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Growth of 11 Introduced Tree Species on Selected Forest Sites in Hawaii

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Research in Hawaii by the Division of Forestry and Wildlife, Hawaii Department of Land and Natural Resources, is conducted in cooperation with the Forest Service, U.S. Department of Agriculture.

Cover: A 40-year-old tallowwood eucalyptus (*Eucalyptus microcorys*) plantation grows in the Kalopa section of the Hamakua Forest Reserve on the island of Hawaii.

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CONTENTS

IN BRIEF...

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Retrieval Terms: Hawaii, *Pinus*, *Eucalyptus*, growth, biomass, hardwoods

To assess growth of tree species introduced to Hawaii, trees on 25 plots representing 11 major species were observed and measured over a 21-year period. Species studied were Australian toon (*Toona ciliata* var. *australis* F. Muell. C. DC.), tropical ash (*Fraxinus uhdei* [Wenzig] Lingelsh.), silk-oak (*Grevillea robusta* A. cunn.), Norfolk-Island-pine (*Araucaria heterophylla* [Salisb.] Franco), redwood (*Sequoia sempervirens* [D. Don] Endl.), slash pine (*Pinus elliottii* Engelm.), loblolly pine (*Pinus taeda* L.), tallowwood eucalyptus (*Eucalyptus microcorys* F. Muell), blackbutt eucalyptus (*Eucalyptus pilularis* Sm.), robusta eucalyptus (*Eucalyptus robusta* Sm.), and saligna eucalyptus (*Eucalyptus saligna* Sm.).

All live trees were recorded and measured at 5-year intervals for diameter-at-breast-height (d.b.h.), bark thickness, and sawtimber-poletimber lengths and total heights. Cubic volume for all species except pines were computed by Smalian's formula. All stands were unmanaged except for redwood.

On the Australian toon, tropical ash, and silk-oak sites, high-quality sawlogs were produced from trees on certain sites. Rotation age should not exceed 45 years on these sites. Silk-oak was found to grow well on dry sites (890 mm [35 inches] rainfall/year) and could produce sawtimber if the rotation age was lengthened. High rainfall or excessive cloud cover is not suitable for silk-oak. Australian toon showed improved form and volume when grown in mixture with silk-oak rather than in a pure stand.

Norfolk-Island-pine trees on all plots sampled survived well and were healthy. Among the five plots, growth rates (to a 10-cm top outside bark) ranged from 730 to 1050 m^3 per ha (10,500 to 15,000 ft^3/acre). Total volume mean annual increment ranged from 15 to 27 m^3 per ha (210 to 395 ft^3/acre). Sawtimber volume ranged from 600 to 770 m^3 per ha (8000 to 11,000 ft^3/acre). For sawtimber, the data suggest that spacings of 3 by 3 m (10 by 10 ft) are desirable.

On the redwood sites, diameter growth of trees increased consistently, about 2.54 cm (1 inch) per 5 years during the last 15 years. Trees at age 48 had sawtimber cubic volume of 1500 m^3 per ha (21,328 ft^3/acre); total cubic volume was 1780 m^3 per ha (24,460 ft^3/acre), and mean annual increment for sawtimber was 30 m^3 per ha (444 ft^3/acre). Site index values for dominant redwood, by height and age, on Maui plots, would have a California site index of 160. Because redwood trees in Hawaii grow slower than redwood trees in California, site curves developed for northern California do not apply to trees grown in Hawaii. Another difference is that Hawaii-grown redwood is less durable and of lower grade than California-grown redwood and should be considered a general construction and utility softwood.

Due to denser stocking, the average diameter of slash pine at 15 years (20.8 cm [8.2 inches]) was less than that of loblolly pine (21.8 cm [8.6 inches]). Despite the smaller average diameter, slash pine stands had higher volume growth. At age 15, slash pine had 290 m^3 per ha (4176 ft^3/acre) volume as compared with 130 m^3 per ha (1860 ft^3/acre) volume for loblolly pine at age 20. Height growth, compared for the two species, indicates that loblolly pine was declining while slash pine maintained vigorous growth. To maximize potential growth, spacings more than 3 by 3 m (10 by 10 ft) should not be used for either species. Early thinnings are recommended when trees are planted closer together. Slash pine should be favored for volume production on marginal sites.

More than 8100 ha (20,000 acres) of eucalyptus species have been planted throughout Hawaii. Among these species, robusta eucalyptus is the more suitable for sawtimber; other species are used mainly for fiber and pulp. For young-growth eucalyptus, best growth at age 18 was a total volume of 650 m^3 per ha (9316 ft^3/acre) and 220 m^3 per ha (3126 ft^3/acre) of sawtimber volume. Total annual increment at age 7 to 18 averaged more than 35 m^3 per ha (500 ft^3/acre) and average diameter increased steadily from 18 to 28 cm (7.1 to 11.1 inches). For old-growth eucalyptus, on the best site, at age 32, the stand's total volume averaged 1425 m^3 per ha (20,358 ft^3/acre) and the average total height of the dominant trees was 60 m (196 ft).

Data from this report show that 10 of the 11 tree species investigated grow fast enough to warrant more extensive plantings that could supply timber or wood fiber for a forest products industry in Hawaii.

During the past 50 years, a wide variety of tree species have been introduced to Hawaii. Some have grown remarkably well and have shown great potential as a source of wood products.

In 1961, the Forest Service's Institute of Pacific Islands Forestry, Honolulu, Hawaii, began a study to determine growth rates within selected stands of 11 introduced timber species grown under tropical forest conditions. The study was done in cooperation with the Hawaii Division of Forestry and Wildlife. Of 42 growth plots established, 25 were selected for this report. Number of growth plots for each species is as follows:

Species	Plots
Australian toon (*Toona ciliata* var. *australis* [F. Muell.] C. DC.)	7
Tropical ash (*Fraxinus uhdei* [Wenzig] Lingelsh.)	7
Silk-oak (*Grevillea robusta* A. cunn.)	7
Norfolk-Island-pine (*Araucaria heterophylla* [Salisb.] Franco)	5
Redwood (*Sequoia sempervirens* [D. Don] Endl.)	1
Slash pine (*Pinus elliottii* Engelm.)	1
Loblolly pine (*Pinus taeda* L.)	1
Tallowwood eucalyptus (*Eucalyptus microcorys* F. Muell.)	2
Blackbutt eucalyptus (*Eucalyptus pilularis* Sm.)	1
Robusta eucalyptus (*Eucalyptus robusta* Sm.)	1
Saligna eucalyptus (*Eucalyptus saligna* Sm.)	6

The growth and volume data provided do not represent yields for whole stands or for a typical cross section of planted stands in Hawaii. They depict growth on sample areas. The yields, therefore, indicate the potential for growth of forests on better-than-average sites. Except for redwood, these are yields for completely unmanaged forests.

Because the plots are unique in site, spacing, and species, specific management practices based on data provided cannot be recommended. The data, however, supply a base for inferences that are given as general observations for each species.

This paper reports results and observations of a 21-year study of growth for 11 major tree species in Hawaii. All live trees on each of the 25 plots were recorded, and their growth measured at 5-year intervals. Each species is described in terms of history, size and growth rates, volume, wood characteristics, and potential uses.

PROCEDURES

Circular (0.04-ha) growth plots were established in forest plantations of selected species showing good vigor and low mortality. All live trees were recorded and their growth measured at 5-year intervals. Diameter-at-breast-height, 1.4 m (4.5 ft) above ground, was measured directly with diameter tapes, bark thickness with bark punches, and sawtimber-poletimber lengths and total heights with relaskops.

