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Periodic Annual Diameter Increment After Overstory Removal in Mixed Conifer Stands

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Abstract

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Diameter growth rates of understory trees were measured for periods both before and after overstory removal on six study areas in northern California. All the species responded with increased diameter growth after adjusting to their new environments. Linear regression equations that predict periodic annual increment of the diameters of the residual trees after treatment are presented for the six species in the study areas.

Retrieval Terms: California red fir, California white fir, Douglas-fir, incense-cedar, increment (diameter), Jeffrey pine, northern California, ponderosa pine, sugar pine

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In Brief...

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Retrieval terms: California red fir, California white fir, Douglas-fir, incense-cedar, increment (diameter), Jeffrey pine, northern California, ponderosa pine, sugar pine

Between 1978 and 1982, a total of 14 timber sale areas on the Plumas, Klamath, Lassen, Modoc, and Shasta-Trinity National Forests and the Swain Mountain Experimental Forest of the Pacific Southwest Research Station, all in northern California, were designed and implemented as overstory removals. Sales were in the true fir (TF), east-side pine (EP), or Sierra Nevada mixed-conifer (MC) timber type. Before cutting, the Silvicultural Development Unit of Region 5 of the USDA Forest Service established two to seven homogeneous units within each sale area for sampling before and after harvest conditions. Overstory volume removed from the timber sale units ranged from 72 to 707 m^3/ha (753 to 9418 ft^3/acre). These units ranged from 0.73 to 3.0 hectares (1.2 to 7.4 acres), depending on stand size and condition. From the 14 sale areas, 6 representative sale areas were selected for this study. Two are in the Lassen National Forest, two in the Plumas National Forest, one in the Shasta-Trinity National Forest, and one in the Swain Mountain Experimental Forest of the Pacific Southwest Research Station (PSW), located in the Lassen National Forest. These six areas are composed of Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco), California white fir (*Abies concolor* [Gord. & Glend.] Lindl.), California red fir (*Abies magnifica* A. Murr.), incense-cedar (*Libocedrus decurrens* Torr.), sugar pine (*Pinus lambertiana* Dougl.), ponderosa pine (*Pinus ponderosa* Laws.), and Jeffrey pine (*Pinus jeffreyi* Grev. & Balf.). Between 1988 and 1989, residual trees 7.62 cm (3 inches) in diameter at breast height (d.b.h.) or larger were measured and cored. The increment core samples were used to age sampled trees and to determine past diameter growth rate. The trees were remeasured in 1994. To show the effect of overstory removal on residual trees, a 2-dimensional bar chart was used to display combined data of periodic annual diameter increment (cm) 8 and 10 years before treatment, periodic annual diameter increment (cm) 8 and 10 years after treatment, and periodic annual diameter increment (cm) 9 to 16 years after treatment, by species, for the entire study area. All the species responded with increased diameter growth after adjusting to their new environments. With time, diameter growth response of sugar pine and Douglas-fir on the average, was the greatest, independent of timber sale area, whereas that of incense-cedar and ponderosa pine showed the least response. Within each timber sale area, units with the most overstory removed showed the highest diameter response, after treatment, whereas units with low amounts of overstory removal showed the least diameter response. Regardless of unit or species, periodic annual diameter increments 8 or 10 years after treatment were not different from their periodic annual diameter increments 8 or 10 years before treatment. However, after the trees adjusted to their new environment, periodic annual diameter increment 9 to 16 years after treatment showed a substantial increase in growth compared to their counterparts 8 or 10 years after treatment. Depending on species, periodic annual diameter increment 8 or 10 years before treatment, the square of periodic annual diameter increment 8 or 10 years before treatment, initial diameter, the square of initial diameter, total basal area per plot of residual trees larger in diameter than that of the subject tree, and total basal area per plot of residual trees larger in diameter than that of the subject tree divided by the subject tree's diameter were good predictors of periodic annual diameter growth response of the residual trees 9 to 16 years after treatment. For developing the regression equations, as a result of analyses of covariance, data on ponderosa pine and Jeffrey pine were combined.

Introduction

Today, in states like California, social, legislative, and economic considerations are compelling public and private forest managers to look for alternatives to clearcutting that will not dramatically change forest appearance. This paradigm shift is a result of one or the combinations of the following factors: (1) our improved understanding of natural ecosystem processes has increased greatly (O'Hara and others 1994, Oliver 1995); (2) management of uneven-aged stands has become a popular alternative because it can achieve biological and ecological diversity, ecosystem health and productivity, and sustainability of forest products and amenities across the landscape (Guldin 1995, Hagle 1995, O'Hara and others 1994); (3) the general public's dislike for even-aged management practices in favor of multi-aged management alternatives (Laacke and Fiddler 1986, Oliver 1995); and (4) the desire to practice ecologically based and socially acceptable forest management—termed the "social phase" of forestry development (Kimmins 1991).

Consequently, this evolution in management philosophy makes silvicultural practices like overstory removal attractive harvest alternatives to clearcutting and regeneration (Guldin 1995, Laacke and Fiddler 1986) because removing overstory can create stands with structural diversity that are well stocked with well-distributed crop trees that clearcutting may not provide (Guldin 1995, Helms and Standiford 1985, Laacke and Fiddler 1986, Oliver 1995). As a result, forest managers are interested in understanding the advantages and disadvantages as well as stand adequacy for overstory removal, because if properly implemented, the residual forest resulting from overstory removal serves as immediate growing stock, reducing the time needed to grow trees of merchantable size. In addition, from an esthetic perspective, the residual forest has an appearance of a continuous forest canopy (Guldin 1995). The residual forest also provides soil protection and cover for wildlife.

Nevertheless, overstory removal has three major disadvantages: (1) it may incorrectly be applied on even-aged stands; (2) skilled loggers familiar with improved harvesting techniques (which cost more) are necessary to protect advanced regeneration from damage and potential disease problems; and (3) logging slash is difficult and costly to remove without harming the advanced regeneration, and if left behind, the slash can be a fire hazard (Weatherspoon and Skinner 1995). The above disadvantages notwithstanding, alternatives like overstory removal, if implemented successfully, can result in uneven-aged mixed-species stands that are well stocked with well-distributed crop trees.

Meanwhile, for a stand to be adequate for overstory removal, it has to exhibit the following characteristics: (a) the stand has to be made up of at least two age classes, with the older class merchantable and removable; and (b) the residual stand should be adequately stocked with well-distributed crop trees, whose value would equal or exceed that attainable should the stand otherwise be regenerated (Laacke and Fiddler 1986).

The paper reports on the response of the diameter growth rate of residual trees (2.54 cm d.b.h. or greater) to varying levels of overstory removal; documents the growth of these trees over a long time in the true fir (TF), east-side pine (EP), and Sierra Nevada mixed-conifer (MC) timber type on the Plumas, Klamath, Lassen, Modoc, and Shasta-Trinity National Forests and on the Swain Mountain Experimental Forest of the Pacific Southwest Research Station, all in northern California; and provides equations for predicting periodic annual diameter increment of residual trees 14 to 16 years after treatment.

Methods

Between 1978 and 1982, a total of 14 timber sale areas on the Plumas, Klamath, Lassen, Modoc, and Shasta-Trinity National Forests and on the Swain Mountain Experimental Forest were designed and implemented as overstory removals. Sales were in the true fir, east-side pine, or Sierra Nevada mixed-conifer timber type. Before cutting, the Silvicultural Development Unit of the USDA Forest service Region 5 established two to seven homogeneous units within each sale area for sampling before and after harvest conditions.

Overstory volume removed from the timber sale units ranged from 72 to 707 m^3/ha (753 to 9418 $ft^3/acre$). The sampling units established within each sale area ranged from 0.73 to 3.0 hectares (1.2 to 7.4 acres), depending on stand size and condition. From the 14 sale areas, six representative sale areas were selected for this study—two on the Lassen National Forest, two on the Plumas National Forest, one on the Shasta-Trinity National Forest, and one on the Swain Mountain Experimental Forest, located in the Lassen National Forest. The six areas are composed of Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco), California white fir (*Abies concolor* [Gord. & Glend.] Lindl.), California red fir (*Abies magnifica* A. Murr.), incense-cedar (*Libocedrus decurrens* Torr.), sugar pine (*Pinus lambertiana* Dougl.), ponderosa pine (*Pinus ponderosa* Laws.), and Jeffrey pine (*Pinus jeffreyi* Grev. & Balf.). Between 1988 and 1989, residual trees 7.62 cm (3 inches) diameter at breast height (d.b.h.) or larger were measured and cored. The increment cores were used to age sampled trees and to determine past diameter growth rate. The trees were remeasured in 1994.

Study Design

Plot Location and Installation

The characteristics of the six selected overstory removal sale areas are shown in *table 1*. Three permanent plots were located in each sale area except for the Johnson's Ravine sale in the Plumas National Forest, which had only two suitable units available for plot installation. One plot was installed in each of these units. The units were selected for plot installation on the basis of the volume of overstory removed. These plots were installed in the units as follows: (1) the first plot was installed in the unit from which the highest volume (m^3/ha) had been removed, (2) the second plot was installed in the unit from which the lowest volume had been removed, and (3) the third

Table 1—Overstory characteristics of timber stands on three National Forests in northern California.

