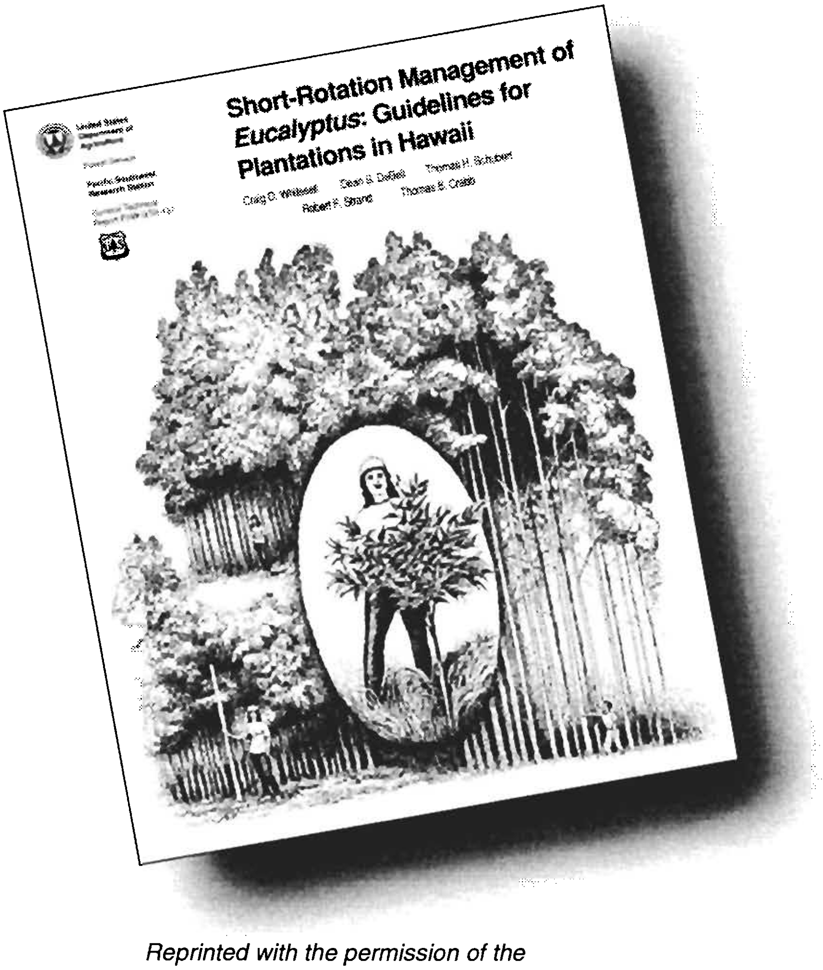
Cooperative Extension Service
C/T/A/H/R
College of Tropical Agriculture & Human Resources
University of Hawaii at Manoa

Resource Management
July 2000
RM-5

Short-Rotation Management of *Eucalyptus*
Guidelines for Plantations in Hawaii

Craig D. Whitesell, Dean S. DeBell, Thomas H. Schubert, Robert F. Strand, Thomas B. Crabb



Reprinted with the permission of the
Pacific Southwest Forest and Range Experiment Station
United States Department of Agriculture, Forest Service
Originally published in November 1992

Published by the College of Tropical Agriculture and Human Resources (CTAHR) and issued in furtherance of Cooperative Extension work, Acts of May 8 and June 30, 1914, in cooperation with the U.S. Department of Agriculture. H. Michael Harrington, Interim Director/Dean, Cooperative Extension Service/CTAHR, University of Hawaii at Manoa, Honolulu, Hawaii 96822. An Equal Opportunity / Affirmative Action Institution providing programs and services to the people of Hawaii without regard to race, sex, age, religion, color, national origin, ancestry, disability, marital status, arrest and court record, sexual orientation, or veteran status. CTAHR publications can be found on the Web site <http://www2.ctahr.hawaii.edu> or ordered by calling 808-956-7046 or sending e-mail to ctahrpub@hawaii.edu.