Sawtimber volume inside bark was calculated for lengths of stems from 30 cm (1 ft) above the base of the tree to a minimum 23-cm (9-inch) top diameter outside bark. Total volume inside bark was calculated for the main stem length, ignoring forks, to a 10-cm (4-inch) top diameter outside bark. Total volumes for pines were calculated for stem lengths from the base to the tip of the tree.

Cubic volume of all species except pines was obtained by Smalian's formula:

$$\text{Cubic volume} = \frac{B + b}{2} L$$

in which:

B = cross-sectional area inside bark at large end of stem
b = cross-sectional area inside bark at small end of stem
L = stem length

Cubic foot volume for pines was computed by these equations (McClure 1977):

Loblolly Pine

Total cubic foot volume inside bark =

$$0.5960 + 0.002115 (D^2TH)$$

Slash Pine

Total cubic foot volume inside bark =

$$0.0255 + 0.002184 (D^2TH)$$

D = d.b.h. in inches (outside bark)

TH = total height from ground level to tip of the main stem in feet.

SPECIES

Australian Toon

Australian toon was introduced to Hawaii in 1914, and planted in small scattered stands on all the islands. A small amount of toon timber in Hawaii has been cut and appears to be an excellent utility hardwood because it is easy to work and resistant to termites. Australian toon may have special applications in home construction as house siding and interior paneling (Skolmen 1974).

Two plots of Australian toon are located in the Kalopa section of the Hamakua Forest Reserve on the island of

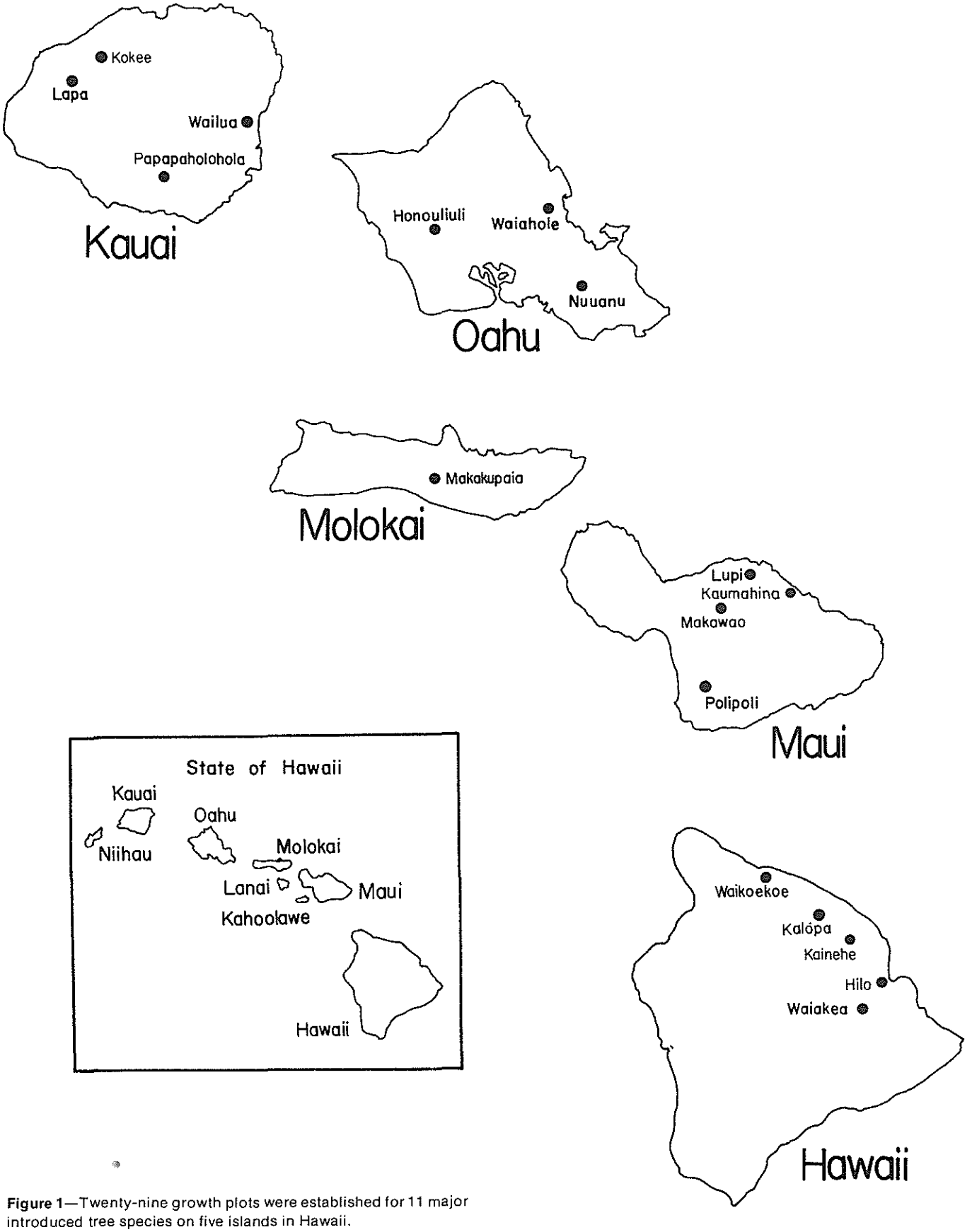

Figure 1—Twenty-nine growth plots were established for 11 major introduced tree species on five islands in Hawaii.

Hawaii (*fig. 1*). One is a pure stand, the other consists of alternating rows of toon and silk-oak (*fig. 2*).

The pure toon plot contained 395 m^3 per ha (5666 ft^3/acre) of sawtimber volume at age 43 (*table 1*). Mean annual increment (MAI) for total volume was 11 m^3 per ha (160 ft^3/acre). Diameter-at-breast-height ranged from 17 to 66 cm (6.7 to 25.9 inches), and averaged 43 cm (17.1 inches), with an average sawtimber stem length of 11 m (35 ft).

The six 43-year-old Australian toon trees on the toon—silk-oak plots ranged from 35 to 57 cm (13.7 to 22.6 inches) d.b.h., averaging 47 cm (18.4 inches). Sawtimber stem length averaged 15 m (49 ft).

Tropical Ash

Tropical ash is a Mexican species that was introduced to the island of Oahu in the late 1800's. It was planted in small stands on all the islands and grew well in some locations. The Division of Forestry began planting ash on a larger scale in the Waiakea Forest Reserve near Hilo, for timber production, but its growth was poor. Tropical ash planting there has since been deemphasized.

Figure 2—Forked Australian toon (*Toona ciliata* var. *australis*) is in the background and silk-oak (*Grevillea robusta* A. cunn.) in the foreground in this mixed stand at Kalopa, island of Hawaii, at age 45.

Tropical ash wood is blond, moderately fine in texture, and straight grained. Because of the early growth habit of the tree, the butt log is often clear of knots to the pith and saws out a high yield of high-grade lumber. It is primarily a furniture and cabinet wood and has been used for furniture parts and finished furniture (Skolmen 1974).

Two tropical ash—silk-oak growth plots are in the Kalopa section of the Hamakua Forest Reserve on the island of Hawaii (*table 1, fig. 3*). Diameters of the 42 tropical ash trees on these plots ranged from 7.0 to 94 cm (2.8 to 37.0 inches) at 43 years, and averaged 33.0 cm (13.0 inches). Average sawtimber stem length was 12.5 m (41 ft).

