculturist must strike a balance between diameter growth and volume growth that is appropriate to the stage of stand development, to the site, and to management objectives.

The curves in figures 24 and 27 indicate that, for stand conditions comparable to LOGS, densities in the range RD20 to RD40 will produce high rates of diameter growth combined with substantially reduced volume production. Densities in the range RD40 to RD60 will produce high volume growth rates, with substantially reduced diameter growth and negligible suppression mortality. The point when emphasis should shift from diameter growth to volume growth will depend on the stand diameter at which thinning is judged financially and operationally feasible and on the choice of harvest age.

The LOGS regimes all maintain stands in an understocked condition during early treatment periods. In the first treatment period, stands were still close to the free-growth condition, in which volume growth is proportional to growing stock. Approximately the same diameters would probably have been produced if the first treatment thinning had been omitted and correspondingly fewer trees left at calibration.

Judged by results through the fourth treatment period, the LOGS low-density regimes (1 and 3) show somewhat higher diameter growth but considerably less total and merchantable volume production than the higher density regimes (5 and 7). The latter combine moderately fast diameter growth with relatively high volume production. At present, regimes analogous to the latter seem more attractive.

The low density regimes (1 and 3) have produced large, vigorous trees that are in excellent condition for future growth. If these stands are allowed time to build up to higher densities following the fifth treatment thinning, they might well develop greater volume, diameter, and value at final harvest.

Results of the LOGS studies to date appear generally consistent with previous stand management recommendations (Curtis and others 1981, Reukema and Bruce 1977). Consideration of possible analogous regimes and the information currently available from both LOGS and previous studies lead to some generalizations. These represent our best judgment rather than specific results of the LOGS studies.

It seems reasonable to reduce a stand at initial precommercial thinning to the number of stems required to produce an RD of about 50 at the time the stand reaches the average diameter selected for the initial commercial thinning. The only limitations on residual number appear to be the possibility of unacceptable wood quality when this target diameter is large and the number of trees correspondingly low; risks of sunscald, snowbreakage, and thinning shock if the initial thinning is delayed in high density stands; and possible brush problems.

Once the target diameter for the first commercial thinning is reached, successive thinnings that keep the period mean of RD in the range of 45-50 appear reasonable. d/D will usually be in the range, 0.85-0.95. Maximum RD should not be more than 55-60 (except immediately before final harvest), and the minimum should not be less than 30-35 at first commercial thinning and somewhat higher in later thinnings.[8] Within these approximate limits, the upper portion of the density range will emphasize volume production while the lower portion will give somewhat greater diameter increment.

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[8] Change in RD can be estimated as:

$$RD = 0.005454N(D_2^{3/2}-D_1^{3/2});$$

where N is number of trees per acre (assuming negligible mortality); D_1 is stand diameter at start of growth period; and D_2 is estimated future stand diameter.

Critique of LOGS Study Design

Hindsight is proverbially clearer than foresight, so it may be useful to point out some difficulties and questions encountered in the LOGS studies, which may influence design of future studies.

Blocked vs. completely randomized treatments.—Treatments were randomized among the 27 plots per installation. According to the original study plan, complete randomization was chosen over a randomized block design because analysis of a completely random design can better accommodate the expected loss of some plots.

To date, only one of the nine installations (Rocky Brook) has lost plots. Major losses occurred at Rocky Brook immediately after calibration; those plots were replaced with spare plots. One plot has since been lost to root rot (1982). It appears that blocking, perhaps on the basis of characteristics such as slope position or tree dimensions at end of the calibration period, would have been a feasible alternative to complete randomization.

Plot size.—The 0.2-acre plots used are too small to allow continuation of thinning beyond the 60 feet of height increment originally planned. Thinning must cease at a stage when differences among treatments are increasing rapidly and when stands are still well short of any biologically reasonable rotation age. The result is a major gap in information. This is not a criticism of the LOGS study design; the study was not intended to extend to later stand development. Rather, it indicates that there was and is a need for concurrent studies addressing the later development of stands having early and continued stocking control.

Buffers.—Associated with the limitations of small plots is the question of possible effect of the lack of buffers. Some edge effects must exist. Although we think such effects are minor, they could have had some influence on the results. The possibility exists for future analysis of this question on those installations that have been stem-mapped or had trees on the inner 0.1 acre identified. Comparisons could also be made using the two Canadian Forestry Service installations, which do have buffers.

Crop Trees.—Well-spaced crop trees, selected after the calibration cut at the rate of 80 per acre, are retained through subsequent thinnings. The utility of this procedure and its possible effect on stand development have sometimes been questioned.

In general, crop trees have been fairly stable over time, although occasional substitutions have been made because of damage or poor growth of initially selected individual crop trees. Limited comparisons of diameters of crop trees with average diameters of the largest 80 trees per acre (see footnote 7), after the calibration thinning, showed that initial average diameter of crop trees was substantially smaller than that of the 80 largest trees per acre. Subsequent diameter growth at Hoskins, Skykomish, and Clemons was slightly greater for the 80 largest trees per acre than for the crop trees. This difference was larger on controls than on thinned plots, because in the later periods on thinned plots these were nearly the same trees.

Slightly larger trees and slightly more volume might have been produced by a more flexible choice of leave trees at each thinning. On the other hand, permanently marked crop trees simplify control of spacing in thinnings and make it easier to maintain comparability of treatments. Marked crop trees are most useful in early thinnings. Their usefulness declines with time, as substitutions are made necessary by individual tree damage and decline in vigor. Rigid adherence to the initial choice of crop trees is neither reasonable nor feasible.

Kind of thinning.—The LOGS study plan specifications produce d/D ratios of about 0.9 in the earlier treatment thinnings and higher growing stock levels, and d/D's near 1.0 after removal of all noncrop trees. Until all noncrop trees have been removed, these d/D ratios represent crown thinnings and appear entirely reasonable. Although strict, low thinning would have produced somewhat different stand structures and might have resulted in slightly more growth in the early years, removal of some of the larger trees is necessary if spacing is to be controlled and crop trees favored.

Justification for a d/D of 1.0 after removal of all noncrop trees is less clear. Low thinning is not possible at this stage because of the absence of lower crown classes, but differences are still evident in individual tree size and vigor that suggest that a d/D of somewhat less than 1.0 would be silviculturally preferable. The reasons for specifying a d/D of 1.0 at this stage are not now clear. They may have been in part simplicity; in part suggested by the requirements of Staebler's (1960) procedure for calculating numerical thinning schedules; and in part an expectation of a narrower range of crop tree diameters than has actually developed.

A d/D of 1.0 is usually attained only in the final thinning at the lowest growing stock levels, and this specification has probably not had much effect on the outcome of the experiment. It does not seem a desirable restriction, however, and we do not recommend it for future studies.