Whitesell, Craig D.; DeBell, Dean S.; Schubert, Thomas H.; Strand, Robert F.; Crabb, Thomas B. 1992. **Short-rotation management of *Eucalyptus*: guidelines for plantations in Hawaii**. Gen. Tech. Rep. PSW-GTR-137. Albany, CA: Pacific Southwest Research Station, Forest Service, U.S. Department of Agriculture; 30 p.

A 10-year research and development program was conducted by the BioEnergy Development Corporation, USDA Forest Service, and U.S. Department of Energy on the island of Hawaii, where nearly 230,000 acres are suitable for growing biomass in short-rotation *Eucalyptus* plantations. Successful techniques are described for seedling production, plantation establishment (site preparation, weed control, planting), maintenance (weed control, fertilization), biomass yield estimation, and harvest. Basic biological relationships are described to aid decisions on site selection, initial spacing, fertilizer schedules, and rotation length. Environmental issues likely to be faced by growers of *Eucalyptus* plantations are discussed, including soil erosion, nutrient depletion, and monocultures. Continuing programs for tree improvement, monitoring, and silviculture research are recommended. Production costs for biomass yields are estimated for three promising management regimes, representing pure *Eucalyptus* plantings at dense and wide spacings and a mixed species plantation where *Albizia* is used as a nurse crop to provide nitrogen needed for optimum *Eucalyptus* growth. This information will help prospective investors decide whether to invest in *Eucalyptus* plantations, and will help growers develop or choose among alternative management regimes.

Retrieval Terms: *Albizia* admixtures, *Eucalyptus* biomass, *Eucalyptus grandis* plantations, *Eucalyptus saligna* plantations, Hawaii, short rotation silviculture

The Authors

Craig D. Whitesell is the project leader of the Pacific Southwest Research Station's American Pacific Islands Forestry Research Unit, and is stationed in Honolulu, Hawaii (Institute of Pacific Islands Forestry, 1151 Punchbowl St., Room 323, Honolulu, HI 96813). **Dean S. DeBell** is team leader for the Pacific Northwest Research Station's research on the biology and silviculture of forests of the Douglas-fir region, with headquarters in Olympia, Washington. **Thomas H. Schubert** is a research silviculturist with the BioEnergy Development Corporation, Hilo, Hawaii. **Robert F. Strand** was formerly a soil scientist with the Pacific Southwest Research Station in Hilo, Hawaii. **Thomas B. Crabb** is vice president and manager of the BioEnergy Development Corporation, a subsidiary of C. Brewer Company, Hilo, Hawaii.

Pen, and pencil Illustrations by Daniel H. Dizon, Pacific Southwest Research Station, Albany, California.

Cover: Height of *Eucalyptus saligna* 6, 18, 36, and 54 months after outplanting. Along Hawaii's Hamakua Coast, height growth averages about 1 foot per month.