Silk-oak

In about 1880, silk-oak was introduced to Hawaii from Australia, and planted on all the main Hawaiian Islands. The tree produces a straight, erect stem even when open-grown, and grows well in plantations, achieving excellent growth on all soils when annual rainfall is 1525 to 2030 mm (60 to 80 inches). Silk-oak also grows on drier sites, 760 mm (30 inches) annual rainfall, but slower. It has become widely naturalized and reproduction is often girdled or poisoned on pasture land, where it is considered a noxious weed (Nelson 1960).

Silk-oak has cream-colored sapwood about 2.5 cm (1 inch) thick, and changes abruptly to a pale pinkish-brown heartwood. It has been used successfully for furniture, paneling, and flooring. Because of its relatively light weight, the wood was found acceptable for pallets used in handling air cargo. Silk-oak is well suited as face veneer and is known by the name of lacewood (Skolmen 1974).

Three growth plots were established in pure silk-oak stands, two plots in silk-oak—tropical ash stands, and one plot in a silk-oak—Australian toon stand. Elevations varied from 440 to 725 m (1450 to 2380 ft) and rainfall ranged from 890 to 4570 mm (35 to 180 inches) (*table 1*). Pure silk-oak plots are located in the Kalopa section of the Hamakua and Waiakea Forest Reserves, island of Hawaii, and the Honouliuli Forest Reserve on the island of Oahu (*fig. 1*).

Of the three pure silk-oak plots, the Kalopa plot had the best growth volume with 490 m^3 per ha (6,971 ft^3/acre) of sawtimber at age 43 (*table 1*). Total volume mean annual increment was 14 m^3 per ha (196 ft^3/acre). Diameters ranged from 19 to 67 cm (7.6 to 26.3 inches) and averaged 40 cm (15.8 inches). Average sawtimber stem length was 16 m (51 ft).

The silk-oak plot in Honouliuli, Oahu, had 350 m^3 per ha (5018 ft^3/acre) of sawtimber at age 49. Diameters ranged from 10 to 52 cm (4.0 to 20.4 inches) and averaged 31 cm (12.2 inches). This is considered a dry site with 890-mm (35-inches) annual rainfall.

The silk-oak plot in Waiakea, Hawaii, had 235 m^3 per ha (3381 ft^3/acre) of sawtimber at age 43. The diameter range was 21 to 47 cm (8.2 to 18.5 inches), with an average diameter of 35 cm (13.9 inches), and average sawtimber

Table 1—*Site and volumetric data of three tree species at seven locations in Hawaii*

Tree species	Site						Species			Volume		
	Plot	Location	Spacing	Elevation	Precipitation	Aspect	Trees in plot	Age	Avg. d.b.h.	Total (10-cm top)	Sawtimber (23-cm top)	Total mean annual increment
			m		*mm*			*years*	*cm*	m^3/ha		
Toona ciliata var. *australis*	1	Kalopa, Hawaii	5.5 by 5.5	715	2080	Northeast	14	27	38.6	[1]—	—	—
							14	32	39.4	—	—	—
							14	38	41.4	345	269	9
							14	43	43.4	483	396	11
Toona ciliata var. *australis*	2	Kalopa, Hawaii	4.9 by 4.9	720	2080	East	17	32	37.1	—	—	—
Grevillea robusta							16	38	41.4	387	262	10
							15	43	43.8	713	597	17
Grevillea robusta *Fraxinus uhdei*	3	Kalopa, Hawaii	3.0 by 3.7	660	2080	North	36	26	26.9	—	—	—
							33	31	27.4	—	—	—
							27	37	26.7	479	284	13
							25	42	26.2	551	367	13
Grevillea robusta *Fraxinus uhdei*	4	Kalopa, Hawaii	3.7 by 4.9	700	2080	Northwest	25	27	36.3	—	—	—
							25	32	38.4	—	—	—
							25	38	38.4	619	441	16
							24	43	39.1	906	688	21
Grevillea robusta	5	Kalopa, Hawaii	4.9 by 4.9	725	2080	North	19	27	32.3	—	—	—
							19	32	33.5	—	—	—
							15	38	37.6	329	231	9
							13	43	40.1	590	488	14
Grevillea robusta	6	Honouliuli, Oahu	2.7 by 3.7	445	890	Northeast	30	38	26.9	—	—	—
							27	43	27.9	482	308	11
							26	49	31.0	550	351	11
Grevillea robusta	7	Waiakea, Hawaii	3.4 by 7.6	445	4600	Level	16	38	34.5	—	—	—
							16	43	35.3	360	237	8

[1]No data

stem length of 9 m (30 ft). This is considered a wet site with 4570-mm (180-inches) annual rainfall.

The 43-year-old mixed silk-oak—Australian toon plot in Kalopa had 11 silk-oak and six Australian toon trees. The silk-oak diameter range was 9 to 57 cm (3.4 to 22.4 inches), average diameter 42 cm (16.4 inches), and average sawtimber stem length of 14 m (47 ft). Average height of the seven dominant silk-oak trees was 32 m (105 ft), compared with 30 m (97 ft) for the six dominant Australian toon trees. All Australian toon trees on the plot were in the dominant crown class with no mortality.

The two silk-oak—tropical ash growth plots in Kalopa included 15 silk-oak trees. At age 43, they had diameters ranging from 18 to 43 cm (7.1 to 17.1 inches) and averaged 33 cm (13.0 inches), with an average sawtimber length of 12 m (39 ft). The average height of dominant silk-oak on the two plots was 29.5 m (97 ft) and of tropical ash was 29.3 m (96 ft). Among the trees of each species, 40 percent were in the dominant crown class.

General observations of growth plot data for Australian toon, tropical ash, and silk-oak are as follows:

- Mortality ranged from 0 to 28 percent. Cull and defects such as multistems, spike branches, sweeps, and crooks were observed on all plots. Few trees had a clean stem for 14.6 m (48 ft). On the one exposed site in Kalopa, windthrow and broken tops were common.
- All stand conditions in these plots, except Honouliuli, were deteriorating. Overstory canopies were opening, and weedy vegetation was entering the understory. If stands are going to be unmanaged as these were, rotation ages for high quality sawlogs on the Kalopa and Waiakea sites should not exceed 45 years. Diameter growth could have been increased on the larger stems by thinning the stand to reduce competition.
- The ability of silk-oak to grow acceptably and with good form on sites as dry as Honouliuli (890 mm [35 inches] rainfall/year) could be utilized by lengthening the rotation age on these dry sites. Growth of silk-oak in Waiakea, where rainfall was 4570 mm (180 inches) per year, was poor, suggesting that high rainfall or heavy cloud cover associated with this high rainfall is not suitable for silk-oak.
- Australian toon showed better form and volume in mixture with silk-oak than in the pure stand. In the mixed plot, average sawtimber stem length of Australian toon was 15 m (49 ft), as compared with 11 m (35 ft) for the pure plot.

Norfolk-Island-Pine

Norfolk-Island-pine and Cook-pine (*Araucaria columnaris*) were introduced to Hawaii in about 1860. The two species probably hybridized, and the hybrids were subsequently dispersed throughout the islands. Norfolk-Island-pine in Hawaii is probably *A. heterophylla xcolumnaris*. All juvenile seedlings today show *A. columnaris* traits.

Norfolk-Island-pines are used as Christmas trees that are marketable locally and on the mainland. Most of the timber harvested is used for residential framing and sheathing, and the lowest grade is used for pallets. Some knotty-pine paneling has been produced and used effectively. The wood is also used to a limited extent in the craft industry (Skolmen 1974).

Generally, forest plantations of Norfolk-Island-pine in Hawaii have been established at 2.4- by 2.4-m to 4.6- by 4.6-m (8- by 8-ft to 15-by 15-ft) spacings at elevations below 610 m (2000 ft). Trees in cooler temperatures at higher elevations do not grow well.