Thinning cycle.—The LOGS thinning cycle was defined as the time required for 10 feet of height growth. Definition in terms of height growth is biologically reasonable and facilitates work scheduling because height growth can be predicted fairly well from standard site curves. The short cycle, though not operationally realistic, is justified in the LOGS study as a means of maintaining close control over growing stock. The resulting light thinnings also avoid any possible exposure effects not directly related to growing stock level.

Height measurements.—Despite the detailed study plan and generally close quality control, some problems exist with height measurements. Inadequate sampling in some periods at Skykomish and Clemons has forced combining height measurements by treatment, thereby preventing adjustment of plot values for height differences or satisfactory assessment of among-plot site differences. The peculiar trend of volumes at Hoskins in treatment period 3 strongly suggests some systematic error in height measurements, despite apparently adequate sampling. These difficulties emphasize the critical importance of adequate sampling and careful measurement of heights.

Initial differences among controls.—Initial differences among controls in different installations could have influenced control plot growth and, therefore, definition of thinning treatments. In retrospect, all controls should probably have been reduced to some standard number of stems at calibration.

Number of installations.—There is some difficulty in generalizing results because of the small number of locations represented. There are five LOGS installations on site II, two on site III, and one each on sites IV and V. Results to date show clearly that, among the site II studies, relationships between growth and growing stock are qualitatively similar but quantitatively considerably different. Five locations are insufficient to establish good regional averages or to identify causes of differences. This will be even more true of the poorer sites.

The combination of stringent uniformity requirements and the relatively large area required to accommodate three replications of nine treatments forced use of small plots and made it difficult to locate suitable areas, thereby limiting the number of installations. If future studies are to sample a wider range of site conditions and geographical areas, they must be less complex and less demanding in area and uniformity requirements to allow more installations. This will probably mean fewer treatments and use of blocking or covariates to reduce the effect of initial variation in site and stand conditions.

Analysis.—The study plan discussed analyses solely in terms of analyses of variance, and contemplated (but did not spell out) a combined ANOVA including all installations. A combined ANOVA does not appear feasible because of uncertain equivalence of thinning treatments in different installations and because of heterogeneous variances. The more meaningful analyses have been by graphic and regression methods. We think this will remain true for future analyses of these studies.

The most productive future use of the LOGS data and the most effective means of applying results to practical management will probably be their use, in combination with other data, in construction and refinement of stand simulators. The LOGS studies provide a unique set of high-quality data from young stands maintained at relatively low densities. This is a condition of crucial importance in evaluating stand management regimes for our future forests, and for which very little other data are now available. The LOGS studies provide basic information on the nature of relationships between growth and growing stock in such stands. The future use of this information in combination with other data should provide greatly improved predictive functions for stand simulation.

The Future of the LOGS Studies

The LOGS program is now over 20 years old and is an outstanding example of continuity and coordination achieved with a minimum of formal organization. Study installation and maintenance have been carried out by the individual cooperators. A number of the studies have now reached a stage where meaningful analyses can be made, and this report is a first effort in such analyses. As additional data become available within the next few years, the LOGS data will be widely recognized as a resource unique in its nature and quality and a "gold mine" for those engaged in growth modeling and stand management research. It is therefore important that there be no loss of interest and continuity and that the studies on the poorer sites—which are developing slowly and unspectacularly—be carried through to completion.

An immediate concern is disposition of the site II studies following completion of the fifth treatment period, which marks the end of the experiment as originally planned and which is now imminent for four LOGS studies. These stands are still well short of any reasonable final harvest age, and the thinning treatments will clearly influence stand development long after the originally planned completion of the experiment. The stands are unique in that they have developed under closely controlled and thoroughly documented conditions, including relatively low densities. Further thinning treatments are not feasible, because of the small size (0.2 acre) of the plots. There are simply too few trees left per plot to allow reasonable thinning.

The stands in the lower density treatments are still relatively open and will undoubtedly make excellent growth for a considerable period without further thinning. Indeed, an extended period of growth without further thinning seems a reasonable management alternative for stands in their present condition.

We recommend that, following completion of the fifth treatment period, these stands be allowed to grow without further treatment for at least two additional growth periods (20 feet of height growth) with remeasurements made after 10 and after 20 feet of height growth.

The present LOGS Committee should continue with all present cooperators, including those that have installations with all five treatments completed. A new version of this report should be prepared as soon as the committee feels sufficient additional data are available. Such a revision, or supplemental reports, should include additional analyses covering topics not treated here. Examples include values produced by thinning regimes; crown development; stem quality; effect of absence of buffer strips; and diameter distributions in relation to other stand characteristics and thinning regimes.

Metric Equivalents

1 inch = 2.54 centimeters
1 foot = 0.3048 meter
1 square foot = 0.09290 square meter
1 acre = 0.4047 hectare
1 square foot per acre = 0.2296 square meter per hectare
1 cubic foot per acre = 0.06997 cubic meter per hectare
1 mile = 1.609 kilometers.

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Appendix 1
Tables 22-51

Table 22—Skykomish study: means of periodic annual increment in gross basal area (all trees), by treatment and period

Treatment	Period 1	2	3	4	Mean
	- - - - - -	Square feet per acre per year	- - - - - -		
Fixed:					
1	7.13	6.34	6.01	4.83	6.08
3	8.03	7.19	7.95	6.58	7.44
5	8.31	7.33	8.12	7.46	7.80
7	9.63	8.86	9.64	8.49	9.16
Mean	8.28	7.43	7.93	6.84	7.62
Increasing:					
2	7.26	6.32	7.15	6.46	6.80
4	7.74	7.42	8.08	6.78	7.51
Mean	7.50	6.87	7.62	6.62	7.15
Decreasing:					
6	8.93	7.71	8.31	6.88	7.96
8	8.83	8.09	8.62	7.37	8.23
Mean	8.88	7.90	8.46	7.12	8.09
Variable:					
Mean	8.19	7.39	8.04	6.87	7.62
Mean, all treatments	8.24	7.41	7.98	6.86	7.62

Table 23—Hoskins study: means of periodic annual increment in gross basal area (all trees), by treatment and period

Treatment	Period 1	2	3	4	Mean
	- - - - - -	Square feet per acre per year	- - - - - -		
Fixed:					
1	11.08	8.23	6.33	5.83	7.87
3	11.80	9.90	8.23	7.15	9.27
5	12.90	11.50	9.83	8.49	10.68
7	13.62	12.39	10.03	8.85	11.22
Mean	12.35	10.51	8.61	7.58	9.76
Increasing:					
2	11.15	8.87	7.50	6.68	8.55
4	11.76	10.07	8.78	7.35	9.49
Mean	11.45	9.47	8.14	7.01	9.02
Decreasing:					
6	13.08	11.24	9.47	7.83	10.40
8	13.36	11.87	9.42	8.52	10.79
Mean	13.22	11.56	9.44	8.18	10.60
Variable:					
Mean	12.34	10.51	8.79	7.60	9.81
Mean, all treatments	12.34	10.51	8.70	7.59	9.78

Table 24—Clemons study: means of periodic annual increment in gross basal area (all trees), by treatment and period