National Forest	*Sale area*	*Mean d.b.h.*	*Unit no.*	*Plot Size*	*Volume removed*	*Trees/ hectare removed*	*Forest type*
		cm		ha	M^3/ha		
Lassen	*Ashpan*	*66.04*	*1*	*3.2*	*148*	*37*	*MC*
		73.66	*3*	*1.7*	*402*	*54*	*MC*
		93.98	*5*	*1.4*	*302*	*27*	*MC*
Lassen	*Baker*	*73.70*	*1*	*1.7*	*71*	*12*	*EP*
		76.20	*2*	*1.9*	*112*	*30*	*EP*
		83.80	*4*	*1.6*	*171*	*25*	*EP*
Plumas	*Johnson*	*71.12*	*3*	*1.2*	*286*	*62*	*MC*
	Ravine	*78.74*	*4*	*1.2*	*438*	*62*	*MC*
Plumas	*Clear Creek*	*83.82*	*1*	*2.0*	*360*	*44*	*MC*
		106.70	*2*	*1.1*	*416*	*30*	*MC*
		91.44	*4*	*3.1*	*591*	*67*	*MC*
Shasta-Trinity	*Algoma*	*94.00*	*2*	*1.5*	*177*	*20*	*MC*
		91.50	*3*	*1.6*	*180*	*20*	*MC*
		124.50	*4*	*1.5*	*117*	*07*	*MC*
Lassen	*Swain Mtn.*	*101.60*	*1*	*1.3*	*467*	*52*	*TF*
	Nuisance	*83.82*	*5*	*2.4*	*659*	*86*	*TF*
		88.90	*6*	*2.2*	*618*	*74*	*TF*

[1]MC = mixed conifer; EP = east-side pine; TF = true fir.

plot was installed in the unit from which the amount of volume removed was nearest the sale area's average. At the time of cutting, the mature stands in all the timber sale areas were all more than 200 years old.

The first growth periods, 8 years or 10 years after treatment, were the length of time from overstory removal to the time the plots were installed. The periods 14, 15 or 16 years after treatment were the length of time from overstory removal to the time the plots were remeasured in 1994.

The permanent plots were 0.1012 hectares (31.82 meters x 31.82 meters), each surrounded by a 10.1-meter buffer strip. Plots were tentatively located on large-scale (1 cm ~ 30.48 m) maps of each unit. Wherever possible, skid trails and other major disturbed areas were avoided. On units with large undisturbed areas, the plot locations were selected randomly.

Tree Measurements

All trees 2.54 cm d.b.h. and larger were tagged and measured. The following characteristics and measurements were recorded for each live tree:

- Tree number
- Species
- Damage and defects
- Age and radial increment
- Diameter at breast height (d.b.h.)
- Total tree height
- Height to base of live crown.

Trees 7.62 cm (3 inches) d.b.h. and larger were cored at breast height (1.4 m above ground level on the uphill side of the tree). Radial growth was measured to the nearest 0.127 cm, ignoring the current year's growth, using a hand lens when necessary to determine diameter growth 8 or 10 years before treatment and 8 or 10 years after treatment. The increment core samples were also used to age sampled trees. However, if it seemed likely that doing so would retard the tree's growth or survival, the tree was not bored.

Study Areas

Ashpan—Lassen National Forest

Unit 1—The unit is at 40° 38' 30" N. latitude and 121° 31' 00" N. longitude (T 32N, R 4E, S 9 NE1/4) at an elevation of 1,646 m with an east exposure. The slope ranges from 0 to 35 percent. Soils are of cinder/basalt origin, and commonly Typic Xerorthents-Yallane family association, generally gravelly stony loam to very gravelly loamy coarse sand. Water runoff is slow. The permeability is moderately rapid to rapid. Mean annual precipitation is 127 cm.

Unit 3—The unit is at 40° 36' 30" N. latitude and 121° 33' 00" N. longitude (T 32N, R 4E, S 20 SW1/4) at an elevation of 1,707 m with a southwest exposure. The slope ranges from 0 to 35 percent. Soils are of basalt origin, and commonly Yallane-Portola families association, gravelly fine sandy loam to very gravelly sandy loam. Water runoff is slow. The permeability is moderately rapid. Mean annual precipitation is 127 cm.

Unit 5—The unit is at 40° 36' 30" N. latitude and 121° 32' 15" N. longitude (T 32N, R 4E, S 29 NE1/4) at an elevation of 1,707 m with a north-northwest exposure. The slope ranges from 0 to 35 percent. Soils are of basalt origin, and commonly Yallane-Portola families association, gravelly fine sandy loam to very gravelly sandy loam. Water runoff is slow. The permeability is moderately rapid. Mean annual precipitation is 127 cm.

The characteristics of the residual forest after overstory removal at the Ashpan area in the Lassen National Forest were:

SPECIES

True Fir Number of observations = 410

	Average	Range
Age (at breast height) (yr)	53	24 to 112
Initial d.b.h. (cm)	13.72	1.02 to 71.12
d.b.h. 8 years before treatment (cm)	14.99	1.52 to 76.20
d.b.h. 8 years after treatment (cm)	16.26	2.03 to 82.55
d.b.h. 15 years after treatment (cm)	17.70	2.54 to 83.82

Incense-cedar Number of observations = 25

	Average	Range
Age (at breast height) (yr)	37	29 to 49
Initial d.b.h. (cm)	5.59	1.78 to 11.68
d.b.h. 8 years before treatment (cm)	6.60	2.29 to 13.46
d.b.h. 8 years after treatment (cm)	7.47	3.05 to 15.24
d.b.h. 15 years after treatment (cm)	8.56	3.56 to 18.29

Sugar pine Number of observations = 26

	Average	Range
Age (at breast height) (yr)	33	21 to 65
Initial d.b.h. (cm)	8.51	2.03 to 28.19
d.b.h. 8 years before treatment (cm)	10.41	2.54 to 35.05
d.b.h. 8 years after treatment (cm)	12.37	3.05 to 43.18
d.b.h. 15 years after treatment (cm)	14.58	3.56 to 48.51

Ponderosa/Jeffrey pine

Number of observations = 33

	Average	Range
Age (at breast height) (yr)	50.5	21 to 89
Initial d.b.h. (cm)	12.45	1.52 to 42.67
d.b.h. 8 years before treatment (cm)	13.46	2.03 to 43.18
d.b.h. 8 years after treatment (cm)	14.48	2.54 to 43.94
d.b.h. 15 years after treatment (cm)	15.65	3.05 to 44.20

Baker—Lassen National Forest

Unit 1—The unit is at 40° 40' 30" N. latitude and 121° 23' 00" N. longitude (T 33N, R 5E, S 35 NE1/4) at an elevation of 1,646 m with a southeast exposure. The slope ranges from 0 to 15 percent. Soils are of andesite and basalt origin, are Bobbitt-Holland-Skalan family association, generally gravelly loam to very gravelly sandy or clay loam, and water runoff is slow. The permeability is moderately slow. Mean annual precipitation is 50.8 cm.

Unit 2—The unit is at 40° 39' 30" N. latitude and 121° 22' 00" N. longitude (T 32N, R 6E, S 6 SW1/4) at an elevation of 1,640 m with a northwest exposure. The slope ranges from 0 to 15 percent. Soils are of andesite and basalt origin, are Bobbitt-Holland-Skalan family association, generally gravelly loam to very gravelly sandy or clay loam, and water runoff is slow. Mean annual precipitation is 76.2 cm.

Unit 4—The unit is at 40° 39' 30" N. latitude and 121° 19' 30" N. longitude (T 32N, R 6E, S 8 SE1/4) at an elevation of 1,683 m with a northwest exposure. The slope ranges from 0 to 35 percent. Soils are of basalt origin, are Trojan-Inville-Patio family association, generally gravelly sandy loam to extremely gravelly clay loam, and water runoff is slow. Mean annual precipitation is 76.2 cm.

The characteristics of the residual forest after overstory removal at the Baker area in the Lassen National Forest were:

SPECIES

True Fir Number of observations = 155

	Average	Range
Age (at breast height) (yr)	58	30 to 95
Initial d.b.h. (cm)	11.33	1.47 to 33.27
d.b.h. 8 years before treatment (cm)	12.60	1.98 to 35.84
d.b.h. 8 years after treatment (cm)	14.20	2.54 to 37.85
d.b.h. 15 years after treatment (cm)	15.82	2.95 to 41.25

Incense-cedar Number of observations = 119

	Average	Range
Age (at breast height) (yr)	59	32 to 102
Initial d.b.h. (cm)	7.44	1.42 to 27.89
d.b.h. 8 years before treatment (cm)	8.43	1.93 to 28.80
d.b.h. 8 years after treatment (cm)	9.65	2.54 to 29.72
d.b.h. 15 years after treatment (cm)	10.85	2.79 to 32.51

Ponderosa/Jeffrey pine Number of observations = 161

	Average	Range
Age (at breast height) (yr)	62	30 to 95
Initial d.b.h. (cm)	8.23	1.50 to 57.53
d.b.h. 8 years before treatment (cm)	9.53	1.98 to 58.95
d.b.h. 8 years after treatment (cm)	11.02	2.54 to 61.21
d.b.h. 15 years after treatment (cm)	12.12	2.95 to 63.50

Johnson's Ravine—Plumas National Forest

Unit 2—The unit is at 40° 2' 30" N. latitude and 121° 4' 00" N. longitude (T 25N, R 8E, S 10 NE 1/4) at an elevation of 1,402 m with a northeast exposure. The slope ranges from 50 to 70 percent. Soils are of slightly fractured schist origin, are of Kistirn-Aiken-Deadwood families complex, generally very gravelly loam to extremely gravely silty clay loam, and water runoff is slow. The permeability is moderately slow. Soils are moderately well drained. Mean annual precipitation is 101.6 cm.