Acknowledgments

Many organizations and individuals have contributed significantly to this paper and the 10-year research program on which it is based. The research program was funded primarily by the Short-Rotation Woody Crops Program (now called the Biofuels Feedstock Development Program) of the U.S. Department of Energy. The work was performed under Subcontract No. 19X-09061C with Oak Ridge National Laboratory under Martin Marietta Energy Systems, Inc., Contract DE-AC05-840R21400 with the U.S. Department of Energy and under Interagency Agreement No. DE-AI05-860R21661. Funds have also been provided by the Governor's Agricultural Coordinating Committee; the Department of Business and Economic Development—Energy Division of the State of Hawaii; the University of Hawaii's Hawaii Natural Energy Institute; and the Hawaiian Sugar Planters Association. J. Warren Ranney, Lynn L. Wright, Judy Trimble, and Janet Cushman provided constructive guidance throughout the period of their agencies' involvement. Susan Miyasaka, University of Hawaii at Hilo, was formerly research agronomist for BioEnergy Development Corporation (BDC) and responsible for installation of many of the field trials. Thomas Cole, Pacific Southwest Research Station (PSW), USDA Forest Service, at Honolulu, performed many of the data analyses. Members of the technical staffs of the BDC and PSW provided much assistance in establishment, maintenance, and measurement of the field trials. Faculty of the University of Hawaii at Manoa participated in several studies: Russell Yost assisted in several studies related to nutrition, and Samir El-Swaify and his students conducted the research on soil erosion. Several members of the North Central Forest Experiment Station's Harvesting Research Work Unit, Houghton, Michigan, provided guidance on harvesting aspects of the program. An earlier draft of the manuscript was reviewed by Russell Yost and Vic Phillips, University of Hawaii at Manoa; Robert Curtis, Pacific Northwest Research Station, USDA Forest Service, Olympia, Washington; and Roger Skolmen (retired), Pacific Southwest Research Station, USDA Forest Service, Honolulu. We thank them all.

Short-Rotation Management of *Eucalyptus:* Guidelines for Plantations in Hawaii

Craig D. Whitesell Dean S. DeBell Thomas H. Schubert
Robert F. Strand Thomas B. Crabb

Contents

In Brief . . .

Whitesell, Craig D.; DeBell, Dean S.; Schubert, Thomas H.; Strand, Robert F.; Crabb, Thomas B. 1992. **Short-rotation management of *Eucalyptus*: guidelines for plantations in Hawaii.** Gen. Tech. Rep. PSW-GTR-137. Albany, CA: Pacific Southwest Research Station, Forest Service, U.S. Department of Agriculture; 30 p.

Retrieval Terms: Albizia admixtures, *Eucalyptus* biomass, *Eucalyptus grandis* plantations, *Eucalyptus saligna* plantations, Hawaii, short rotation silviculture

In 1978 , the USDA Forest Service's Pacific Southwest Research Station and the C. Brewer Co. Ltd. started a joint study of establishing and managing short-rotation (5 to 8 years) *Eucalyptus* plantations in Hawaii. Funded largely by the U.S. Department of Energy's Short Rotation Woody Crops Program, the study has sought to determine whether woody biomass is a suitable source of bioenergy. Test plots were located along the wet Hamakua Coast and in the drier Ka'u District on the island of Hawaii. Since the start of the study, results at periodic intervals have been reported. The guidelines offered here are based on results since the first plantings, spacing trials, fertilization tests, species comparisons, and provenance or progeny evaluations.

• *Species*: The most promising species to date are *Eucalyptus grandis* and *E. saligna*. Specific provenances (place of seed origin in Australia) have been identified for these two species from which seed should be obtained for future planting.

• *Seedlings*: Seedlings were raised in plastic dibble tubes, grown in a shadehouse for about a month and then moved into full sunlight for an additional 2 to 3 months.

• *Planting Sites*: Suitable sites include ranch lands, abandoned lands, and sugarcane fields, from sea level to about 3000 feet, totaling nearly 230,000 acres. Rainfall there ranges from 40 to 250 inches annually, usually well distributed or with an occasional dry season of no more than 3 months. Planting sites are cleared of brush, abandoned cane, and other vegetation by a combination of crawler tractor and harrow or crushing roller, and herbicides. Shallow and poorly drained soils should be avoided.

• *Tree Spacing*: Initial spacing should allow at least 72 ft^2 of growing space per tree, to reach a minimum mean stand d.b.h. (diameter breast height, 4.5 ft above the ground) of 6 inches at 5 years of age. This spacing is equivalent to a spacing of 8.5 ft between and within rows. A similar spacing of 7 ft by 10 ft would provide room for mowing machines and other equipment. Wider spacings, providing more initial growing space per tree, could also be used if larger tree sizes, longer rotation ages, or higher yields per acre at harvest are desired.