Treatment	Period 1	2	3	4	Mean
	- - - - - - Square feet per acre per year - - - - - -				
Fixed:					
1	6.65	5.96	5.79	4.59	5.75
3	7.11	6.67	6.66	5.58	6.50
5	7.58	8.03	7.60	6.64	7.46
7	7.78	7.94	7.10	5.79	7.16
Mean	7.28	7.15	6.77	5.65	6.72
Increasing:					
2	7.02	6.16	5.82	4.51	5.88
4	7.33	6.93	6.97	5.72	6.74
Mean	7.18	6.54	6.39	5.11	6.31
Decreasing:					
6	8.16	7.57	7.00	5.38	7.03
8	7.38	7.71	7.31	5.77	7.04
Mean	7.77	7.64	7.16	5.58	7.04
Variable:					
Mean	7.48	7.09	6.78	5.34	6.67
Mean, all treatments	7.38	7.12	6.78	5.50	6.69

Table 25—Francis study: means of periodic annual increment in gross basal area (all trees), by treatment and period

Treatment	Period 1	2	3	4	Mean
	- - - - - - Square feet per acre per year - - - - - -				
Fixed:					
1	8.33	7.55	6.38	4.98	6.81
3	8.73	9.92	8.19	6.62	8.37
5	10.69	11.62	8.97	8.20	9.87
7	12.27	12.74	11.43	9.50	11.48
Mean	10.00	10.46	8.74	7.32	9.13
Increasing:					
2	7.92	7.80	6.88	5.92	7.13
4	9.26	10.40	9.75	8.49	9.47
Mean	8.56	9.10	8.32	7.21	8.30
Decreasing:					
6	11.29	11.21	9.16	7.72	9.84
8	11.28	11.52	9.56	8.23	10.15
Mean	11.28	11.37	9.36	7.98	10.00
Variable:					
Mean	9.94	10.23	8.84	7.59	9.15
Mean, all treatments	9.97	10.35	8.79	7.46	9.14

Table 26—Skykomish study: means of gross basal area growth percent (all trees), by treatment and period

Treatment	Period 1	2	3	4	Mean
	Percent				
Fixed:					
1	11.1	9.2	8.3	6.6	8.8
3	10.9	8.8	8.3	6.3	8.6
5	10.2	7.6	7.1	5.6	7.6
7	10.7	8.0	7.0	5.3	7.7
Mean	10.7	8.4	7.7	5.9	8.2
Increasing:					
2	11.1	9.0	8.6	6.5	8.8
4	10.6	8.7	7.7	5.4	8.1
Mean	10.8	8.9	8.2	6.0	8.4
Decreasing:					
6	10.9	8.2	7.8	6.2	8.3
8	9.9	7.6	6.8	5.3	7.4
Mean	10.4	7.9	7.3	5.7	7.8
Variable:					
Mean	10.6	8.4	7.7	5.9	8.2
Mean, all treatments	10.7	8.4	7.7	5.9	8.2

Table 27—Hoskins study: means of gross basal area growth percent (all trees), by treatment and period

Treatment	Period 1	2	3	4	Mean
	Percent				
Fixed:					
1	14.3	11.3	9.0	7.5	10.5
3	13.4	10.3	8.2	6.4	9.6
5	12.8	9.5	7.5	5.8	8.9
7	12.1	8.7	6.3	4.9	8.0
Mean	13.2	9.9	7.7	6.1	9.2
Increasing:					
2	14.2	11.2	8.9	6.8	10.3
4	13.2	9.9	7.7	5.6	9.1
Mean	13.7	10.5	8.3	6.2	9.7
Decreasing:					
6	12.9	9.8	8.0	6.1	9.2
8	11.9	8.7	6.4	5.3	8.1
Mean	12.4	9.2	7.2	5.7	8.6
Variable:					
Mean	13.0	9.9	7.8	6.0	9.2
Mean, all treatments	13.1	9.9	7.8	6.0	9.2

Table 28—Clemons study: means of gross basal area growth percent (all trees), by treatment and period

Treatment	Period 1	2	3	4	Mean
	Percent				
Fixed:					
1	12.8	11.6	10.8	8.0	10.8
3	12.3	10.2	9.1	6.5	9.5
5	11.5	10.0	8.2	6.0	8.9
7	11.0	8.6	6.6	4.6	7.7
Mean	11.9	10.1	8.7	6.3	9.2
Increasing:					
2	13.4	11.2	9.4	6.2	10.0
4	12.3	10.0	8.5	6.0	9.2
Mean	12.8	10.6	8.9	6.1	9.6
Decreasing:					
6	12.1	9.9	8.4	6.2	9.1
8	10.7	8.6	7.2	5.1	7.9
Mean	11.4	9.3	7.8	5.6	8.5
Variable:					
Mean	12.1	9.9	8.4	5.9	9.1
Mean, all treatments	12.0	10.0	8.5	6.1	9.2

Table 29—Francis study: means of gross basal area growth percent (all trees), by treatment and period

Treatment	Period 1	2	3	4	Mean
	Percent				
Fixed:					
1	18.1	14.2	11.2	8.6	13.0
3	17.4	13.1	9.3	6.7	11.6
5	15.6	12.0	7.6	5.9	10.3
7	16.3	11.0	7.6	5.4	10.0
Mean	16.9	12.6	8.9	6.6	11.2
Increasing:					
2	17.2	13.4	9.6	6.7	11.7
4	17.8	12.8	9.0	6.5	11.5
Mean	17.5	13.1	9.3	6.6	11.6
Decreasing:					
6	16.8	12.3	8.8	7.0	11.2
8	16.0	10.7	7.2	5.5	9.9
Mean	16.4	11.5	8.0	6.3	10.5
Variable:					
Mean	16.9	12.3	8.6	6.5	11.1
Mean, all treatments	16.9	12.4	8.8	6.6	11.2

Table 30—Skykomish study: means of periodic annual increment in gross volume (all trees), by treatment and period

Treatment	Period 1	2	3	4	Mean
	- - - - - - Cubic feet per acre per year - - - - -				
Fixed:					
1	245	251	260	243	250
3	258	288	349	308	301
5	295	302	413	408	355
7	314	338	440	454	387
Mean	278	295	366	353	323
Increasing:					
2	242	254	323	337	389
4	254	319	377	330	320
Mean	248	286	350	334	305
Decreasing:					
6	296	322	360	361	335
8	320	336	417	349	355
Mean	308	329	389	355	345
Variable:					
Mean	278	303	369	344	325
Mean, all treatments	278	301	367	349	324

Table 31—Hoskins study: means of periodic annual increment in gross volume (all trees), by treatment and period