Unit 3—The unit is at 40° 3' 00" N. latitude and 121° 3' 30" N. longitude (T 25N, R 8E, S 2 SW 1/4) at an elevation of 1,463 m with a northwest exposure. The slope ranges from 40 to 80 percent. Soils are of slightly fractured schist origin, are of Kistirn-Aiken-Deadwood families complex, generally very gravelly loam to extremely gravely silty clay loam, and water runoff is slow. The permeability is moderately slow. Soils are moderately well drained. Mean annual precipitation is 101.6 cm.

The characteristics of the residual forest after overstory removal at the Johnson's Ravine area in the Plumas National Forest were:

SPECIES

True Fir Number of observations = 405

	Average	Range
Age (at breast height) (yr)	59	30 to 119
Initial d.b.h. (cm)	4.06	1.47 to 26.77
d.b.h. 8 years before treatment (cm)	4.72	1.98 to 28.78
d.b.h. 8 years after treatment (cm)	5.51	2.54 to 32.77
d.b.h. 15 years after treatment (cm)	6.38	2.79 to 35.5

Incense-cedar Number of observations = 17

	Average	Range
Age (at breast height) (yr)	97	45 to 245
Initial d.b.h. (cm)	8.26	1.63 to 35.15
d.b.h. 8 years before treatment (cm)	8.92	2.18 to 35.76
d.b.h. 8 years after treatment (cm)	9.70	2.79 to 36.07
d.b.h. 15 years after treatment (cm)	10.95	3.30 to 38.61

Sugar pine Number of observations = 10

	Average	Range
Age (at breast height) (yr)	79	71 to 88
Initial d.b.h. (cm)	5.11	1.70 to 8.81
d.b.h. 8 years before treatment (cm)	5.74	2.44 to 9.12
d.b.h. 8 years after treatment (cm)	6.45	3.05 to 9.91
d.b.h. 15 years after treatment (cm)	7.77	4.06 to 10.67

Douglas-fir Number of observations = 177

	Average	Range
Age (at breast height) (yr)	72	35 to 130
Initial d.b.h. (cm)	7.16	0.102 to 38.94
d.b.h. 8 years before treatment (cm)	7.90	1.98 to 40.67
d.b.h. 8 years after treatment (cm)	8.74	2.54 to 42.67
d.b.h. 15 years after treatment (cm)	10.01	2.79 to 45.21

Clear Creek—Plumas National Forest

Unit 1—The unit is at 40° 7' 00" N. latitude and 121° 8' 00" N. longitude (T 26N, R 8E, S 18 NW 1/4) at an elevation of 1,402 m with a southeast exposure. The slope ranges from 50 to 70 percent. Soils are of slightly fractured schist origin, are of Kistirn-Aiken-Deadwood families complex, generally very gravelly loam to silty clay loam, and water runoff is slow. The permeability is moderately slow. Soils are well-drained. Mean annual precipitation is 101.6 cm.

Unit 2—The unit is at 40° 8' 00" N. latitude and 121° 8' 00" N. longitude (T 26N, R 8E, S 6 SW 1/4) at an elevation of 1,402 m with a northeast exposure. The slope ranges from 10 to 50 percent. Soils are of slightly fractured schist origin, are of Kistirn-Aiken-Deadwood families complex, generally very gravelly loam to silty clay loam, and water runoff is slow. The permeability is moderately slow. Soils are well-drained. Mean annual precipitation is 101.6 cm.

Unit 4—The unit is at 40° 7' 45" N. latitude and 121° 7' 15" N. longitude (T 26N, R 8E, S 7 SW 1/4) at an elevation of 1,341 m with a northeast exposure. The slope ranges from 50 to 70 percent. Soils are of slightly fractured schist origin, are of Kistirn-Aiken-Deadwood families complex, generally very gravelly loam to silty clay loam, and water runoff is slow. The permeability is moderately slow. Soils are well-drained. Mean annual precipitation is 101.6 cm.

The characteristics of the residual forest after overstory removal at the Clear Creek area in the Plumas National Forest were:

SPECIES

True Fir Number of observations = 363

	Average	Range
Age (at breast height) (yr)	67	30 to 113
Initial d.b.h. (cm)	9.17	1.47 to 67.26
d.b.h. 10 years before treatment (cm)	10.21	1.98 to 72.11
d.b.h. 10 years after treatment (cm)	11.38	2.54 to 76.96
d.b.h. 16 years after treatment (cm)	12.83	2.54 to 80.01

Incense-cedar Number of observations = 60

	Average	Range
Age (at breast height) (yr)	69	37 to 123
Initial d.b.h. (cm)	10.59	2.08 to 64.54
d.b.h. 10 years before treatment (cm)	11.48	2.64 to 67.59
d.b.h. 10 years after treatment (cm)	12.42	3.30 to 70.61
d.b.h. 16 years after treatment (cm)	13.41	3.56 to 74.93

Sugar pine Number of observations = 8

	Average	Range
Age (at breast height) (yr)	80	26 to 114
Initial d.b.h. (cm)	20.70	1.70 to 43.38
d.b.h. 10 years before treatment (cm)	22.73	2.21 to 47.12
d.b.h. 10 years after treatment (cm)	25.32	2.79 to 50.55
d.b.h. 16 years after treatment (cm)	30.23	3.30 to 53.59

Douglas-fir Number of observations = 93

	Average	Range
Age (at breast height) (yr)	69	40 to 102
Initial d.b.h. (cm)	11.89	1.70 to 38.30
d.b.h. 10 years before treatment (cm)	12.95	2.21 to 41.20
d.b.h. 10 years after treatment (cm)	14.43	2.79 to 45.21
d.b.h. 16 years after treatment (cm)	16.84	3.30 to 49.02

Algoma—Shasta-Trinity National Forest

Unit 2—The unit is at 41° 14' 30" N. latitude and 121° 53' 00" N. longitude (T 39N, R 1E, S 6 SW 1/4) at an elevation of 1,312 m with a north-northeast exposure. The slope ranges from 0 to 20 percent. Soils are of weathered metavolcanic rock origin, are of Holland Family-Ashy association, generally sandy clay loam, and water runoff is slow. The permeability is moderately rapid to rapid. Mean annual precipitation is 127 cm.

Unit 3—The unit is at 41° 15' 00" N. latitude and 121° 54' 30" N. longitude (T 39N, R 1W, S 1 SE 1/4) at an elevation of 1,158 m with a north-southwest exposure. The slope ranges from 0 to 20 percent. Soils are of basalt origin, are of Sadie family association, generally stony sandy loam, and water runoff is slow. The permeability is moderately rapid. Mean annual precipitation is 127 cm.

Unit 4—The unit is at 41° 14' 30" N. latitude and 121° 53' 00" N. longitude (T 39N, R 1E, S 5 NW 1/4) at an elevation of 1,158 m with a west exposure. The slope ranges from 0 to 35 percent. Soils are of basalt origin, are of Sadie family association, generally stony sandy loam, and water runoff is slow. The permeability is moderately rapid. Mean annual precipitation is 127 cm.

The characteristics of the residual forest after overstory removal at the Algoma area in the Shasta-Trinity National Forest were:

SPECIES

True Fir Number of observations = 293

	Average	Range
Age (at breast height) (yr)	56	20 to 139
Initial d.b.h. (cm)	9.53	1.02 to 43.74
d.b.h. 10 years before treatment (cm)	10.80	1.88 to 46.86
d.b.h. 10 years after treatment (cm)	12.55	2.54 to 51.56
d.b.h. 16 years after treatment (cm)	13.79	2.54 to 59.44

Incense-cedar Number of observations = 281

	Average	Range
Age (at breast height) (yr)	51	23 to 115
Initial d.b.h. (cm)	8.36	1.42 to 72.59
d.b.h. 10 years before treatment (cm)	9.45	1.93 to 78.00
d.b.h. 10 years after treatment (cm)	10.59	2.54 to 82.55
d.b.h. 16 years after treatment (cm)	11.48	2.54 to 85.85

Sugar pine Number of observations = 5

	Average	Range
Age (at breast height) (yr)	63	43 to 74
Initial d.b.h. (cm)	22.83	1.93 to 59.16
d.b.h. 10 years before treatment (cm)	26.26	2.44 to 68.05
d.b.h. 10 years after treatment (cm)	30.58	3.05 to 79.50
d.b.h. 16 years after treatment (cm)	33.17	3.56 to 86.11

Ponderosa/Jeffrey pine Number of observations = 35

	Average	Range
Age (at breast height) (yr)	63	30 to 86
Initial d.b.h. (cm)	29.16	7.85 to 57.15
d.b.h. 10 years before treatment (cm)	31.45	9.83 to 59.56
d.b.h. 10 years after treatment (cm)	33.78	10.67 to 68.07
d.b.h. 16 years after treatment (cm)	36.75	10.67 to 73.66

Douglas-fir Number of observations = 42

	Average	Range
Age (at breast height) (yr)	59	35 to 86
Initial d.b.h. (cm)	10.90	1.93 to 38.56
d.b.h. 10 years before treatment (cm)	12.47	2.44 to 44.32
d.b.h. 10 years after treatment (cm)	14.96	3.05 to 52.07
d.b.h. 16 years after treatment (cm)	17.02	3.30 to 57.15

Nuisance—Swain Mountain Experimental Forest (Located in Lassen N.F.)