• *Planting*: Planting and initial fertilization have been done manually but could be mechanized. Post-planting weed control is needed twice during the first 6 months and must be done carefully with manual backpack sprayers because young *Eucalyptus* seedlings are highly susceptible to herbicide damage. Mechanized mowing is an option where appropriate spacings are used.

• *Fertilization*: A complete nitrogen, phosphorus, and potassium (N-P-K) fertilizer is applied at planting and again about 6 months later. Subsequently, only N is needed on most sites. The total amount required depends on the N status of the topsoil and may range from 200 to 600 lb/acre in four to eight applications (depending on site quality and rotation length). Experiments with mixed plantations of *Eucalyptus* and *Albizia falcataria*, a nitrogen-fixing tree, showed that the need for N fertilizer after the first year can be eliminated along the Hamakua Coast by establishing appropriate admixtures of these two species. Further research on fertilizer types, rates, and timing and method of application is needed.

• *Harvesting*: In limited harvesting trials, felling, chipping, and hauling represented more than 50 percent of the total delivered cost of wood chips from short-rotation plantations. Logistics as well as tree size are major determinants of the cost and productivity of harvesting operations. A balanced system in which all machines work close to capacity is needed.

• *Regeneration*: Short-rotation plantations after harvest can be regenerated with seedlings or rooted cuttings for several generations as improved, higher-yielding stock is developed. A tree improvement effort should be started by using selected superior trees from the existing plantations, and by acquiring the best *E. grandis* and *E. saligna* provenances from Australia, and possibly material of *E. urophylla* for eventual hybridization with *E. grandis*.

• *Production Costs*: Biomass yields and production costs are presented, based on three potential management regimes: (a) a 5-year rotation with 620 trees/acre producing an average 6 in. d.b.h. tree, (b) a 6-year rotation with 360 trees/acre producing an average 8 in. d.b.h. tree, and (c) a mixed *Eucalyptus/Albizia* plantation with 218 *Eucalyptus* and 311 *Albizia* trees/acre producing an average 9 in. d.b.h. *Eucalyptus* tree on an 8-year rotation without supplementary N fertilization. Costs of chipped *Eucalyptus* biomass at the mill are estimated to be $54/dry ton for 45 ton/acre for the 5-year rotation, $45/dry ton for 50 ton/acre for the 6-year rotation, and $35/dry ton for 80 ton/acre of *Eucalyptus* only for the 8-year rotation.

A continuing program of monitoring and research is recommended to detect and respond to any problems in the plantations and to refine and improve fertilization and other management practices.

Introduction

The need for wood supplies in excess of amounts available from native forests has led to interest in establishing *Eucalyptus* plantations in many parts of the world, particularly in the tropics and subtropics. Many *Eucalyptus* species are noted for rapid growth, adaptability to a wide range of climates, relative freedom from pest damage, and suitability for a variety of purposes such as structural wood products, fiber, and fuel. Extensive plantations have been established in South Africa, Brazil, Chile, India, Spain, Portugal, and many other countries (FAO 1979, Florence 1986). Industrial plantations of *Eucalyptus* have also been established in Florida (Geary and others 1983), but on a much more modest scale.

The first *Eucalyptus* plantations in Hawaii were established more than a century ago (LeBarron 1962). Those early plantings usually consisted of *E. robusta* and *E. globulus*. Between 1932 and 1960, a total of 437,000 *E. saligna* seedlings were planted on the forest reserves (Skolmen 1963). These and more recent plantings of *E. saligna* have shown impressive yields (Pickford and LeBarron 1960, Walters 1980).

During the energy crises of the early 1970's, Szego and Kemp (1973) suggested the concept of short-rotation, intensively cultured tree farms for fuel production. This concept had considerable appeal in Hawaii because the State depends on imported oil to meet 90 percent of its energy needs, and there was a long history of generating electrical power from bagasse (residue from sugarcane). Moreover, thousands of acres of underutilized agricultural land as well as commercial forest land seemed to be available for the culture of *Eucalyptus*.