Treatment	Period 1	2	3	4	Mean
	- - - - - Cubic feet per acre per year - - - - -				
Fixed:					
1	322	293	223	256	274
3	349	385	316	344	348
5	398	439	408	416	415
7	428	494	437	471	458
Mean	374	403	346	372	374
Increasing:					
2	328	325	286	301	310
4	356	384	357	361	365
Mean	342	355	321	331	337
Decreasing:					
6	396	427	376	368	392
8	423	485	378	453	435
Mean	409	456	377	411	413
Variable:					
Mean	376	405	349	371	375
Mean, all treatments	375	404	348	371	374

Table 32—Clemons study: means of periodic annual increment in gross volume (all trees), by treatment and period

Treatment	Period 1	2	3	4	Mean
	- - - - - - Cubic feet per acre per year - - - - -				
Fixed:					
1	188	190	198	189	191
3	196	232	263	238	232
5	206	250	286	259	250
7	233	293	277	257	265
Mean	206	241	256	236	235
Increasing:					
2	187	216	212	206	205
4	201	232	264	234	233
Mean	194	224	238	220	219
Decreasing:					
6	228	256	283	234	250
8	217	279	273	260	257
Mean	222	267	278	247	254
Variable:					
Mean	208	246	258	234	236
Mean, all treatments	207	243	257	235	236

Table 33—Francis study: means of periodic annual increment in gross volume (all trees), by treatment and period

Treatment	Period 1	2	3	4	Mean
	- - - - - Cubic feet per acre per year - - - - -				
Fixed:					
1	168	196	194	180	184
3	188	274	260	258	245
5	239	331	334	360	316
7	272	369	417	408	367
Mean	217	292	302	301	278
Increasing:					
2	184	222	225	233	216
4	208	290	336	343	294
Mean	196	256	281	288	255
Decreasing:					
6	249	312	311	304	294
8	256	342	366	371	334
Mean	252	327	338	338	314
Variable:					
Mean	224	292	310	313	285
Mean, all treatments	221	292	306	307	281

Table 34—Skykomish study: means of gross volume growth percent (all trees), by treatment and period

Treatment	Period 1	2	3	4	Mean
	- - - -	- - - -	Percent	- - - -	- - - -
Fixed:					
1	14.7	12.6	10.9	9.0	11.8
3	14.5	13.0	11.7	8.4	11.9
5	14.8	11.3	11.1	8.3	11.4
7	13.8	11.0	10.3	8.0	10.8
Mean	14.4	12.0	11.0	8.4	11.5
Increasing:					
2	15.1	13.1	12.1	9.4	12.4
4	14.3	13.4	11.2	7.4	11.6
Mean	14.7	13.3	11.7	8.4	12.0
Decreasing:					
6	14.4	12.2	10.6	9.0	11.6
8	14.3	11.2	10.3	7.0	10.7
Mean	14.3	11.7	10.4	8.0	11.1
Variable:					
Mean	14.5	12.5	11.0	8.2	11.6
Mean, all treatments	14.5	12.2	11.0	8.3	11.5

Table 35—Hoskins study: means of gross volume growth percent (all trees), by treatment and period

Treatment	Period 1	2	3	4	Mean
	- - - -	- - - -	Percent	- - - -	- - - -
Fixed:					
1	19.3	15.8	11.4	10.7	14.3
3	18.4	15.5	11.0	9.7	13.7
5	18.4	14.2	11.0	9.0	13.1
7	17.8	13.5	9.6	8.3	12.3
Mean	18.4	14.8	10.8	9.4	13.3
Increasing:					
2	19.3	15.8	11.9	9.8	14.2
4	18.3	14.5	10.9	8.7	13.1
Mean	18.8	15.2	11.4	9.2	13.7
Decreasing:					
6	18.3	14.6	11.4	9.3	13.4
8	17.3	13.7	9.0	8.8	12.2
Mean	17.8	14.2	10.2	9.0	12.8
Variable:					
Mean	18.3	14.7	10.8	9.2	13.2
Mean, all treatments	18.4	14.7	10.8	9.3	13.3

Table 36—Clemons study: means of gross volume growth percent (all trees), by treatment and period

Treatment	Period 1	2	3	4	Mean
	- - - - - -	- - - - -	Percent	- - - - -	- - - - - -
Fixed:					
1	18.4	16.0	14.1	11.1	14.9
3	17.3	15.2	13.4	9.1	13.7
5	16.6	14.1	12.4	8.4	12.9
7	16.1	13.2	9.5	6.9	11.4
Mean	17.1	14.6	12.3	8.9	13.2
Increasing:					
2	17.8	16.5	12.6	9.4	14.1
4	17.2	14.4	12.3	8.4	13.1
Mean	17.5	15.5	12.5	8.9	13.6
Decreasing:					
6	17.4	14.5	12.8	8.9	13.4
8	15.9	13.3	10.2	7.9	11.8
Mean	16.6	13.9	11.5	8.4	12.6
Variable:					
Mean	17.1	14.7	12.0	8.6	13.1
Mean, all treatments	17.1	14.7	12.2	8.8	13.2

Table 37—Francis study: means of gross volume growth percent (all trees), by treatment and period

Treatment	Period 1	2	3	4	Mean
	- - - - - -	- - - - -	Percent	- - - - -	- - - - - -
Fixed:					
1	23.6	19.0	14.7	11.8	17.3
3	23.4	18.1	12.6	9.9	16.0
5	21.4	17.0	11.7	9.2	14.8
7	22.9	16.2	11.7	8.5	14.8
Mean	22.8	17.6	12.7	9.8	15.7
Increasing:					
2	23.0	17.9	12.5	9.5	15.7
4	23.9	17.5	12.8	9.5	15.9
Mean	23.4	17.7	12.7	9.5	15.8
Decreasing:					
6	22.6	17.0	12.5	10.2	15.6
8	22.2	15.8	11.4	8.9	14.6
Mean	22.4	16.4	12.0	9.5	15.1
Variable:					
Mean	22.9	17.0	12.3	9.5	15.4
Mean, all treatments	22.9	17.3	12.5	9.7	15.6

Table 38—Skykomish study: means of periodic annual increment in quadratic mean diameter (all trees), by treatment and period

Treatment	Period 1	2	3	4	Mean
	Inches per year				
Fixed:					
1	0.445	0.443	0.499	0.489	0.469
3	.404	.377	.431	.400	.403
5	.375	.322	.345	.314	.339
7	.409	.349	.356	.301	.354
Mean	.408	.373	.408	.376	.391
Increasing:					
2	.411	.387	.440	.397	.409
4	.439	.419	.442	.362	.415
Mean	.425	.403	.441	.379	.412
Decreasing:					
6	.397	.350	.392	.376	.379
8	.362	.318	.329	.293	.326
Mean	.380	.334	.361	.334	.352
Variable:					
Mean	.402	.369	.401	.357	.382
Mean, all treatments	.405	.371	.404	.367	.387

Table 39—Hoskins study: means of periodic annual increment in quadratic mean diameter (all trees), by treatment and period