Unit 1—The unit is at 40° 25' 15" N. latitude and 121° 7' 00" N. longitude (T 30N, R 8E, S 32 NW1/4) at an elevation of 2,073 m with a west exposure. The slope ranges from 0 to 35 percent. Soils are of weathered basalt origin, are De Masters-Klicker family association, generally sandy loam to extremely gravelly loam, and water runoff is slow. The permeability is moderate. Mean annual precipitation is 127 cm.

Unit 5—The unit is at 40° 29' 30" N. latitude and 121° 5' 30" N. longitude (T 30N, R 8E, S 21 NW1/4) at an elevation of 1,823 m with a north-northeast exposure. The slope ranges from 0 to 35 percent. Soils are of weathered basalt origin, are De Masters-Klicker family association, generally sandy loam to extremely gravelly loam, and water runoff is slow. The permeability is moderate. Mean annual precipitation is 127 cm.

Unit 6—The unit is at 40° 26' 30" N. latitude and 121° 5' 00" N. longitude (T 30N, R 8E, S 21 NW1/4) at an elevation of 1,798 m with an east exposure. The slope ranges from 0 to 35 percent. Soils are of weathered basalt origin, are De Masters-Klicker family association, generally sandy loam to extremely gravelly loam, and water runoff is slow. The permeability is moderate. Mean annual precipitation is 127 cm.

The characteristics of the residual forest after overstory removal at Nuisance area in the Swain Mountain were:

SPECIES

White fir Number of observations = 151

	Average	Range
Age (at breast height) (yr)	83	37 to 139
Initial d.b.h. (cm)	16.23	0.33 to 56.57
d.b.h. 8 years before treatment (cm)	17.30	2.79 to 59.13
d.b.h. 8 years after treatment (cm)	19.03	3.30 to 62.99
d.b.h. 14 years after treatment (cm)	20.55	3.81 to 68.33

SPECIES

Red fir	Number of observations = 421	
	Average	Range
Age (at breast height) (yr)	59	30 to 129
Initial d.b.h. (cm)	10.03	1.47 to 65.10
d.b.h. 8 years before treatment (cm)	4.35	1.98 to 68.81
d.b.h. 8 years after treatment (cm)	4.85	2.54 to 73.66
d.b.h. 14 years after treatment (cm)	5.38	2.79 to 76.96

Analysis

Past outside bark diameters at breast height, for each sample tree at the time of overstory removal and 8 or 10 years before overstory removal, were calculated using bark growth adjustment factors developed for each species (Dolph 1984). The following formula was used:

$$Dob_p = Dob_c - (k \bullet r)$$

In which,

Dob_p= past diameter at breast height, outside bark

Dob_c= current diameter at breast height, outside bark

r = average radial wood growth in inches for a specified number of years, as measured on increment cores taken at breast height.

k = species-specific constant

Species	*k*
Douglas-fir	2.2627
Ponderosa and Jeffrey pine	2.2304
Sugar pine	2.2566
White fir	2.2444
Incense-cedar	2.3883

To show the effects of overstory removal on residual trees, 2-dimensional bar charts were used to depict periodic annual diameter increment (cm) 8 or 10 years before treatment, periodic annual diameter increment (cm) 8 or 10 years after treatment, and periodic annual diameter increment (cm) 9 to 16 years after treatment for the six species within the timber sale areas (figs. 1—13).

Linear regression equations were used to select the model that provided the best fit for periodic annual diameter increment of all the residual trees after treatment. The best linear regression equation was defined as the model that minimized the residual mean square error, was closest to meeting the assumptions of regression analysis, and contained predictor variables with low multicollinearity.

Change in d.b.h. can be expressed either as a diameter growth rate or as basal area growth rate (Hann and Larsen 1990). In this analysis, periodic annual diameter increment 14, 15, or 16 years after treatment was selected as the dependent variable for the species within the six timber sale areas. The standard linear regression model used was:

$$Y = \beta_0 + \beta_1 \cdot X_1 + \beta_2 \cdot X_2 + \beta_3 \cdot X_3 + e$$

where Y is the value of periodic annual diameter increment (cm) 14, 15, or 16 years after treatment; X_1 is initial d.b.h. (cm) or periodic annual diameter increment (cm) 8 or 10 years before treatment; X_2 is the square of X_1; and X_3 is total basal area per plot of residual trees larger in diameter than that of the subject tree or total basal area per plot of residual trees larger in diameter than that of the subject tree divided by the subject tree's diameter (m^2); e is the measurement's error component, with an expected e value of zero and variance of σ^2; and β_0, β_1, β_2, β_3 are regression coefficients to be estimated. For developing the regression equations, as a result of analysis of covariance, ponderosa pine and Jeffrey pine data were combined. Each of the study areas was composed of more than two species with the exception of the Nuisance area, which had only red and white fir. White fir was the predominant species at each of the study areas with the exception of the Nuisance units which were composed of about 75 percent red fir and 25 percent white fir.

Results

Regardless of species, the residual trees responded by increasing their diameter growth after adjusting to their new environment (*figs. 1—13*). However, on the basis of the observations we can say that white fir, Douglas-fir, and sugar pine responded to release sooner than the other species. The following periods were evaluated: 8 or 10 years before overstory removal, 8 or 10 years after overstory removal, and 9 to 16 years after overstory removal.

For predicting periodic annual diameter increment 9 to 16 years after treatment, all the independent variables strengthened the regression model. However, initial diameter (cm), the square of initial diameter, and total basal area per plot of residual trees larger in diameter than that of the subject tree provided the best fit for fitting ponderosa pine and sugar pine, (*tables 2* and *3*), whereas periodic annual diameter increment (cm) 8 or 10 years before treatment, the square of periodic annual diameter increment (cm) 8 or 10 years before treatment, and total basal area per plot of residual trees larger in diameter than that of the subject tree divided by the subject tree's diameter (m^2) provided the best fit for fitting white fir, red fir, incense-cedar, and Douglas-fir (*tables 4*, *5*, *6*, and *7*).

Ashpan units on the Lassen National Forests

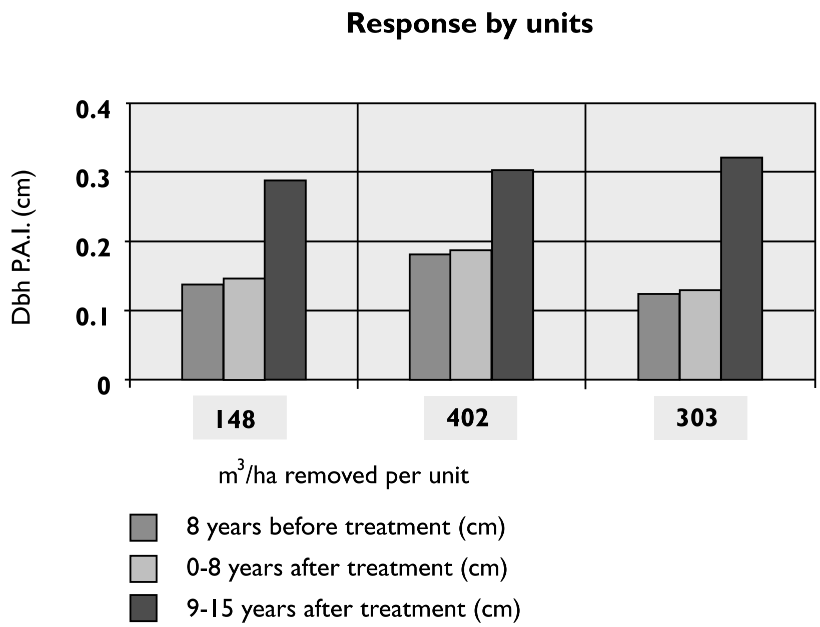

Figure 1—Periodic annual diameter increment (P.A.I.), at breast height, of residual trees by units after varying levels of overstory removal in mixed conifer stands (diameter classes combined) 8 years before treatment, 0 to 8 years after treatment, and 9 to 15 years after treatment for Ashpan units on the Lassen National Forest.