In 1978, BioEnergy Development Corporation, a wholly-owned subsidiary of C. Brewer and Company Ltd., and the USDA Forest Service launched a joint research and development project to produce woody biomass for energy. The project was funded by the U.S. Department of Energy's Short-Rotation Woody Crops Program for 10 years, and resulted in the establishment of more than 700 acres of plantations containing both short-term and long-term studies *(fig. 1)*. Information has been developed on many significant matters related to site selection, plantation establishment, stand culture, harvest, and other management considerations. Much of the data has been published in a variety of research papers.

This paper summarizes and integrates data and observations from formal investigations, development efforts, and management experiences into guidelines for short-rotation culture of *Eucalyptus*. These guidelines are based primarily on work conducted on the island of Hawaii that was focused on maximizing production of biomass for energy, but the information should be useful—at least in principle—for establishing and managing short-rotation *Eucalyptus* plantations in other regions and for other end products.

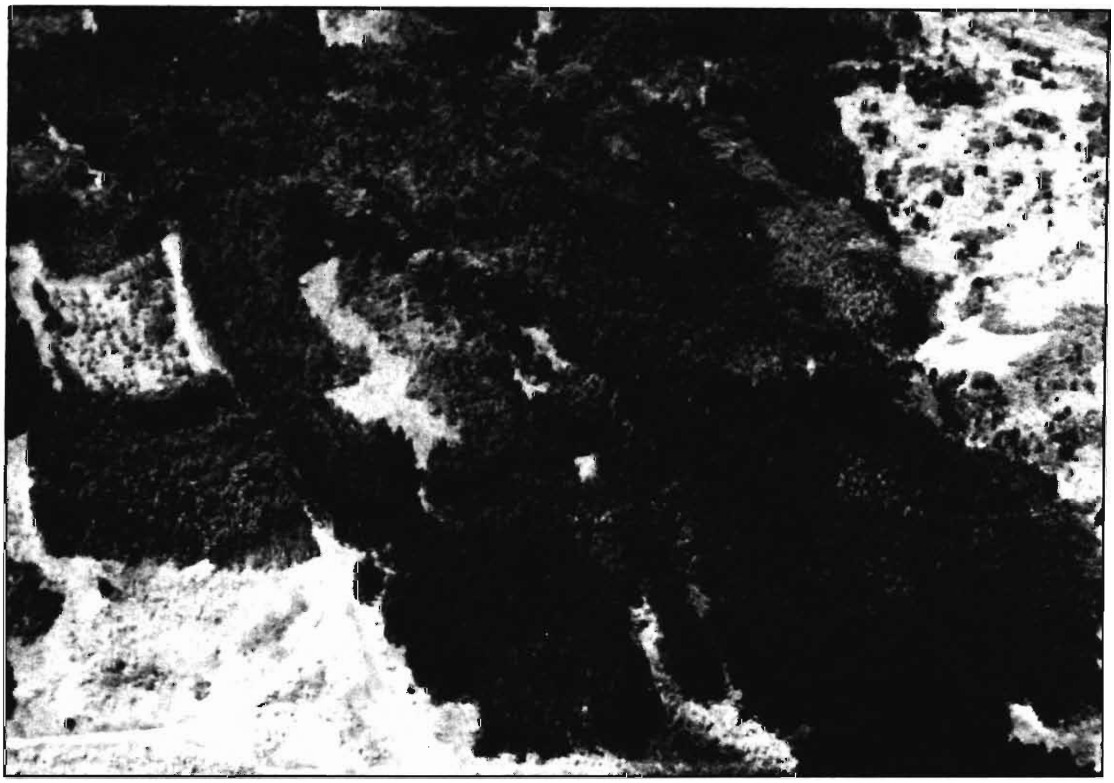


Figure 1—Aerial view of BioEnergy's *Eucalyptus* plantations at Kamae on the Hamakua Coast.