Treatment	Period 1	2	3	4	Mean
	Inches per year				
Fixed:					
1	0.588	0.603	0.559	0.537	0.572
3	.545	.519	.472	.416	.488
5	.498	.449	.398	.341	.422
7	.488	.415	.333	.287	.381
Mean	.530	.497	.440	.395	.465
Increasing:					
2	.601	.610	.570	.487	.567
4	.548	.506	.442	.363	.465
Mean	.575	.558	.506	.425	.516
Decreasing:					
6	.527	.492	.456	.396	.468
8	.476	.416	.340	.306	.385
Mean	.502	.454	.398	.351	.426
Variable:					
Mean	.538	.506	.452	.388	.471
Mean, all treatments	.534	.501	.446	.392	.468

Table 40—Clemons study: means of periodic annual increment in quadratic mean diameter (all trees), by treatment and period

Treatment	Period 1	Period 2	Period 3	Period 4	Mean
			Inches per year		
Fixed:					
	0.407	0.465	0.527	0.471	0.468
3	.384	.392	.415	.342	.383
5	.344	.357	.338	.282	.330
7	.330	.305	.261	.203	.275
Mean	.366	.380	.385	.324	.364
Increasing:					
2	.456	.485	.492	.389	.455
4	.394	.391	.382	.304	.368
Mean	.425	.438	.437	.346	.411
Decreasing:					
6	.375	.373	.365	.306	.355
8	.308	.292	.277	.223	.275
Mean	.342	.332	.321	.265	.315
Variable:					
Mean	.383	.385	.379	.305	.363
Mean, all treatments	.375	.383	.382	.315	.364

Table 41—Francis study: means of periodic annual increment in quadratic mean diameter (all trees), by treatment and period

Treatment	Period 1	Period 2	Period 3	Period 4	Mean
			Inches per year		
Fixed:					
1	0.551	0.589	0.624	0.580	0.586
3	.543	.540	.485	.422	.497
5	.477	.472	.372	.325	.411
7	.482	.412	.340	.272	.376
Mean	.513	.503	.455	.400	.468
Increasing:					
2	.589	.625	.579	.483	.569
4	.565	.535	.469	.398	.491
Mean	.577	.580	.524	.440	.530
Decreasing:					
6	.519	.495	.440	.420	.468
8	.455	.385	.311	.271	.356
Mean	.487	.440	.375	.346	.412
Variable:					
Mean	.532	.510	.450	.393	.471
Mean, all treatments	.523	.507	.452	.396	.469

Table 42—Skykomish study: means of quadratic mean diameter growth percent (all trees), by diameter and period

Treatment	Period 1	2	3	4	Mean
	- - - - - -	- - - - -	Percent	- - - - -	- - - - -
Fixed:					
1	5.57	4.65	4.17	3.31	4.42
3	5.48	4.42	4.20	3.17	4.32
5	5.15	3.83	3.56	2.82	3.84
7	5.38	3.99	3.54	2.64	3.89
Mean	5.40	4.22	3.87	2.98	4.12
Increasing:					
2	5.57	4.52	4.32	3.29	4.42
4	5.32	4.38	3.89	2.72	4.08
Mean	5.44	4.45	4.10	3.01	4.25
Decreasing:					
6	5.48	4.14	3.93	3.11	4.16
8	4.98	3.81	3.43	2.66	3.72
Mean	5.23	3.98	3.68	2.88	3.94
Variable:					
Mean	5.34	4.21	3.89	2.94	4.20
Mean, all treatments	5.37	4.22	3.88	2.96	4.11

Table 43—Hoskins study: means of quadratic mean diameter growth percent (all trees), by treatment and period

Treatment	Period 1	2	3	4	Mean
	- - - - - -	- - - - -	Percent	- - - - -	- - - - -
Fixed:					
1	7.32	5.70	4.49	3.77	5.32
3	6.84	5.16	4.10	3.21	4.83
5	6.51	4.78	3.76	2.89	4.48
7	6.16	4.35	3.14	2.46	4.03
Mean	6.71	5.00	3.87	3.08	4.66
Increasing:					
2	7.28	5.62	4.47	3.42	5.20
4	6.71	4.96	3.85	2.82	4.58
Mean	6.99	5.29	4.16	3.12	4.89
Decreasing:					
6	6.57	4.93	4.02	3.08	4.65
8	6.02	4.37	3.22	2.64	4.06
Mean	6.29	4.65	3.62	2.86	4.36
Variable:					
Mean	6.64	4.97	3.89	2.99	4.62
Mean, all treatments	6.68	4.98	3.88	3.04	4.64

Table 44—Clemons study: means of quadratic mean diameter growth percent (all trees), by treatment and period

Treatment	Period 1	Period 2	Period 3	Period 4	Mean
	Percent				
Fixed:					
1	6.49	5.87	5.45	4.03	5.46
3	6.24	5.13	4.58	3.26	4.80
5	5.85	5.01	4.11	3.01	4.49
7	5.58	4.33	3.30	2.29	3.87
Mean	6.04	5.08	4.36	3.15	4.66
Increasing:					
2	6.80	5.63	4.71	3.14	5.07
4	6.26	5.01	4.28	2.99	4.63
Mean	6.53	5.32	4.49	3.06	4.85
Decreasing:					
6	6.15	4.98	4.22	3.09	4.61
8	5.40	4.32	3.60	2.58	3.97
Mean	5.77	4.65	3.91	2.83	4.29
Variable:					
Mean	6.15	4.99	4.20	2.95	4.57
Mean, all treatments	6.10	5.04	4.28	3.05	4.62

Table 45—Francis study: means of quadratic mean diameter growth percent (all trees), by treatment and period

Treatment	Period 1	Period 2	Period 3	Period 4	Mean
	Percent				
Fixed:					
1	9.22	7.24	5.68	4.35	6.62
3	8.88	6.68	4.68	3.38	5.90
5	7.93	6.11	3.92	2.96	5.23
7	8.26	5.58	3.80	2.68	5.08
Mean	8.57	6.40	4.52	3.34	5.71
Increasing:					
2	8.74	6.83	4.82	3.39	5.94
4	9.06	6.52	4.56	3.28	5.85
Mean	8.90	6.67	4.69	3.34	5.90
Decreasing:					
6	8.53	6.23	4.42	3.54	5.68
8	8.12	5.43	3.64	2.78	4.99
Mean	8.33	5.83	4.03	3.16	5.34
Variable:					
Mean	8.61	6.25	4.36	3.25	5.62
Mean, all treatments	8.59	6.32	4.44	3.29	5.66

Table 46—Gross cubic volume yield in trees 1.6 inches d.b.h. and larger (material removed in calibration cut excluded), by treatment and age, for the Skykomish, Hoskins, Clemons, Francis, and Iron Creek studies