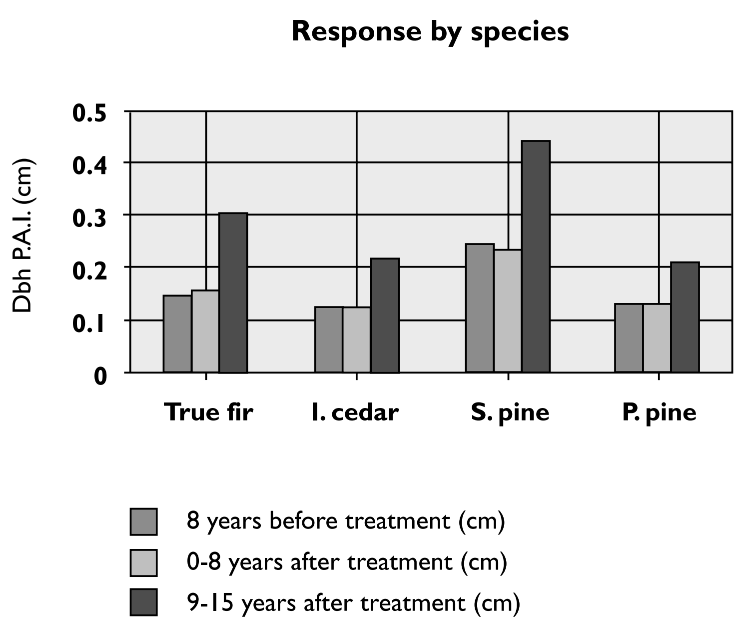

Figure 2—Periodic annual diameter increment (P.A.I.), at breast height, of residual trees by species after varying levels of overstory removal in mixed conifer stands (diameter classes combined) 8 years before treatment, 0 to 8 years after treatment, and 9 to 15 years after treatment for Ashpan units on the Lassen National Forest.

Baker units on the Lassen National Forest

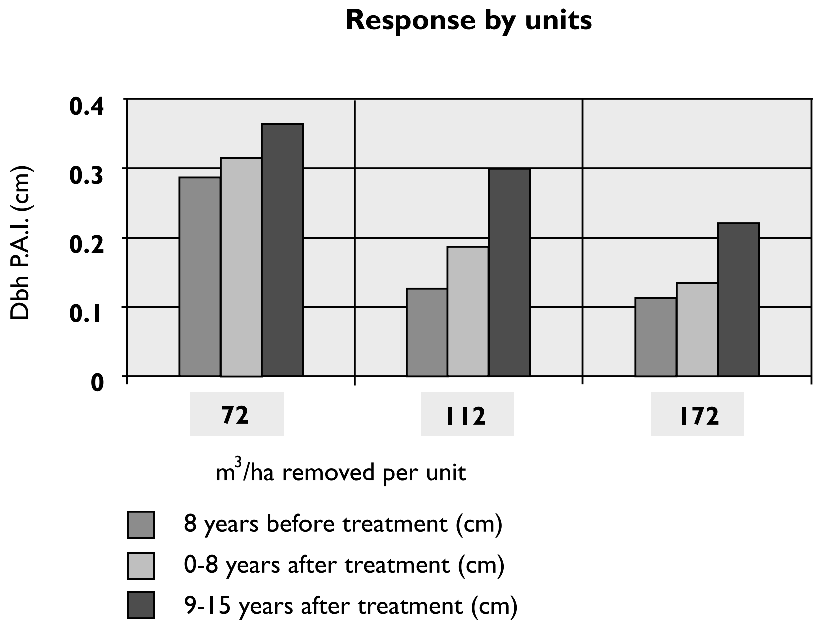

Figure 3—Periodic annual diameter increment (P.A.I.), at breast height, of residual trees by units after varying levels of overstory removal in mixed conifer stands (diameter classes combined) 8 years before treatment, 0 to 8 years after treatment, and 9 to 15 years after treatment for Baker units on the Lassen National Forest.

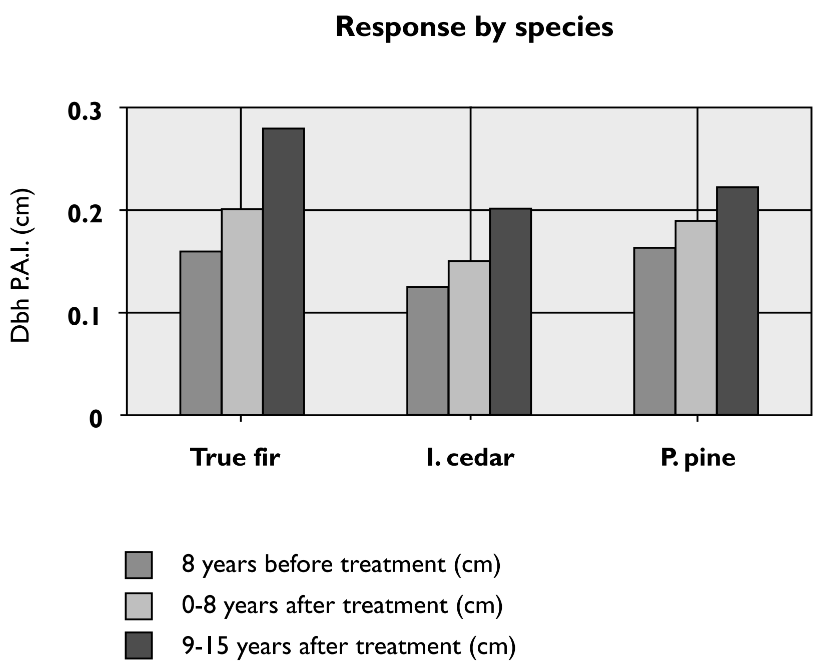

Figure 4—Periodic annual diameter increment (P.A.I.), at breast height, of residual trees by species after varying levels of overstory removal in mixed conifer stands (diameter classes combined) 8 years before treatment, 0 to 8 years after treatment, and 9 to 15 years after treatment for Baker units on the Lassen National Forest.

Johnson's Ravine units on the Plumas National Forest

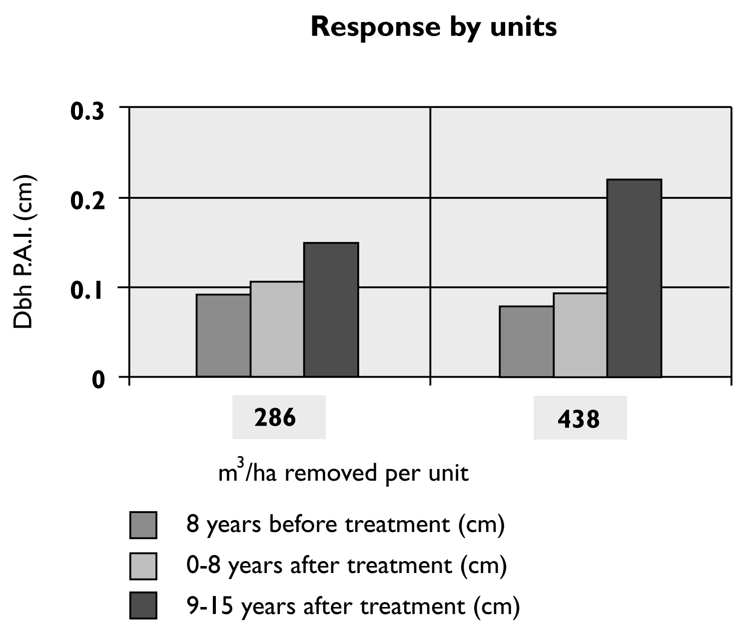

Figure 5—Periodic annual diameter increment (P.A.I.), at breast height, of residual trees by units after varying levels of overstory removal in mixed conifer stands (diameter classes combined) 8 years before treatment, 0 to 8 years after treatment, and 9 to 15 years after treatment for Johnson's Ravine units on the Plumas National Forest.

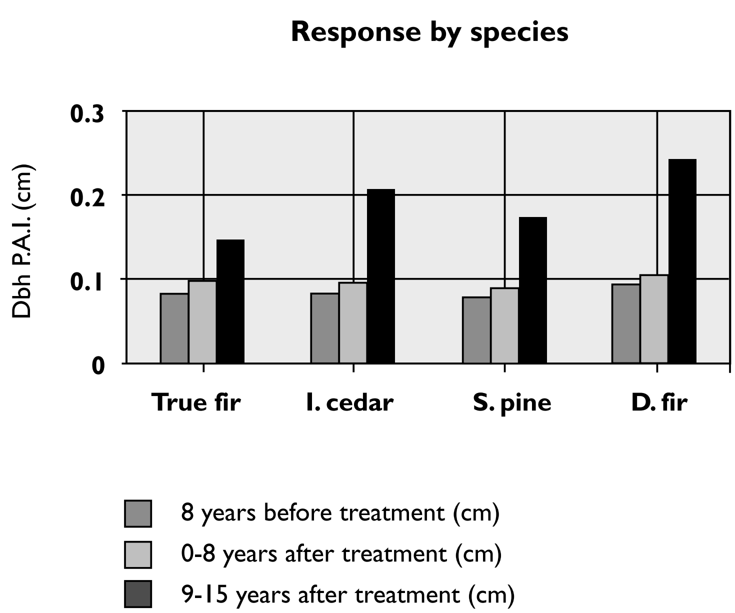

Figure 6—Periodic annual diameter increment (P.A.I.), at breast height, of residual trees by species after varying levels of overstory removal in mixed conifer stands (diameter classes combined) 8 years before treatment, 0 to 8 years after treatment, and 9 to 15 years after treatment for Johnson's Ravine units on the Plumas National Forest.