Five plots were established in representative areas. One is on the island of Hawaii on the land of Waikoekoe, near Waipio Valley, one on Kauai in the Papapaholahola Spring Forest Reserve near Kalaheo, and three on Oahu (two at different elevations in Nuuanu Valley and one on a ridge at Waiahole on the windward side of the island) (*fig. 1*). Elevations range from 90 to 550 m (300 to 1800 ft) and annual rainfall from 1300 to 3175 mm (50 to 125 inches) (*table 2*). Spacings range from 3 by 3 m to 4.3 by 4.6 m (10 by 10 ft to 14 by 15 ft).

The greatest total volume per acre found in a single stand was on the land of Waikoekoe, with more than 1050 m^3 per ha (15,000 ft^3) at 38 years (*table 2*). This stand also had the most sawtimber cubic foot volume per acre with 750 m^3 per ha (10,815 ft^3) and the highest total volume mean annual increment of 27 m^3 per ha (395 ft^3). This plot had the closest spacing of 3 by 3 m (10 by 10 ft) and the highest elevation at 550 m (1800 ft).

Because no trees died in any plot, the initial planting spacings represent the present stocking level. Spacings ranged from 3 by 3 m (10 by 10 ft) for plot 1 (420 trees/acre) to 3.7 by 3.7 m (12 by 12 ft) for plot 5 (300 trees/acre) (*table 2*).

Trees on the sparsely-stocked plots (2 and 5) had the largest diameter growth. The largest d.b.h. was 60 cm (23.6 inches) for a 47-year-old tree in plot 5.

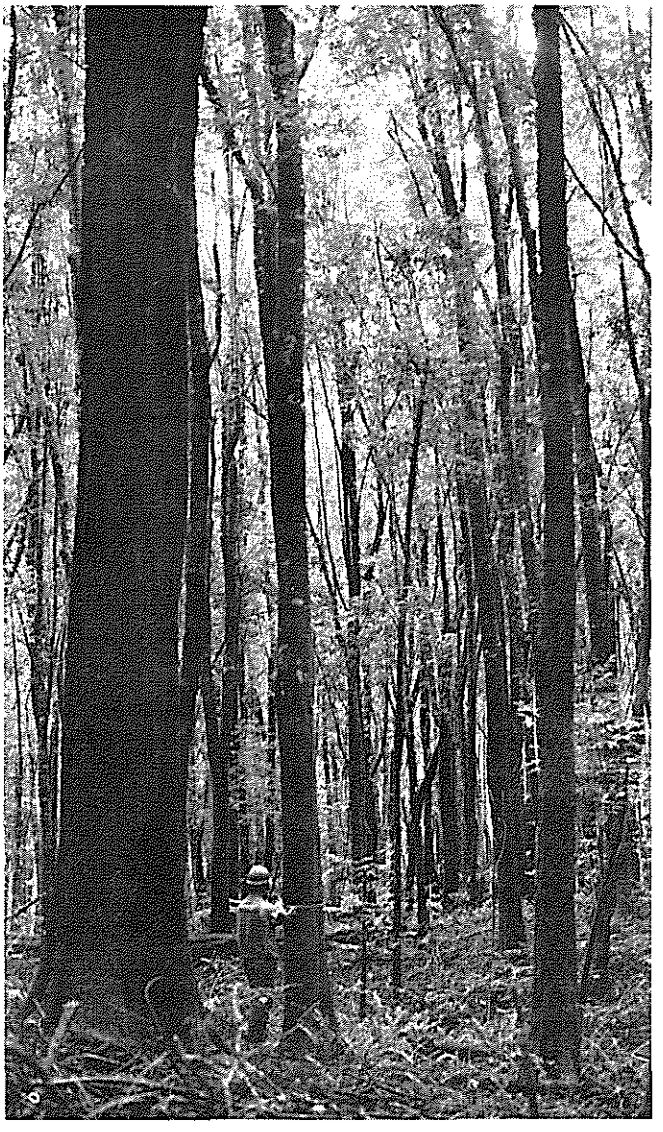

Figure 3—Tropical ash (*Fraxinus uhdei* Wenzig Lingelsh.) grows with silk-oak (*Grevillea robusta* A. cunn.) in this 44-year-old stand at Kalopa, island of Hawaii. Note the poorer form of the tropical ash.

Table 2—*Site and volumetric data of Norfolk-Island-pine (*Araucaria heterophylla*) at five locations in Hawaii*

Plot	Location	Spacing	Elevation	Precipitation	Aspect	Trees in plot	Age	Average		Volume		
								Diameter	Height of dominant/codominant	Total (10-cm top)	Sawtimber (23-cm top)	Total annual increment
		m		*mm*			*years*	*cm*	*m*	m^3/ha		
1	Waikoekoe, Hawaii	3.0 by 3.0	550	2030	Northwest	42	28	29.5	[1]—	—	—	—
						41	32	31.8	—	—	—	—
						41	38	32.8	34.4	1050	757	28
2	Nuuanu, Oahu	3.7 by 4.0	215	2540	Northwest	38	25	35.8	—	—	—	—
						25	43	39.4	22.6	641	514	15
						25	47	40.6	26.8	868	732	18
3	Waiahole, Oahu	3.4 by 3.7	90	2540	North	37	34	31.2	—	—	—	—
						33	42	33.3	29.6	862	617	20
						33	46	34.0	30.5	989	743	21
4	Papapahola-hola, Kauai	3.7 by 3.7	305	2080	Southwest	31	49	36.8	25.3	546	452	11
						31	54	38.9	29.3	793	565	15
5	Nuuanu, Oahu	4.3 by 4.6	365	3175	South	21	42	37.1	23.2	524	442	12
						21	47	40.6	27.7	733	592	16

[1]No data

Tree height growth was most vigorous on plots 1 and 3, indicating these were probably the best sites. At age 38, dominant and codominant trees of plot 1 averaged 34 m (113 ft) tall, with the tallest tree measuring 43 m (142 ft).

General observations of the Norfolk-Island-pine growth plots are the following:

- Among the five Norfolk-Island-pine plots, growth rates (to a 10-cm top outside bark) ranged from 730 to 1050 m^3 per ha (10,500 to 15,000 ft^3/acre), and total volume mean annual increment ranged from 15 to 27 m^3 per ha (210 to 395 ft^3/acre).
- Sawtimber volume ranged from 600 to 770 m^3 per ha (8000 to 11,000 ft^3/acre).
- These yields were obtained in stands that were planted 28 to 49 years before they were measured. The ages at which maximum yields can be obtained cannot be determined during this short period of measurement, but the stands appear to be thriving and continuing to grow at high rates.
- For Norfolk-Island-pine sawtimber, spacings of 3 by 3 m (10 by 10 ft), with thinning, appear to be desirable.
- Although some plots showed slower growth rates, trees on all sites sampled had excellent survival and health. Of those sampled, plot 1 at Waikoekoe was the best site for Norfolk-Island-pine.

Redwood

Redwood is established on the islands of Maui, Kauai, and Hawaii. Maui, the island on which most redwood has been planted, has 113 ha (280 acres) of planted redwood containing 6.2 million board feet of sawtimber (Wong and others 1969). Redwood is difficult to establish in plantations because young trees grow slowly and need weeding to remove competing vegetation.

The main problems of Hawaii-grown redwood lumber are its low durability and grade; therefore, it is not a good substitute for top-grade redwood lumber imported from California. Hawaii-grown redwood should be considered a general construction and utility softwood suitable for house framing and similar uses (Skolmen 1974).