			Gross volume yield by treatments								
			Fixed				Increasing		Decreasing		
	Age	H40	T-1	T-3	T-5	T-7	T-2	T-4	T-6	T-8	Control
	Years	Feet	Cubic feet per acre								
Skykomish	24	48	960	918	932	976	888	895	947	934	1,271
	28	60	2,081	1,897	1,903	2,151	1,914	1,921	2,001	2,010	2,460
	31	69	2,816	2,671	2,788	3,091	2,641	2,684	2,890	2,970	3,682
	34	77	3,569	3,534	3,696	4,107	3,402	3,641	3,856	3,977	5,023
	38	90	4,609	4,932	5,347	5,868	4,696	5,147	5,296	5,646	6,863
	42	100	5,581	6,166	6,980	7,686	6,045	6,468	6,739	7,041	8,854
Hoskins	20	40	744	746	720	750	729	749	743	768	1,982
	23	50	1,581	1,581	1,570	1,574	1,616	1,628	1,599	1,637	3,389
	27	63	2,868	2,975	3,160	3,286	2,926	3,054	3,182	3,330	5,680
	30	73	3,748	4,131	4,477	4,769	3,902	4,206	4,463	4,784	7,430
	32	78	4,195	4,763	5,294	5,643	4,473	4,920	5,215	5,540	8,310
	36	89	5,217	6,139	6,956	7,527	5,679	6,366	6,689	7,352	10,618
Clemons	19	36	477	470	438	492	524	507	459	469	854
	22	46	1,028	1,016	920	1,044	1,156	1,067	1,021	951	1,599
	26	57	1,780	1,800	1,743	1,976	1,905	1,872	1,933	1,819	2,766
	29	66	2,350	2,495	2,491	2,856	2,554	2,567	2,699	2,656	3,907
	32	74	2,942	3,283	3,349	3,688	3,189	3,350	3,649	3,476	4,949
	36	82	3,700	4,236	4,386	4,716	4,014	4,296	4,484	4,516	6,242
Francis	15	29	304	318	350	281	382	361	329	283	543
	18	39	802	867	895	793	994	918	881	779	1,328
	21	46	1,307	1,432	1,613	1,609	1,547	1,542	1,627	1,547	2,439
	25	58	2,091	2,528	2,937	3,083	2,437	2,703	2,875	2,917	4,123
	29	68	2,866	3,570	4,311	4,753	3,338	4,047	4,119	4,379	5,958
	33	77	3,585	4,602	5,757	6,387	4,272	5,420	5,357	5,867	7,666
Iron Creek	19	39	600	648	733	734	735	771	629	763	1,115
	23	50	1,389	1,488	1,606	1,619	1,673	1,721	1,454	1,678	2,342
	26	58	2,039	2,227	2,486	2,618	2,392	2,506	2,286	2,618	3,561
	30	68	2,889	3,327	3,766	4,039	3,338	3,662	3,559	3,952	5,329
	33	77	3,471	4,187	4,881	5,267	4,070	4,672	4,537	4,997	6,768

T-n = treatment "n."

Table 47—Quadratic mean diameters (after thinning), by treatment and age, for the Skykomish, Hoskins, Clemons, Francis, and Iron Creek studies

			Quadratic mean d.b.h. (after thinning), by treatment								
			Fixed				Increasing		Decreasing		
	Age	H40	T-1	T-3	T-5	T-7	T-2	T-4	T-6	T-8	Control
	Years	Feet	Inches								
Skykomish 1/	24	48	5.3 (6.4) 1/	5.0 (5.6)	5.1 (6.2)	5.2 (6.0)	5.0 (5.7)	5.5 (6.2)	4.9 (5.6)	5.1 (6.2)	4.7 (5.6)
	28	60	7.3 (8.8)	6.8 (7.4)	6.7 (8.3)	7.0 (7.9)	6.8 (7.4)	7.6 (8.4)	6.6 (7.3)	6.7 (7.9)	5.8 (6.8)
	31	69	8.8(10.4)	8.0 (8.8)	7.8 (9.7)	8.2 (9.3)	8.0 (8.4)	8.9 (9.9)	7.8 (8.6)	7.9 (9.1)	6.6 (7.7)
	34	77	10.9(12.3)	9.4(10.4)	8.9(11.0)	9.3(10.4)	9.3 (9.8)	10.4(11.4)	9.1(10.1)	8.9(10.2)	7.2 (8.4)
	38	90	13.8(14.8)	11.8(13.0)	10.4(13.1)	10.8(12.2)	11.3(12.0)	12.5(13.5)	11.2(12.8)	10.4(12.2)	8.2 (9.8)
	42	100	15.8(17.1)	14.2(15.4)	12.0(15.0)	12.1(13.9)	13.0(14.0)	14.2(15.2)	13.5(15.2)	11.9(14.1)	9.3(11.2)
Hoskins	20	40	5.1	5.1	5.0	5.2	5.2	5.3	5.2	5.3	3.8
	23	50	6.9	6.9	6.7	6.9	7.1	7.1	7.0	7.0	4.6
	27	63	9.7	9.3	8.7	8.9	9.9	9.5	9.3	8.9	5.8
	30	73	11.9	11.0	10.2	10.3	12.2	11.1	10.9	10.2	6.6
	32	78	13.2	12.1	11.1	11.1	13.3	12.2	12.0	11.0	7.2
	36	89	15.7	14.0	12.6	12.3	15.4	13.7	13.9	12.3	8.2
Clemons	19	36	4.1	4.1	4.0	4.0	4.2	4.2	4.1	4.0	4.0
	22	46	5.4	5.4	5.2	5.2	5.8	5.4	5.4	5.1	4.9
	26	57	7.2	7.0	6.6	6.6	7.9	7.1	6.9	6.3	5.9
	29	66	8.9	8.5	7.7	7.5	9.7	8.3	8.1	7.3	6.6
	32	74	10.7	9.8	8.7	8.4	11.6	9.5	9.4	8.2	7.2
	36	82	12.6	11.8	10.0	9.3	13.6	10.8	10.8	9.1	7.9
Francis	15	29	3.6	3.7	3.7	3.5	3.9	3.8	3.6	3.4	3.3
	18	39	5.2	5.3	5.3	5.1	5.9	5.4	5.3	4.9	4.0
	21	46	7.0	7.0	6.8	6.6	7.9	7.1	6.9	6.3	4.8
	25	58	9.7	9.4	8.8	8.3	10.8	9.3	9.1	7.9	5.7
	29	68	12.2	11.6	10.4	9.6	13.2	11.3	11.1	9.2	6.4
	33	77	14.7	13.6	11.7	10.7	15.2	12.9	13.2	10.4	7.0
Iron Creek	19	39	4.8	5.0	5.1	5.1	5.1	5.1	4.8	5.1	4.1
	23	50	6.7	6.8	6.9	6.7	7.0	7.0	6.6	6.9	4.5
	26	58	8.3	8.3	8.3	8.0	8.5	8.5	8.0	8.3	5.1
	30	68	10.6	10.1	9.9	9.4	10.6	10.4	9.6	9.8	5.7
	33	77	12.2	11.4	10.8	10.3	11.9	11.6	10.9	10.9	6.2

T-n = treatment "n."

1/ Values for Douglas-fir only given in parentheses.