Clear Creek units on the Plumas National Forest

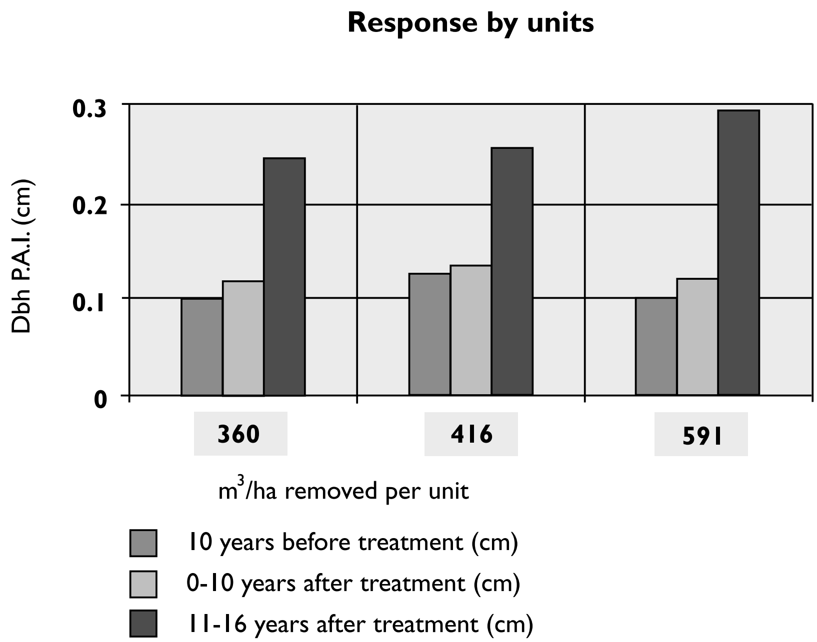

Figure 7—Periodic annual diameter increment (P.A.I.), at breast height, of residual trees by units after varying levels of overstory removal in mixed conifer stands (diameter classes combined) 10 years before treatment, 0 to 10 years after treatment, and 11 to 16 years after treatment for Clear Creek units on the Plumas National Forest.

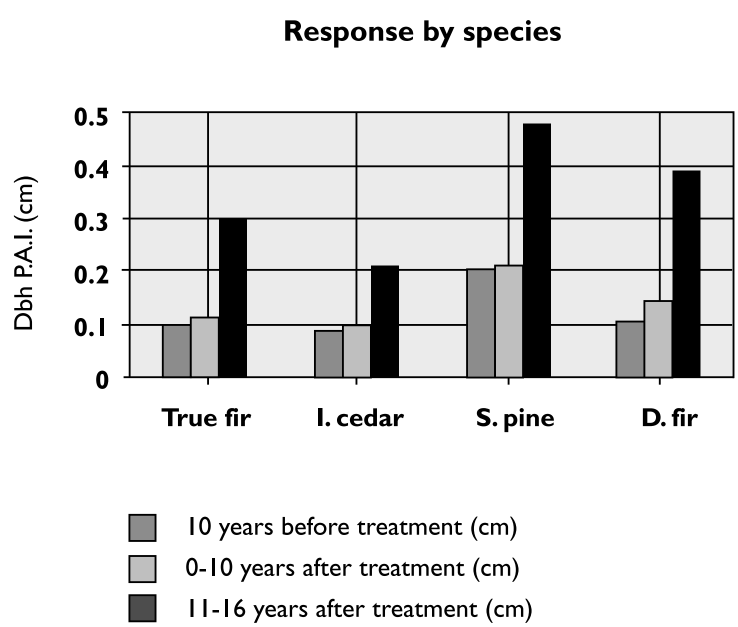

Figure 8—Periodic annual diameter increment (P.A.I.), at breast height, of residual trees by species after varying levels of overstory removal in mixed conifer stands (diameter classes combined) 10 years before treatment, 0 to 10 years after treatment, and 11 to 16 years after treatment for Clear Creek units on the Plumas National Forest.

Algoma units on the Shasta-Trinity National Forest

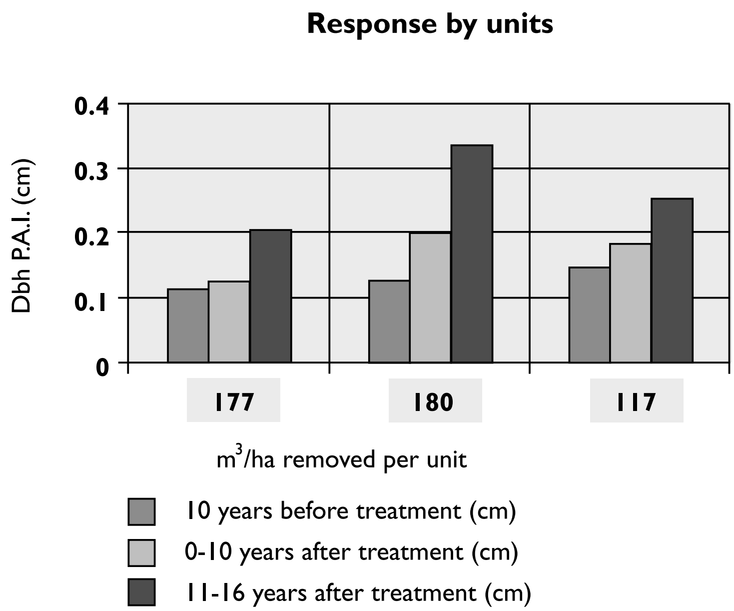

Figure 9—Periodic annual diameter increment (P.A.I.), at breast height, of residual trees by units after varying levels of overstory removal in mixed conifer stands (diameter classes combined) 10 years before treatment, 0 to 10 years after treatment, and 11 to 16 years after treatment for Algoma units on the Shasta-Trinity National Forest.

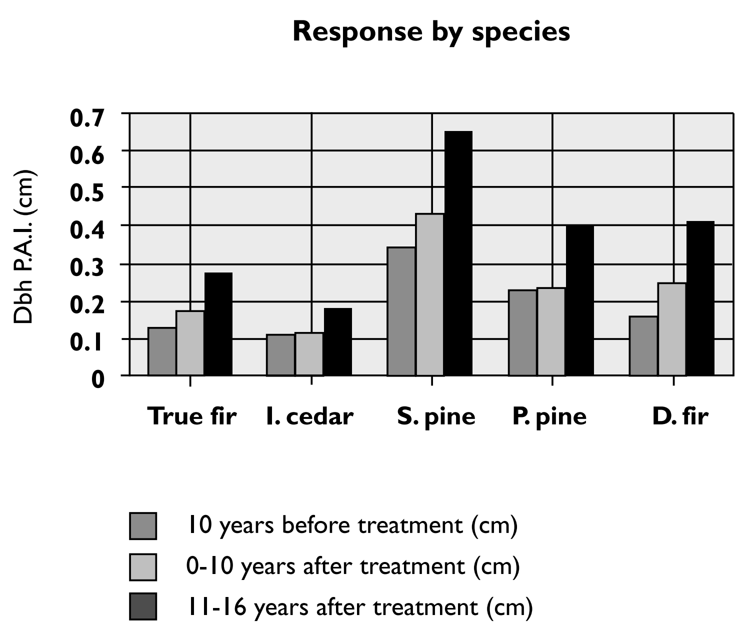

Figure 10—Periodic annual diameter increment (P.A.I.), at breast height, of residual trees by species after varying levels of overstory removal in mixed conifer stands (diameter classes combined) 10 years before treatment, 0 to 10 years after treatment, and 11 to 16 years after treatment for Algoma units on the Shasta-Trinity National Forest.

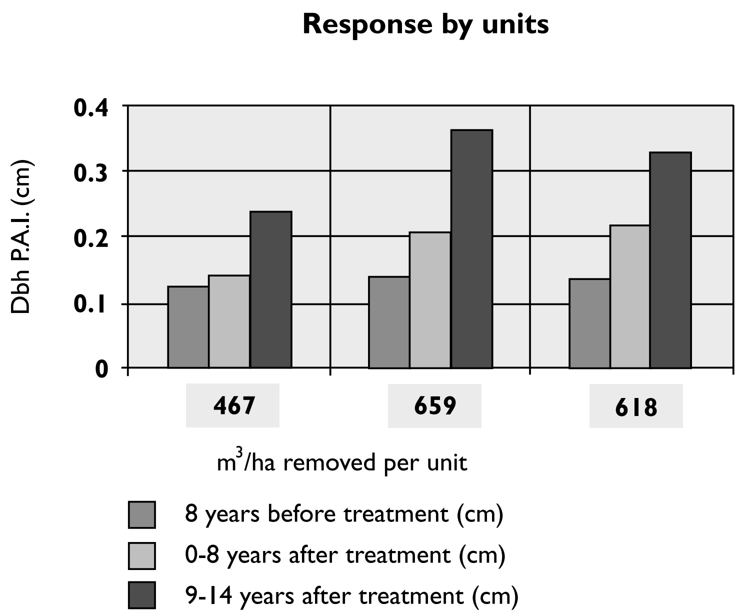

Figure 11—Periodic annual diameter increment (P.A.I.), at breast height, of residual trees by units after varying levels of overstory removal in mixed conifer stands (diameter classes combined) 8 years before treatment, 0 to 8 years after treatment, and 9 to 14 years after treatment for Nuisance units on the Swain Mountain Experimental Forest.