The redwood growth plot is located at 1750-m (5700-ft) elevation at Polipoli, in the Kula Forest Reserve on the island of Maui (*fig. 1*). Annual rainfall is 890 mm (35 inches) and afternoon fog and cloud cover are common. Soil on the site is a deep light-brown silty clay loam with no rocks.

The stand was planted in 1930, at 3- by 3-m (10- by 10-ft) spacings with seed from California. Six suppressed trees were removed in 1958, and the remaining 38 stems were pruned.

The average tree diameter for 48-year-old trees was 48 cm (18.8 inches). Diameter growth has been increasing consistently, about 2.54 cm (1 inch) per 5 years during the last 15 years (*table 3*).

At age 48, trees had a sawtimber cubic volume of 1500 m^3 per ha (21,328 ft^3/acre), and total cubic volume was 1780 m^3 per ha (24,460 ft^3/acre). The mean annual increment for sawtimber was 30 m^3 per ha (444 ft^3/acre) at age 48, and the current annual increment during the last 6 years was 110 m^3 per ha (1604 ft^3/acre).

The largest tree on the plot at age 48 was 87 cm (34.1 inches) at d.b.h. and 61 cm (24 inches) diameter on top of the first 5-m (16-ft) log, 20 m (67 ft) to a 23-cm (9-inch) top outside bark, and a total height of 37 m (120 ft).

In comparison to site index values of California redwood, redwood trees on the Maui plot would have a California site index of 160 (Lindquist and Palley 1963). Site indexes for redwood in northern California range from a high of 100 to 240. The low site index of the Maui redwoods might be caused by the slower start of planted stock in Hawaii as compared with the frequent coppice origin of young-growth redwood in California, or perhaps by a reaction of the tree's physiology to day-length differences in Hawaii. Redwood trees in Hawaii are growing slower in height, but more rapidly in diameter than redwood in California. Site curves developed for northern California, therefore, do not apply well to trees grown in Hawaii.

Loblolly Pine and Slash Pine

Hawaii has no native conifers. During the past 100 years, however, more than 45 species of pine have been planted experimentally. A few species have grown well in certain locations. Some have been planted fairly extensively (162

Table 3—*Growth of redwood* (Sequoia sempervirens) *at Poli-Poli, Maui, during 16 years of measurement*[1]

Age (years)	Average		Volume		Sawtimber	
	Diameter-at-breast-height (d.b.h.)	Height dominant/codominant	Total (10-cm top)	Sawtimber (23-cm top)	Mean annual increment	Periodic annual increment
	cm	*m*	*m^3/ha*			
32	39.6	24.4	[2]—	—	—	—
36	43.2	27.1	—	—	—	—
42	45.2	31.4	1173	819	20	—
48	47.8	31.7	1781	1492	31	112

[1]3.0- by 3.0-m spacing (38 plot trees), Kula Forest Reserve.
[2]No data.

Figure 4—A loblolly pine (*Pinus taeda* L.) plantation at 2.4 by 2.7 m (8 by 9 ft) spacing on the island of Molokai. Trees on this plot are age 17.

ha [400 acres] loblolly and slash pines) on the island of Molokai (*fig. 4*).

Wood from slash pine grown near Olinda proved to be suitable for millwork and pattern stock, but not for construction (Bohr 1958). Its specific gravity was lower than normal for slash pine, indicating low strength. Exploratory tests of slash pine suggested that growth conditions in Hawaii might produce unusual variations in wood quality (Skolmen 1963).

Two growth plots are located in stands of loblolly and slash pines on Makakupaia Ridge, island of Molokai (*fig. 1*). Annual rainfall is 1000 mm (40 inches) and slope 0 to 5 percent with a north aspect. The soil is a strongly acidic silty clay loam. The loblolly pine stand was planted in January 1957, with 3.6- by 4.6-m (12- by 15-ft) spacings (598 trees/ha). Slash pine was planted in January 1962, with 2.4- by 2.7-m (8- by 9-ft) spacings (1494 trees/ha). Because no trees died in either plot, stocking is represented by the original spacing.

Despite the denser stocking of slash pine, its average diameter at 15 years—20.8 cm (8.2 inches)—was slightly less than that of loblolly pine—21.8 cm (8.6 inches) (*table 4*). The largest diameter for loblolly pine was 36 cm (14.1 inches) and 31 cm (12.1 inches) for slash pine.

A comparison of volume growth of the two species indicates a higher productivity for the slash pine plot, which corresponds with its closer spacing (*fig. 5*). The loblolly pine 3.6- by 4.6-m (12- by 15-ft) spacings do not seem to fully utilize the site potential. Slash pine had 290 m^3 per ha (4176 ft^3/acre) volume at age 15, as compared with 130 m^3 per ha (1860 ft^3/acre) volume at age 20 for loblolly pine (*table 4*).

Average height growth for slash pine was 13 m (43.8 ft) at 15 years, greater than the loblolly pine with 12 m (39.8 ft) at 20 years. The tallest slash pine was 17 m (56 ft) and the tallest loblolly pine was 15.5 m (51 ft). A comparison of height growth between the two species indicates that loblolly pine is decreasing while slash pine is maintaining vigorous growth (*fig. 6*).

Loblolly pine in a similar study at Olinda, Maui (Whitesell 1974), had better d.b.h. and total height growth rates at similar or denser spacings (2.4 by 2.4 m [8 by 8 ft]) than the Molokai loblolly pines (3.7 by 4.6 m [12 by 15 ft]). Another study (Schubert and Korte 1969), shows the growth of slash pine at 9 years as slightly faster than that of loblolly at 1.8- by 1.8-m (6- by 6-ft) and 2.7- by 2.7-m (9- by 9-ft) spacings at the Olinda site. The Olinda site has greater annual rainfall and better soil than the Molokai site.

For conifer plantings on marginal sites similar to the Molokai pine growth plots, slash pine seems to be a more desirable species than loblolly pine for maximum sawtimber and cubic volume growth per acre. As sites improve, growth differences between the two species lessen. The Olinda site may be ideal for either species.

To maximize potential growth, spacings more than 3- by 3-m (10- by 10-ft) should not be used for slash or loblolly pine. Early thinnings are recommended when trees are planted closer. For loblolly spacing, Whitesell (1974) recommended 3- by 3-m (10- by 10-ft) spacings for sawtimber and 2.4- by 2.4-m (8- by 8-ft) spacings for posts, poles, or fuelwood. Early thinnings in the closer spacings would increase growth rates and improve the quality of residual trees.

Table 4—*Growth of loblolly* (Pinus taeda) *and slash* (Pinus elliottii) *pines to age 20, on Molokai, by stand age*

Stand age (years)	Loblolly pine[1]			Slash pine[2]		
	Average		Total volume	Average		Total volume
	Diameter-at-breast-height (d.b.h.)	Height		Diameter-at-breast-height (d.b.h.)	Height	
	cm	*m*	m^3/ha	*cm*	*m*	m^3/ha
5	[3]—	—	—	11.7	6.1	40
10	16.3	7.8	55	18.0	10.0	153
15	21.8	10.2	95	20.8	13.4	292
20	21.6	12.1	130	—	—	—

[1]3.7- by 4.6-m spacing (25-plot trees).
[2]2.4- by 2.7-m spacing (57-plot trees).
[3]No data.