Table 48—Periodic annual gross volume increment (PAI) by treatment and period, for all trees 1.6 inches d.b.h. and larger, for the Skykomish, Hoskins, Clemons, Francis, and Iron Creek studies

Study	Period ages	Period H40	Periodic annual gross volume increment, by treatment									
			Fixed				Increasing		Decreasing		Control	Control, net
			T-1	T-3	T-5	T-7	T-2	T-4	T-6	T-8		
	Years	Feet	Cubic feet per acre per year									
Skykomish	24-28	48-60	280	245	243	294	257	256	264	269	297	297
	28-31	60-69	245	258	295	314	242	254	296	320	407	401
	31-34	69-77	251	288	303	338	254	319	322	336	447	439
	34-38	77-90	260	349	413	440	323	377	360	417	460	381
	38-42	90-100	243	308	408	454	337	330	361	349	498	422
Hoskins	20-23	40-50	279	278	283	275	296	293	285	290	469	460
	23-27	50-63	322	349	398	428	328	356	396	423	573	512
	27-30	63-73	293	385	439	494	325	384	427	485	583	514
	30-32	73-78	223	316	408	437	286	357	376	378	1/ 440	1/ 276
	32-36	78-89	256	344	416	471	301	361	368	453	577	451
Clemons	19-22	36-46	184	182	161	184	211	187	187	161	248	247
	22-26	46-57	188	196	206	233	187	201	228	217	292	289
	26-29	57-66	190	232	249	293	216	232	256	279	381	374
	29-32	66-74	198	263	286	277	212	264	283	273	347	303
	32-36	74-82	189	238	259	257	206	234	234	260	323	290
Francis	15-18	29-39	166	183	182	171	204	186	184	165	262	258
	18-21	39-46	168	188	239	272	184	208	249	256	370	366
	21-25	46-58	196	274	331	369	222	290	312	342	421	412
	25-29	58-68	194	261	343	418	225	335	311	366	459	437
	29-33	68-77	180	258	360	408	233	343	310	372	427	415
Iron Creek	19-23	39-50	197	210	218	221	234	238	206	229	307	303
	23-26	50-58	216	246	293	333	240	262	277	320	406	394
	26-30	58-68	212	275	320	355	237	289	318	328	442	415
	30-33	68-77	213	293	372	424	266	345	331	360	480	322

T-n = treatment "n."

1/ Includes one plot with unexplained very low volume growth in this period; this was excluded from regression analyses.

Table 49—Mean annual increment (MAI) in gross volume,[1] by treatment and period, for all trees 1.6 inches d.b.h. and larger, for the Skykomish, Hoskins, Clemons, Francis, and Iron Creek studies

				Mean annual gross volume increment, by treatment								
				Fixed				Increasing		Decreasing		
Study	Period	Midperiod age	Midperiod H40	T-1	T-3	T-5	T-7	T-2	T-4	T-6	T-8	Control
		Years	Feet	Cubic feet per acre per year								
Skykomish	C	26	54	58	54	54	60	54	54	57	57	72
	1	29.5	65	83	77	80	89	77	78	83	84	104
	2	32.5	73	98	95	110	111	93	97	104	118	134
	3	36	84	114	118	126	138	112	122	127	138	165
	4	40	95	127	139	154	169	134	145	150	159	196
Hoskins	C	21.5	45	54	54	53	54	54	55	54	56	125
	1	25	57	89	91	95	97	91	94	96	99	181
	2	28.5	68	116	125	134	141	120	127	134	142	230
	3	31	76	128	143	158	168	135	147	156	166	254
	4	34	84	138	160	180	194	149	166	175	190	278
Clemons	C	20.5	41	37	36	33	37	41	38	36	35	60
	1	24	51	58	59	55	63	64	61	62	58	91
	2	27.5	61	75	78	77	88	81	81	84	81	121
	3	30.5	70	87	95	96	107	94	97	102	100	145
	4	34	78	98	111	114	124	106	113	118	118	165
Francis	C	16.5	34	34	36	38	32	42	39	37	32	57
	1	19.5	43	54	59	64	62	65	63	64	60	97
	2	23	52	74	86	99	102	87	92	115	97	143
	3	27	63	92	113	134	145	107	125	130	135	187
	4	31	72	104	132	162	180	123	153	153	165	220
Iron Creek	C	21	45	47	51	56	56	57	59	49	58	82
	1	24.5	54	70	76	84	86	83	86	76	88	120
	2	28	63	88	99	112	119	102	110	104	118	159
	3	31.5	73	101	119	137	148	118	132	128	142	192

T-n = treatment "n."

1/ Computations based on age at midpoint of growth period.

Table 50—Volumes produced in trees larger than 1.6, 7.6, 9.6, 11.6, and 13.6 inches d.b.h., at end of 4th treatment period, for the Skykomish and Hoskins studies

		Skykomish		Hoskins	
Treatment	Size class	Live stand	Total production 1/	Live stand	Total production 1/
	Inches d.b.h.	- - - - - - - - Cubic feet per acre - - - - - - - -			
1	1.6+	3,172	5,581	2,906	5,218
	7.6+	3,172	4,827	2,906	4,640
	9.6+	3,172	3,972	2,906	3,986
	11.6+	3,085	3,476	2,906	3,549
	13.6+	2,693	2,924	2,423	2,528
2	1.6+	4,262	6,045	3,686	5,679
	7.6+	4,262	5,395	3,686	5,235
	9.6+	4,018	4,438	3,671	4,627
	11.6+	3,260	3,436	3,487	3,935
	13.6+	2,312	2,449	2,993	3,109
3	1.6+	4,219	6,166	4,222	6,138
	7.6+	4,175	5,479	4,222	5,675
	9.6+	3,941	4,509	4,047	4,924
	11.6+	3,457	3,658	3,912	4,383
	13.6+	2,687	2,733	2,714	2,949
4	1.6+	5,142	6,468	4,865	6,366
	7.6+	5,103	5,960	4,855	5,948
	9.6+	4,959	5,330	4,731	5,331
	11.6+	4,255	4,299	4,485	4,770
	13.6+	3,614	3,614	3,138	3,240
5	1.6+	5,720	6,980	5,475	6,956
	7.6+	5,594	6,369	5,374	6,433
	9.6+	4,564	4,885	5,137	5,754
	11.6+	3,424	3,484	4,381	4,653
	13.6+	2,721	2,781	2,655	2,763
6	1.6+	4,673	6,738	4,717	6,688
	7.6+	4,616	5,989	4,694	6,333
	9.6+	4,205	4,860	4,623	5,702
	11.6+	3,336	3,565	4,224	4,646
	13.6+	2,413	2,503	3,127	3,230
7	1.6+	6,576	7,686	6,562	7,527
	7.6+	6,255	7,001	6,411	7,212
	9.6+	5,514	5,947	6,080	6,561
	11.6+	4,155	4,363	5,136	5,237
	13.6+	2,820	2,820	2,773	2,773
8	1.6+	5,638	7,040	6,026	7,352
	7.6+	5,467	6,411	5,886	7,042
	9.6+	4,664	5,214	5,490	6,269
	11.6+	3,802	4,096	4,714	5,157
	13.6+	2,803	2,928	2,458	2,458
Control	1.6+	8,192	--	9,312	--
	7.6+	6,909	--	6,955	--
	9.6+	4,867	--	4,555	--
	11.6+	3,315	--	2,335	--
	13.6+	1,908	--	1,044	--

-- = not applicable.