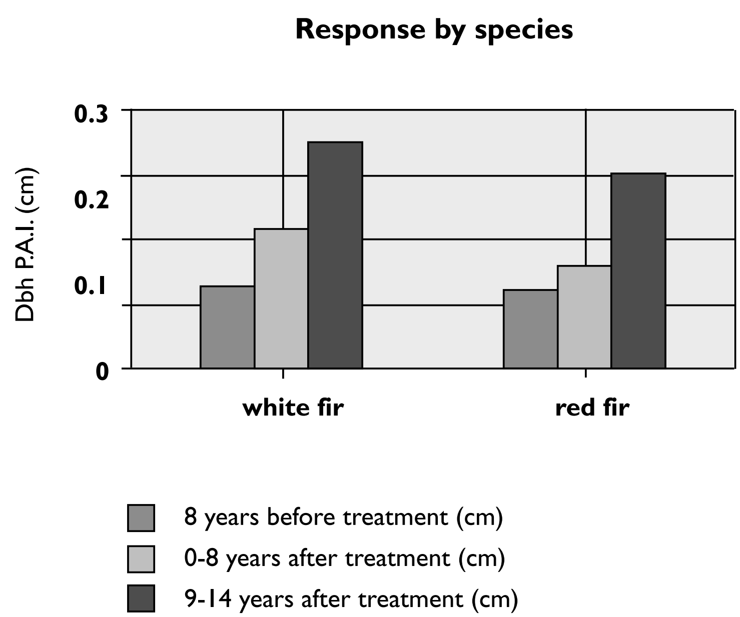

Figure 12—Periodic annual diameter increment (P.A.I.), at breast height, of residual trees by species after varying levels of overstory removal in mixed conifer stands (diameter classes combined) 8 years before treatment, 0 to 8 years after treatment, and 9 to 14 years after treatment for Nuisance units on the Swain Mountain Experimental Forest.

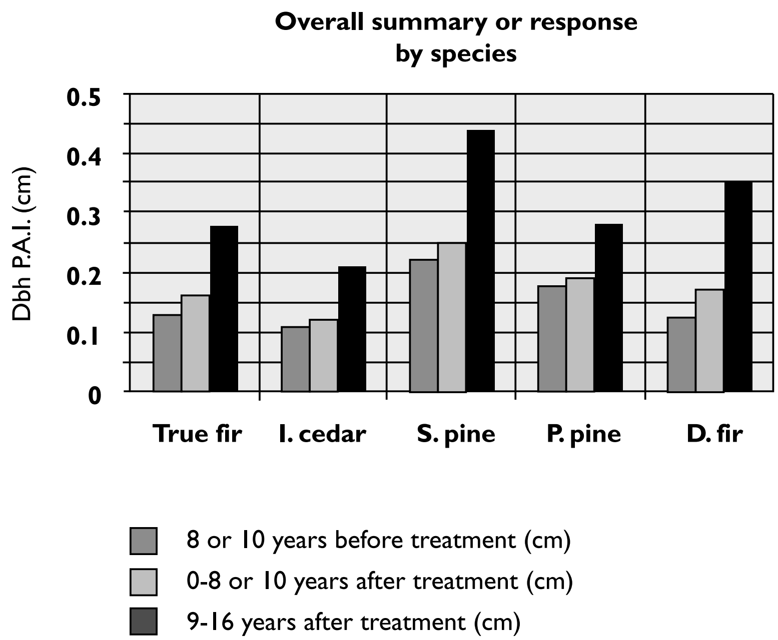

Figure 13—Periodic annual diameter increment (P.A.I.), at breast height, of residual trees by species after varying levels of overstory removal in mixed conifer stands (diameter classes combined) 8 to 10 years before treatment, 0 to 8 years or 10 years after treatment, and 9 to 16 years after treatment.

Discussion

The amount of overstory removed was arbitrarily chosen and was not replicated. As a result, it is not possible to directly test the effects of levels of overstory removed. Additionally, removal intensity (e.g., volume removed/initial volume), a likely independent variable, was not used in the regression equations because there was little variation among units.

Nevertheless, as shown in *figs. 1—13*, regardless of timber sale area and species, residual trees responded to overstory removal by increasing their diameter growth after adjusting to their new environment (the 9- to 16-year period). Within each timber sale area, units with the most overstory removed showed the highest increase in diameter after treatment, whereas units with low amounts of overstory removal showed the smallest increase in diameter (figs. *1, 3, 5, 7, 9,* and *11*). This result corresponds to the findings of Gordon (1973) for northern California. However, we cannot determine how many years it took the residual trees to adjust to their new environment, because measurements were not done on an annual basis. But on the basis of observations, we can say that it took the residual trees between 3 and 7 years to adjust to their new environment, depending on the best combinations of amount of overstory removed, stand condition, and tree potential (Oliver and Larson 1996, p. 95). This result corresponds to the findings of McCaughey and Schmidt (1982).

Furthermore, on average, diameter growth response of sugar pine was the greatest (regardless of timber sale area), followed by that of Douglas-fir and white fir. Incense-cedar and ponderosa pine showed the least response. This result corresponds well to the findings of Oliver and Dolph (1992) for northern California.

On average, periodic annual diameter increments 8 or 10 years after treatment were not different from those 8 or 10 years before treatment (*fig. 13)*. However, after the residual trees had adjusted to their new environment, periodic annual diameter increment 9 to 16 years after treatment showed a substantial increase in growth response compared to their counterparts 8 or 10 years after treatment. Although how long this acceleration in growth will continue is uncertain, studies have shown that it can continue 21 to 30 years after treatment (Herring and McMinn 1980, Roe and DeJarnette 1965).

***Table 2**—Equation parameter estimates and summary statistics of periodic annual diameter increment for ponderosa pine after overstory removal in mixed conifer stands.*

		95 pct Confidence interval			
Parameters	Estimate	S. E.	Tolerance	T-statistic	P(2-tail)
β_0	0.11500	0.01581	.	7.27220	0.00000
β_1	0.01164	0.00175	0.11148	6.65058	0.00000
β_2	-0.00011	0.00004	0.11167	-3.19883	0.00158
β_3	-0.25098	0.04439	0.98643	-5.65404	0.00000

$E\ (Y) = \beta_0 + \beta_1 \cdot X_1 + \beta_2 \cdot X_2 + \beta_3 \cdot X_3$; $R^2 = 0.440$; *Standard error of estimate = 0.10418; N = 237*

Variables	Observations	Minimum	Maximum	Mean	Standard Dev.
Y (cm)	237	0.02371	0.91916	0.17875	0.13827
X_1 *(cm)*	234	1.50000	57.53000	11.97363	11.73668
X_2 *(cm)*	234	2.25000	3309.70090	280.53613	567.86875
X_3 (m²)	234	0.00000	0.84000	0.16912	0.16332

E (Y) (cm) is the expected value of periodic annual diameter increment 14 to 16 years after treatment.
X_1 (cm) initial diameter.
X_2 (cm_2) is the square of X_1.
X_3 (m^2) is the sum of the residual trees' basal area in trees with dbh larger than the subject tree's dbh_1.
N is the number of observations.

***Table 3**—Equation parameter estimates and summary statistics of periodic annual diameter increment for sugar pine after overstory removal in mixed conifer stands.*

		95 pct Confidence interval			
Parameters	Estimate	S. E.	Tolerance	T-statistic	P(2-tail)
β_0	0.09657	0.04254	.	2.27022	0.02826
β_1	0.01733	0.00526	0.08611	3.29563	0.00197
β_2	-0.00004	0.00010	0.08573	-0.36602	0.71614
β_3	-0.15214	0.14024	0.95708	-1.08484	0.28404

$Y = \beta_0 + \beta_1 \cdot X_1 + \beta_2 \cdot X_2 + \beta_3 \cdot X_3 + e$; $R^2 = 0.440; = 0.704$; *Standard error of estimate (e) = 0.12847; N = 47*

Variables	Observations	Minimum	Maximum	Mean	Standard Dev.
Y (cm)	47	0.05249	1.12871	0.26292	0.22814
X_1 *(cm)*	47	1.70000	59.16000	11.26735	12.14813
X_2 *(cm²)*	47	2.89000	3499.90560	271.51830	630.66983
X_3 (m²)	47	0.00000	0.49000	0.16490	0.13775

E (Y) (cm) is the expected value of periodic annual diameter increment 14 to 16 years after treatment.
X_1 (cm) initial diameter.
X_2 (cm) is the square of X_1.
X_3 (m^2) is the sum of the residual trees' basal area in trees with dbh larger than the subject tree's dbh_1.
N is the number of observations.