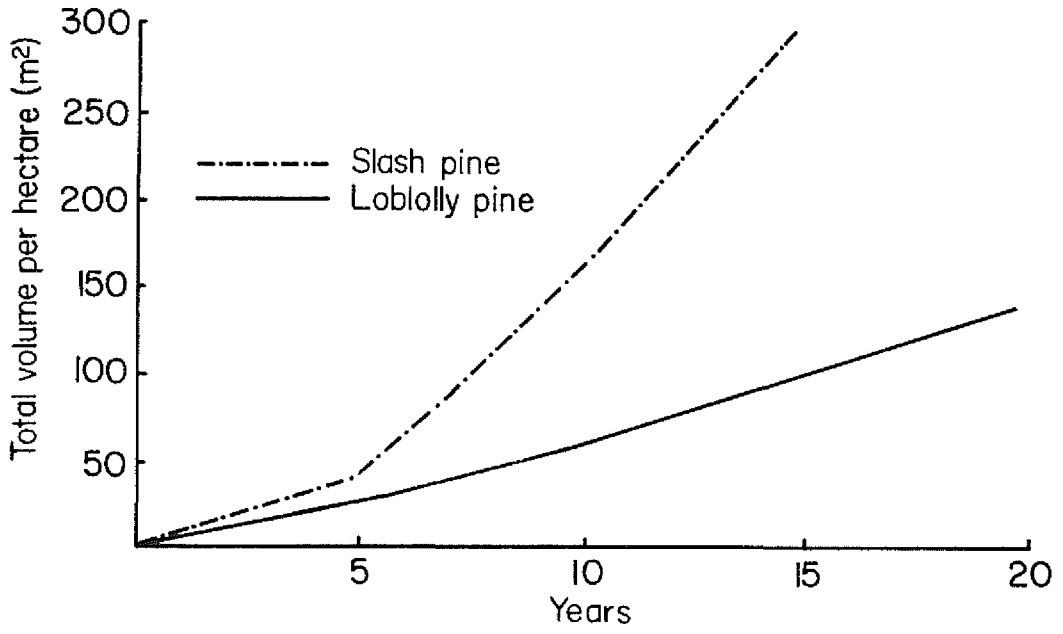

Figure 5—Volume growth compared for loblolly (*Pinus taeda L.*) and slash pine (*Pinus elliottii* Engelm.) shows a higher productivity for slash pine, which corresponds with its closer spacing. Loblolly pine spacing: 3.6 by 4.6 m (12 by 15 ft); slash pine spacing: 2.4 by 2.7 m (8 by 9 ft).

Eucalyptus Species

Eucalyptus species were introduced to Hawaii in the late 1860's to early 1900's. Their rapid growth on a variety of sites has made them a desired species for reforestation on all the main islands. More than 8100 ha (20,000 acres) of eucalyptus have been planted throughout the State.

Wood uses for eucalyptus are species-dependent. Robusta eucalyptus is more suitable for sawtimber than for fiber products. Its wood has been used for house siding, flooring, and paneling. The main uses for the other species have been for fiber and pulp.

This report covers 10 eucalyptus growth plots: one group with three plots representing a young age group from 7 to 18 years, and seven others representing an older age group from 25 to 45 years.

Young Eucalyptus Growth Plots

The younger group of growth plots was established in 7-year-old stands of saligna eucalyptus. Two were located

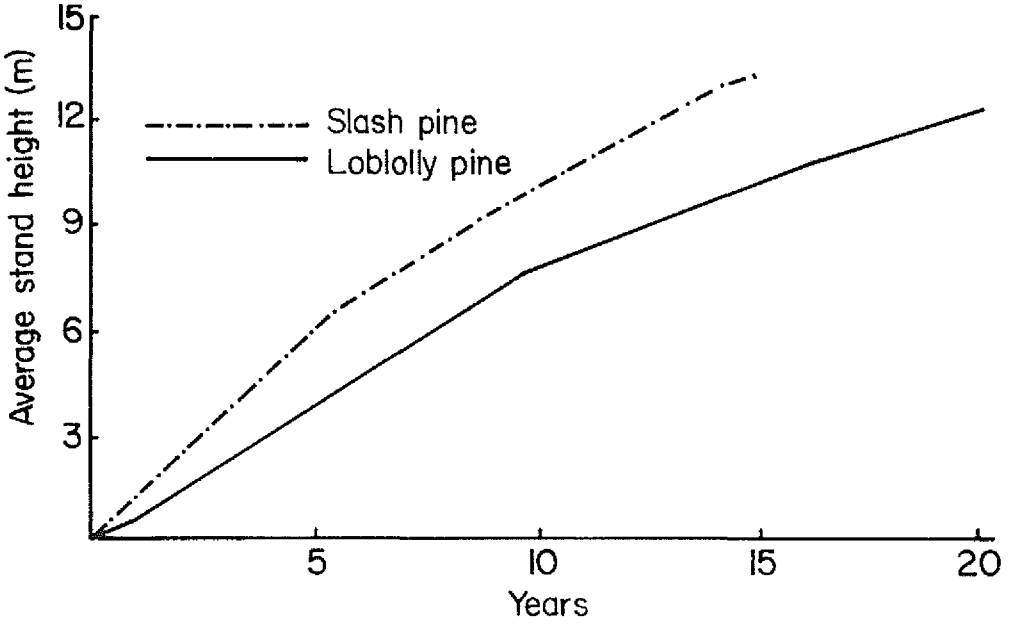

Figure 6—Height of loblolly pine (*Pinus taeda* L.) decreased as slash pine (*Pinus elliotti* Engelm.) maintained vigorous growth. The loblolly pine spacings (3.6 by 4.6 m [12 by 15 ft]) did not seem to fully utilize the site potential.

in the Lupi and Kaumahina sections of the Koolau Forest Reserve on the island of Maui, and the third was in the Waiakea Forest Reserve on the island of Hawaii (*fig. 1*). Data on elevations, rainfall, and spacings for each plot are provided (*table 5*).

The Kaumahina plot showed the best growth of the three plots. At age 18, it produced a total volume of 650 m^3 per ha (9316 ft^3/acre) and 220 m^3 per ha (3126 ft^3/acre) of sawtimber volume. The total measurement of mean annual increment at age 7 to 18 averaged more than 35 m^3 per ha (500 ft^3/acre) and average diameter increased steadily from 18 to 28 cm (7.1 to 11.1 inches).

Average total height of the 13 dominant and codominant trees on the plot at age 18 was 48 m (156 ft). The largest tree on the plot was 58 cm (23.05 inches) at d.b.h., 34 m (113 ft) to a 23-cm (9-inch) top, and 51 m (167 ft) tall.

A 15-year-old spacing study was done in Kaumahina which showed growth rates for the similar spacing slightly higher than those measured in the growth plots (Walters 1980). A significant feature reinforced by our growth plot data is the peaking of the mean annual increment volume at age 7. This peaking indicates that harvesting for optimal biomass production should be done at age 7.

The Lupi and Waiakea growth plots had lower growth rates than those at Kaumahina (*table 5*). The Lupi site had less than 2500-mm (100-inches) annual rainfall and the Waiakea site had more than 5000 mm (200 inches) per year. Again, the mean annual increment volume peaked at age 7. All sites suffered severe windthrow during the 1980 winter storm.

Older Eucalyptus Growth Plots

Much of this older eucalyptus growth data is historical in nature. Current management practices for eucalyptus favor short rotation and subsequent coppice management for high yields of fiber. The data show site quality for certain planting areas and volume estimates for existing, older eucalyptus plantations.

Seven plots were established in different species of eucalyptus (*table 6*). Six are on the island of Hawaii—three in the Kalopa section, Hamakua Forest Reserve, one each in the Kainehe and Waikoekoe units, Hamakua Forest Reserve, and one in the Hilo Reservoir area of Hilo Forest Reserve (*fig. 1*). The last plot is on Lapa Ridge in the Puu Ka Pele Forest Reserve, on the island of Kauai.