1/ Live stand + thinnings + mortality.

Table 51—Volumes produced in trees larger than 1.6, 7.6, 9.6, 11.6, and 13.6 inches d.b.h., at end of 4th treatment period, for the Clemons and Francis studies

Treatment	Size class	Clemons		Francis	
		Live stand	Total production 1/	Live stand	Total production 1/
	Inches d.b.h.	Cubic feet per acre			
1	1.6+	2,081	3,700	1,884	3,585
	7.6+	2,081	2,942	1,884	2,951
	9.6+	2,059	2,442	1,864	2,606
	11.6+	1,724	1,850	1,804	2,234
	13.6+	695	744	1,343	1,484
2	1.6+	2,569	4,015	2,931	4,273
	7.6+	2,569	3,250	2,931	3,736
	9.6+	2,423	2,694	2,931	3,356
	11.6+	2,209	2,297	2,906	3,087
	13.6+	1,278	1,278	2,705	2,845
3	1.6+	3,098	4,236	3,134	4,601
	7.6+	3,044	3,517	3,134	4,074
	9.6+	2,592	2,754	3,003	3,547
	11.6+	1,994	1,994	2,564	2,803
	13.6+	696	696	1,797	1,797
4	1.6+	3,218	4,296	4,293	5,421
	7.6+	3,034	3,596	4,282	4,930
	9.6+	2,470	2,771	4,731	4,582
	11.6+	1,741	1,811	3,608	3,800
	13.6+	701	701	2,003	2,061
5	1.6+	3,516	4,387	4,610	5,757
	7.6+	3,147	3,604	4,557	5,322
	9.6+	2,404	2,590	4,002	4,451
	11.6+	1,307	1,350	3,057	3,132
	13.6+	591	591	1,581	1,581
6	1.6+	3,063	4,483	3,590	5,358
	7.6+	2,943	3,828	3,573	4,924
	9.6+	2,382	2,658	3,395	4,106
	11.6+	1,452	1,542	2,732	2,918
	13.6+	372	372	1,503	1,555
7	1.6+	4,194	4,716	5,645	6,386
	7.6+	3,640	3,898	5,459	6,035
	9.6+	2,531	2,581	4,310	4,575
	11.6+	969	969	2,662	2,768
	13.6+	238	238	873	873
8	1.6+	3,752	4,517	4,930	5,867
	7.6+	3,194	3,535	4,657	5,352
	9.6+	2,158	2,290	3,783	4,120
	11.6+	910	910	1,889	1,978
	13.6+	251	251	646	646
Control	1.6+	5,941	--	7,468	--
	7.6+	4,387	--	5,265	--
	9.6+	2,713	--	3,184	--
	11.6+	1,418	--	1,287	--
	13.6+	929	--	151	--

-- = not applicable.

1/ Live stand + thinnings + mortality.

Appendix 2
The Nine Cooperative Study Areas

Study Area	Cooperator
Skykomish	Western Forestry Research Dept. Weyerhaeuser Company Tacoma, Washington
Hoskins	College of Forestry Oregon State University Corvallis, Oregon
Rocky Brook	USDA Forest Service Pacific Northwest Research Station and Pacific Northwest Region Portland, Oregon
Clemons	Western Forestry Research Dept. Weyerhaeuser Company Tacoma, Washington
Francis	Washington State Department of Natural Resources Olympia, Washington
Iron Creek	USDA Forest Service Pacific Northwest Research Station and Pacific Northwest Region Portland, Oregon
Stampede Creek	USDA Forest Service Pacific Northwest Research Station and Pacific Northwest Region Portland, Oregon
Sayward Forest	Canadian Forestry Service Department of the Environment Victoria, British Columbia
Shawnigan Lake	Canadian Forestry Service Department of the Environment Victoria, British Columbia

Glossary

Age—Total age (years from seed).

Age b.h.—Age at breast height (years since attaining breast height).

ANOVA—Analysis of variance.

B.h.—Breast height (4.5 feet above ground).

C—Symbol representing control treatment.

CT—Commercial thinning.

CVTS—Cubic volume of bole including stump and tip.

Dg—Quadratic mean diameter at breast height.

D.b.h.—Diameter at breast height.

d/D—Ratio of quadratic mean diameter of cut trees to quadratic mean diameter of all trees before cutting.

dD—Periodic annual increment in d.b.h.

dG—Periodic annual increment in basal area

dH—Periodic annual increment in height.

dV—Periodic annual increment in volume (CVTS).

G—Basal area.

g/G—Ratio of basal area of cut trees to basal area of stand before cutting.

H—Height.

H40—Mean height of the 40 largest (by diameter) trees per acre.

Hi/Hm—Ratio of plot value of H40 to installation mean value of H40.

ln—Natural logarithm (logarithm to base e).

LOGS—Acronym for Levels-Of-Growing-Stock.

MAI—Mean annual increment.

n/N—Ratio of number of trees cut to number of trees before cutting.

PAI—Periodic annual increment.

PCT—Precommercial thinning.

RD—A measure of relative density, defined as $G/Dg^{1/2}$.

RDn—A relative density value of n.

R^2—Coefficient of determination; equals the proportion of total sum of squares accounted for by regression.

SEEy—Standard error of estimate of the variable y.

SI_{50}—Site index value based on reference age 50 years b.h.

Tn—Treatment n.

TPn—Treatment period n.

V—Volume (equals CVTS as used in this report).

Curtis, Robert O.; Marshall, David D. Levels-of-growing-stock cooperative study in Douglas-fir: Report No. 8—The LOGS study: twenty-year results. Res. Pap. PNW-356. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station; **1986**. 113 p.

This progress report reviews the history and status of the cooperative levels-of-growing-stock study in coast Douglas-fir, begun in 1961, in Oregon, Washington, and British Columbia. It presents new analyses, including comparisons among some installations. Data now available are primarily from the site II installations, which are approaching completion of the study. Growth is strongly related to growing stock. Thinning treatments have produced marked differences in volume distribution by tree sizes. During the fourth treatment period, current annual increment was still about double the mean annual increment, and differences in volumes and size distributions among treatments have been increasing rapidly. There are considerable differences in productivity among installations, beyond those accounted for by site index differences. The LOGS study design is evaluated.

Keywords: Thinnings, (-stand volume, growing stock, (-increment/yield, Douglas-fir, *Pseudotsuga menziesii*, series—Douglas-fir LOGS.

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