Linear regression equations were developed to predict periodic annual diameter increment 14 to 16 years after treatment. The equations were developed for each species for the entire timber sale area. For developing the regression equations, data on ponderosa pine and Jeffrey pine were combined as a result of analysis of covariance. The independent variables were X_1, initial diameter (cm) or periodic annual diameter increment (cm) 8 or 10 years before treatment; X_2, the square of X_1; and X_3, the total basal area per plot of residual trees larger in diameter than that of the subject tree or total basal area per plot of residual trees larger in diameter than that of the subject tree divided by the subject tree's diameter (m^2). X_1, periodic annual diameter increment (cm) 8 or 10 years before treatment; X_2, the square of X_1; and X_3, the total basal area per plot of residual trees larger in diameter than that of the subject tree divided by the subject tree's diameter (m^2), provided the best fit for white fir, red fir, incense-cedar, and Douglas-fir, whereas X_1, initial diameter (cm); X_2, the square of X_1; and X_3, the total basal area per plot of residual trees larger in diameter than that of the subject tree's diameter (m^2), provided the best fit for ponderosa

Table 4*—Equation parameter estimates and summary statistics of periodic annual diameter increment for white fir after overstory removal in mixed conifer stands.*

	95 pct Confidence interval				
Parameters	Estimate	S. E.	Tolerance	T-statistic	P(2-tail)
β_0	0.03227	0.00503	.	6.41563	0.00000
β_1	2.14009	0.08277	0.11550	26.00021	0.00000
β_2	-1.33025	0.24385	0.11909	-5.45520	0.00000
β_3	-0.28469	0.03667	0.91434	-7.76285	0.00000

$E(Y) = \beta_0 + \beta_1 \cdot X_1 + \beta_2 \cdot X_2 + \beta_3 \cdot X_3$; $R^2 = 0.712$; *Standard error of estimate = 0.07591; N = 1774*

Variables	Observations	Minimum	Maximum	Mean	Standard Dev.
E (Y) (cm)	1774	0.01863	1.13030	0.17229	0.14126
X_1 *(cm)*	1774	0.01368	0.63500	0.07622	0.06687
X_2 *(cm²)*	1774	0.00019	0.40323	0.01028	0.02391
X_3 (m²)	1774	0.00000	1.03030	0.04083	0.06011

Y (cm) is the expected value of periodic annual diameter increment 14 to 16 years after treatment.
X_1 (cm) is periodic annual diameter increment 8 to 10 years before treatment.
X_2 (cm²) is the square of X_1.
X_3 (m^2) is the sum of the residual trees' basal area in trees with dbh larger than the subject tree's dbh_1 divided by the subject tree's diameter.
N is the number of observations.

Table 5*—Equation parameter estimates and summary statistics of periodic annual diameter increment for red fir after overstory removal in mixed conifer stands.*

	95 pct Confidence interval				
Parameters	Estimate	S. E.	Tolerance	T-statistic	P(2-tail)
β_0	0.00937	0.01307	.	0.71698	0.47389
β_1	2.25729	0.18499	0.09287	12.06021	0.00000
β_2	-2.07631	0.50329	0.10026	-4.12546	0.00005
β_3	-0.19411	0.08047	0.78756	-2.41236	0.01639

$E(Y) = \beta_0 + \beta_1 \cdot X_1 + \beta_2 \cdot X_2 + \beta_3 \cdot X_3$; $R^2 = 0.720$; *Standard error of estimate = 0.07634; N = 421*

Variables	Observations	Minimum	Maximum	Mean	Standard Dev.
Y (cm)	421	0.03556	0.75692	0.16628	0.14358
X_1 *(cm)*	421	0.02149	0.46111	0.07847	0.06816
X_2 *(cm²)*	421	0.00046	0.21262	0.01079	0.02374
X_3 (m²)	421	0.00000	0.39378	0.06083	0.06134

E (Y) (cm) is the expected value of periodic annual diameter increment 14 to 16 years after treatment.
X_1 (cm) initial diameter.
X_2 (cm²) is the square of X_1.
X_3 (m^2) is the sum of the residual trees' basal area in trees with dbhs larger than the subject tree's dbh_1 divided by the subject tree's diameter.
N is the number of observations.

pine and sugar pine. Total basal area per plot of residual trees larger in diameter than that of the subject tree divided by the subject tree's diameter was an effective predictor because trees across the plots may have identical X_{3i} values but not identical dbh_i values. Although all the independent variables strengthened the regression model, initial diameter and periodic annual diameter increment 8 or 10 years before treatment were the best predictors of periodic annual diameter increment 9 to 16 years after treatments.

Residual trees compete for the growing space previously occupied by the removed overstory trees, and the growing space is influenced by species composition and crown position (Oliver and Larson 1996, p. 95). X_3 was included in the equations to estimate the competitive position that a residual tree holds within a plot after overstory removal. X_3 has been used as a tree-position variable in equations for predicting basal area growth because it defines a tree's position in relation to all trees

Table 6*—Equation parameter estimates and summary statistics of periodic annual diameter increment for incense-cedar after overstory removal in mixed conifer stands.*

		95 pct Confidence interval			
Parameters	Estimate	S. E.	Tolerance	T-statistic	P(2-tail)
β_0	*0.02593*	*0.01051*	.	*2.46779*	*0.01399*
β_1	*1.73447*	*0.18182*	*0.10236*	*9.53970*	*0.00000*
β_2	*-1.11102*	*0.65484*	*0.10809*	*-1.69662*	*0.09051*
β_3	*-0.13430*	*0.05806*	*0.84698*	*-2.31314*	*0.02120*

$E\ (Y) = \beta_0 + \beta_1 \cdot X_1 + \beta_2 \cdot X_2 + \beta_3 \cdot X_3$; *$R^2$= 0.618 ; Standard error of estimate = 0.06043; N = 428*

Variables	Observations	Minimum	Maximum	Mean	Standard Dev.
E (Y) (cm)	*428*	*0.03493*	*0.55721*	*0.14371*	*0.09692*
X_1 *(cm)*	*428*	*0.02032*	*0.36407*	*0.07133*	*0.04807*
X_2 *(cm²)*	*428*	*0.00041*	*0.13254*	*0.00739*	*0.01276*
X_3 (m²)	*428*	*0.00000*	*0.41104*	*0.05514*	*0.07037*

Y (cm) is the expected value of periodic annual diameter increment 14 to 16 years after treatment.
X_1 (cm) initial diameter.
X_2 (cm²) is the square of X_1.
X_3 (m^2) is the sum of the residual trees' basal area in trees with dbh larger than the subject tree's dbh_1 divided by the subject tree's diameter.
N is the number of observations.

Table 7*—Equation parameter estimates and summary statistics of periodic annual diameter increment for Douglas-fir after overstory removal in mixed conifer stands.*

		95 pct Confidence interval			
Parameters	Estimate	S. E.	Tolerance	T-statistic	P(2-tail)
β_0	*0.03459*	*0.01337*	.	*2.58642*	*0.01018*
β_1	*2.44742*	*0.22947*	*0.13376*	*11.00170*	*0.00000*
β_2	*-1.30855*	*0.65383*	*0.13913*	*-2.00136*	*0.04627*
β_3	*-0.33468*	*0.12834*	*0.90131*	*-2.60769*	*0.00958*

$E\ (Y) = \beta_0 + \beta_1 \cdot X_1 + \beta_2 \cdot X_2 + \beta_3 \cdot X_3$; *$R^2$= 0.683 ; Standard error of estimate = 0.08090; N = 312*

Variables	Observations	Minimum	Maximum	Mean	Standard Dev.
Y (cm)	*312*	*0.03556*	*0.83661*	*0.18091*	*0.14288*
X_1 *(cm)*	*312*	*0.00339*	*0.48651*	*0.06841*	*0.05982*
X_2 *(cm²)*	*312*	*0.00001*	*0.23669*	*0.00825*	*0.02291*
X_3 (m²)	*312*	*0.00000*	*0.80000*	*0.03075*	*0.05844*

E (Y) (cm) is the expected value of periodic annual diameter increment 14 to 16 years after treatment.
X_1 (cm) initial diameter.
X_2 (cm²) is the square of X_1.
X_3 (m^2) is the sum of the residual trees' basal area in trees with dbh larger than the subject tree's dbh_1 divided by the subject tree's diameter.
N is the number of observations.

measured in a plot or stand (Dolph 1988, Ritchie and Hann 1985, Wykoff 1986). Because X_3 is the sum of basal area of the residual trees in trees with diameter larger than the subject tree's diameter, the largest-diameter tree in the plot would have an X_3 value of zero, whereas the smallest-diameter tree in the plot would have an X_3 value near but somewhat less than the plots's total basal area.

Additionally, the increment attained by an individual tree is also dependent on its competitive status relative to neighboring trees—a tree's relative size. As a result, relative size is tied to stand density. Therefore, in sparsely stocked plots or stands, dominance would be less of a factor, because the more open-grown the tree, the less it is influenced by competitors (Wykoff 1990). The effect of competitive stress due to neighboring trees is represented by X_3, because for a given tree, diameter increment should decrease as X_3 increases and vice versa. Consequently, the coefficient of X_3 is negative, indicating a competition modifier that would reduce diameter growth rates relative to a tree's competitive status. Also, the size of the coefficient of X_3 for the various species indicates their competitive status relative to other species in the plot.

Conclusion

Regardless of timber sale area and species, residual trees responded to overstory removal by increasing their diameter growth after adjusting to their new environment (the 9- to 16-year period) (*fig. 13*). Although not statistically tested, units with the most overstory removed showed the highest diameter response after treatment, whereas units with low amounts of overstory removal showed the least diameter response regardless of timber sale area (*Figs. 1—13*).

Finally, examination of the linear regression equations developed to predict periodic annual diameter increment 14 to 16 years after treatment shows that the equations are consistent with our current biological and silvicultural knowledge. Although the coefficients for some of the species were not statistically significant, all the independent variables strengthened the regression equations.

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