The best site for eucalyptus was the Kainehe unit, island of Hawaii. At age 32, the stand's total volume averaged 1425 m^3 per ha (20,358 ft^3/acre), and the average total height of the dominant trees was 60 m (196 ft).

The largest saligna eucalyptus tree measured was in the Hilo Reservoir plot (*fig. 7*). At age 44, it measured 95 cm (37 inches) d.b.h., 46 m (151 ft) to a 23-cm (9-inch) top, and 65 m (215 ft) in total height.

The blackbutt eucalyptus plot at Waikoekoe produced a total volume of 1590 m^3 per ha (22,687 ft^3/acre) at age 45 (*fig. 8*). It had the largest spacings, 4.9 by 6.1 m (16 by 20 ft), which explains its largest average d.b.h. of 65 cm (25.70 inches). The average total height of the dominant trees was 58 m (190 ft), indicating a very good site.

Biomass Energy Tree Farm Survey

In 1979, the Division of Forestry inventoried statewide the existing young forest plantations under the Biomass Energy Tree Farm Program. More than 1450 ha (3600 acres) of eucalyptus and 650 ha (1700 acres) of pines were included. Groups of plantations or strata were chosen to represent specific species, ages, and planting locations. A dendrometer was used to ensure precise tree measurements. Formal and more detailed island supplement reports have been published, but the additional growth information provided here may be of value (Buck and others 1979, Imoto and Ching 1979).

Total volume of the main stem to a 0.25-cm (0.1-inch) top was computed from the dendrometer measurements. Strata range from 65 to 270 ha (160 to 660 acres) each and represent more realistic volume estimates than the previously described 0.04-ha (0.1-acre) growth plots (*table 7*). Original spacings designed for sawtimber averaged 3 by 3 m (10 by 10 ft). Approximately 10 percent of tree deaths were due to windthrow and competing vegetation. Basal

Table 5—*Site and volumetric data of saligna eucalyptus* (Eucalyptus saligna) *7 to 19 years old, at three locations*

Location	Spacing	Elevation	Precipitation	Aspect	Age	Trees in plot	Average		Volume		
							Diameter-at-breast-height (d.b.h.)	Height dominant/ codominant	(10-cm top)	(23-cm top)	Mean annual increment
	m		*mm*		*years*		*cm*	*m*	*m^3/ha*		
Waiakea, Hawaii	3.0 by 3.0	550	5080	Northeast	7	44	15.7	18.6	188	25	27
					12	33	22.4	32.9	308	108	26
Lupi, Maui	3.0 by 3.0	250	2540		8	42	17.0	20.1	207	11	29
					13	37	21.3	29.9	288	68	22
					19	34	24.4	38.1	438	200	23
Kaumahina, Maui	2.7 by 3.7	150	3800	Northwest	7	39	18.3	23.5	221	41	36
					12	36	23.1	37.2	393	184	33
					18	30	28.2	47.5	652	219	36

Table 6—*Site and volumetric data for seven Eucalyptus plots over 22 years old*

Tree species	Plot	Location	Site: Spacing	Site: Elevation	Site: Precipitation	Site: Aspect	Species: Trees in plot	Species: Age	Species: Avg. (d.b.h.)	Species: Height dominant/ codominant	Volume: Total (10-cm top)	Volume: Sawtimber (23-cm top)	Volume: Total mean annual increment
			m	*mm*				*years*	*cm*		*m^3/ha*		
Saligna eucalyptus (*Eucalyptus saligna*)	1	Kainehe, Hawaii	2.4 by 3.7	700	3560	North	38	22	25.1	[1]—	—	—	—
							35	27	26.9	54.6	—	—	—
Tallowwood eucalyptus (*Eucalyptus microcorys*)	1	Kainehe, Hawaii	2.4 by 3.7	700	3560	North	33	32	29.7	59.7	1424	1311	44
Saligna eucalyptus (*Eucalyptus saligna*)	2	Hilo, Hawaii Res.	2.7 by 3.0	370	5720		51	33	24.4	45.4	968	740	29
							49	38	26.9	45.4	—	—	—
							44	43	29.5	49.1	1251	1043	28
Saligna eucalyptus (*Eucalyptus saligna*)	3	Lapa Ridge, Kauai	3.0 by 3.0	880	1020		16	31	41.1	36.3	—	—	—
							16	36	43.9	38.7	782	663	22
							16	41	45.4	38.1	998	893	24
Robusta eucalyptus (*Eucalyptus robusta*)	4	Kalopa, Hawaii	2.4 by 3.0	650	2080	North-east	38	27	29.5	45.4	—	—	—
							38	32	30.5	—	—	—	—
							37	37	31.5	51.2	854	779	23
							32	43	36.6	48.8	1140	967	27
Blackbutt eucalyptus (*Eucalyptus pilularis*)	5	Waikoekoe, Hawaii	4.9 by 6.1	520	1960	North	23	27	49.0	—	—	—	—
							20	32	55.9	55.5	—	—	—
							20	37	59.4	55.8	1162	1119	31
							19	45	65.3	57.9	1587	1534	35
Tallowwood eucalyptus (*Eucalyptus microcorys*)	6	Kalopa, Hawaii	3.0 by 3.7	700	2080	North	26	27	35.8	45.7	—	—	—
							26	32	37.3	44.5	—	—	—
							26	39	38.6	49.7	880	650	23
							26	45	40.1	49.7	1101	901	26
Tallowwood eucalyptus (*Eucalyptus microcorys*	7	Kalopa, Hawaii	3.0 by 3.7	700	2080	North-east	27	28	29.2	44.5	—	—	—
							29	33	30.7	45.7	740	627	22
							29	38	31.8	49.7	—	—	—
							28	43	33.5	53.0	941	764	22

[1]No data.

Table 7—*Total volume and bark volume per hectare by species, age, and location, for 1979 Hawaii biomass inventory*

Species and location	Age	Area inventoried	Volume: Total	Volume: Bark	Basal area
	years	*ha*	*m^3/ha*		*m^2/ha*
Eucalyptus saligna					
Lupi, Maui	19	69	333	53	23.4
Kaumahina, Maui	18	96	354	67	24.3
Makawao, Maui	16	104	150	30	14.2
Wailua, Kauai	12	212	229	53	17.7
Waiakea, Hawaii	12	269	113	26	8.5
Waiakea, Hawaii	10	144	87	25	6.4
Eucalyptus robusta					
Waiakea, Hawaii	12	132	96	32	11.5
Waiakea, Hawaii[1]	10	65	143	43	15.2
Pinus taeda					
Kokee, Kauai	18	146	138	33	21.6
Pinus elliotti					
Makakupaia, Molokai	17	142	129	23	15.6
Pinus radiata					
Poli Poli, Maui	13	78	50	9	8.0

[1]Coppice.

area values indicate stocking at time of measurement. Biomass plantings with closer spacing and intensive management would yield higher total volume per acre.

The highest saligna eucalyptus volume yield per hectare was the Kaumahina, Maui, stratum with 350 m^3 per ha (5055 ft^3/acre) at age 18. Its total volume of mean annual increment was 20 m^3 per ha (281 ft^3/acre). The Wailua, Kauai stratum produced 230 m^3 per ha (3277 ft^3/acre) at age 12, with a total volume mean annual increment of 19 m^3 per ha (273 ft^3/acre). The percent bark volume was inversely proportional to age. The 19-year-old Lupi, Maui, stratum averaged 16 percent bark volume and the 10-year-old Waiakea, Hawaii, stratum averaged 29 percent bark volume.

The coppice robusta eucalyptus stratum produced 140 m^3 per ha (2044 ft^3/acre) at age 10. This was significantly higher than the volume yield of the 12-year-old noncoppice robusta stratum that produced 96 m^3 per ha (1377 ft^3/acre).

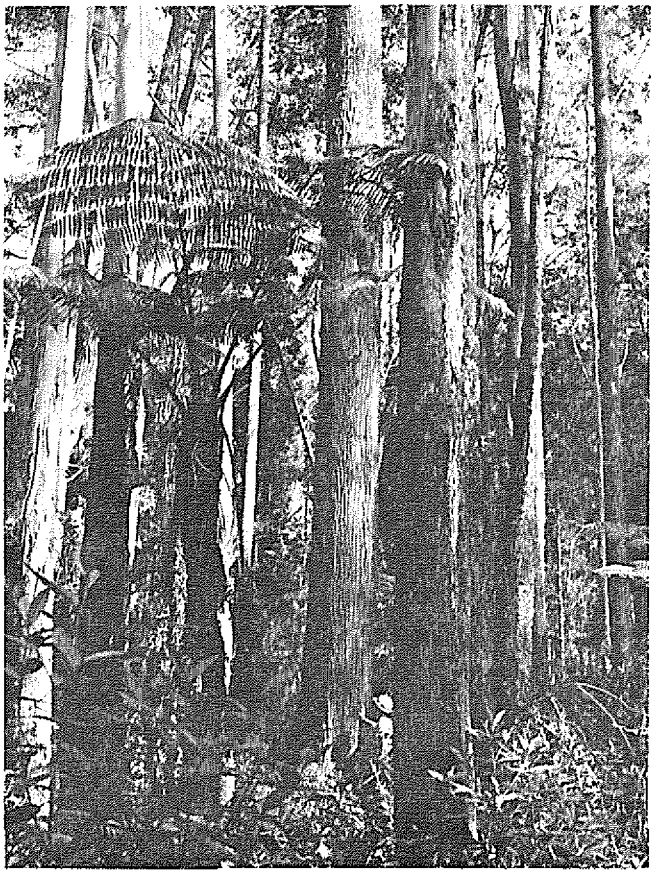

Figure 7—This saligna eucalyptus (*Eucalyptus saligna* Sm.) plot at the Hilo Reservoir, island of Hawaii, contained the largest saligna eucalyptus tree measured. At age 44, it measured 95 cm (37 inches) diameter-at-breast-height (d.b.h.), 46 m (151 ft) to a 23-cm (9-inch) top, and 65 m (215 ft) in total height.

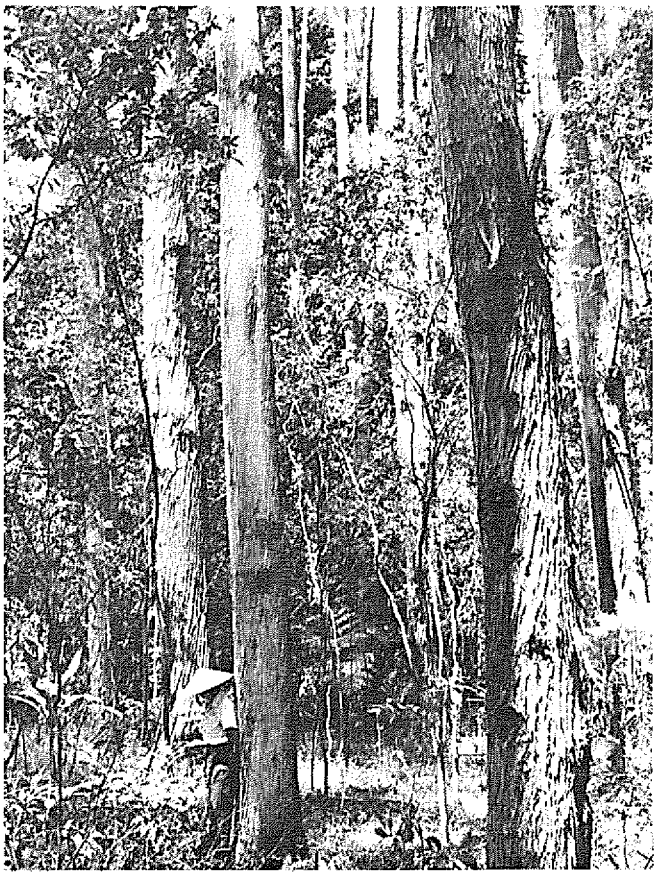

Figure 8—Blackbutt eucalyptus (*Eucalyptus pilularis* Sm.) growing on the Waikoekoe plot, island of Hawaii, had the largest spacings (4.9 by 6.1 m [16 by 20 ft]) and the largest average diameter-at-breast-height (d.b.h.) of 65 cm (26 inches).

MANAGEMENT IMPLICATIONS

Although specific management practices cannot be recommended on the basis of the limited data of this study, some general observations for particular species may be significant.

Australian toon, tropical ash, and silk-oak: In unmanaged stands for high-quality sawlogs, rotation age should not exceed 45 years. Silk-oak can grow acceptably and with good form on dry sites (890 mm [35 inches] per year), but the rotation age should be lengthened. High rainfall or heavy cloud cover associated with high rainfall is not suitable for silk-oak. Australian toon may grow better in mixture with silk-oak than in pure stands.

Norfolk-Island-pine: Spacings of 3 by 3 m (10 by 10 ft) with thinning seem to be desirable for maximum growth.

Trees at age 49 are healthy and growing at a rate that suggests rotation age of more than 50 years is possible.

Redwood: Although difficult to establish in plantations because of slow early growth, redwood attains good growth rates in Hawaii. Redwood trees in Hawaii grow slower in height but more rapidly in diameter than redwood in California.

Loblolly Pine and Slash Pine: Both species have been established successfully in plantations on a variety of sites in Hawaii. On dry marginal sites, slash pine is the more desirable species for volume production. As sites improve, growth differences between the two species lessen. To maximize growth, spacings larger than 3 by 3 m (10 by 10 ft) are not recommended for either species.

Eucalyptus: Rapid growth on a variety of sites has made eucalyptus a desired species for reforestation in Hawaii. The mean annual increment for volume peaks at age 7. Sawtimber growth at spacings of 3 by 3 m (10 by 10 ft) has produced volumes up to 1425 m^3 per ha (20,358 ft^3/acre) at age 32. At 3- by 3-m (10- by 10-ft) spacings, coppice volume growth was significantly higher than noncoppice growth at similar ages.

The data reported show that 10 tree species can grow fast enough to warrant more extensive plantings that could supply timber or wood fiber for a forest products industry in Hawaii. Forest managers in tropical countries throughout the world will be able to use the information to improve decisionmaking in selecting trees and in managing plantations.

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Buck, Michael G.; Imoto, Roger H. **Growth of 11 introduced tree species on selected forest sites in Hawaii.** Res. Paper PSW-169. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1982. 12 p.

Growth and volume data for trees on 25 plots representing 11 introduced species in Hawaii were recorded during a 21-year period. Trees were measured at about 5-year intervals to determine overall growth and stand development. The sites selected were considered better-than-average in terms of elevation, amount of precipitation, and soil quality. Except for redwood, stands were unmanaged. The data reported suggest that 10 tree species can grow fast enough to warrant more extensive plantings for timber or wood fiber production.

Retrieval Terms: Hawaii, *Pinus*, *Eucalyptus*, growth, biomass, hardwoods