Background

Availability of Suitable Lands

The State of Hawaii, with its year-round subtropical climate, provides an ideal environment for forest development. Growth rates for plantations of *Eucalyptus saligna* (Pickford and LeBarron 1960) and *Pinus taeda* (DeBell and others 1989b) in Hawaii are among the highest reported for these species anywhere in the world. Of the various islands in the Hawaiian chain, the island of Hawaii (the Big Island) offers the greatest potential for production of short-rotation woody biomass. It has the largest land area suitable for biomass plantations and has primarily an agricultural economy.

Commercial forest land on the island of Hawaii totals more than 600,000 acres (Metcalf and others 1978), but much of this land is unsuited to short-rotation intensive culture. The inventory of prime forest lands prepared by the Hawaii State Department of Lands and Natural Resources (1981) provides a good indication of locations and areas of suitable land. This survey identified land having the soil and site characteristics capable of providing good forest yields, regardless of current vegetative cover or use (excluding urban land use). The categories labeled Prime 1 and Prime 2 in the report (*fig. 2*) represent the areas most suitable for intensive culture of *Eucalyptus* and other fast-growing tree species. More than 600,000 acres are included in these two categories, of which about 230,000 acres are now in brush, range, pasture, and sugarcane, or lie fallow (*fig. 3*). These 230,000 acres offer the best opportunity for short-rotation management. Nearly all of the remaining 370,000 acres of prime lands are now in forest, portions of which may be suitable for such management.

Regardless of growth capability of the land, there may be other significant factors that affect availability or suitability. Other agricultural enterprises may offer more profitable uses. Restrictions due to topography or soil conditions may preclude the use of machinery normally associated with production of woody biomass. Sociopolitical considerations, such as public desire to maintain or preserve significant portions of native forests, may prevent the conversion to short-rotation plantations. On the other hand, some lands may provide substantial economic advantages for woody biomass production because of their proximity to mill or conversion sites and because of existing road networks. In addition, many agricultural field records provide detailed information regarding soil quality, weather conditions, and comparative sugarcane yields that may be useful to managers of short-rotation woody crops.

Environmental Setting for Short-Rotation Research Project

Local records on the island of Hawaii showed that *Eucalyptus saligna* grew well in plantations at elevations ranging from 1,750 to 6,600 ft with precipitation levels of 45 to 250 inches (Pickford and LeBarron 1960); planting recommendations by Carlson and Bryan (1959) extended this range to sea level.

Our field trials were established at sites located along the Hamakua Coast and in the Ka'u District at elevations from 1,000 to 2,000 ft (*fig. 4*). The Hamakua sites are very wet, receiving 200 to 245 inches of rain annually. Soils are highly weathered silty clay loams developed on volcanic ash (Hydrandepts). Hydrandepts are known for high phosphorus retention and for low availability of nutrient cations (Yost and Fox 1981). The Ka'u sites receive much less rainfall (40-90 in/yr). They have rocky, organic soils (Tropofolists) that have low nutrient-retention capacity (Sato and others 1973). Soil test results for sites at Ka'u and Hamakua are presented in *table 1*.

Total soil nitrogen (N) concentrations vary substantially within both areas, and these differences may be associated with past land use. Sites which have been under forest or grass generally have higher soil nitrogen concentrations. Prime caneland and more recently abandoned caneland generally have lower concentrations of soil nitrogen. The length of time the area was managed for sugarcane also influences soil properties, because the amounts of nitrogen and organic matter generally diminish with successive crops.

The guidelines proposed in this report were developed from data collected at the above-mentioned sites. Some recommendations, such as seedling production and initial spacing, have general applicability to other areas. Other recommendations, including species or provenance selection and fertilizer treatments, are much more site specific and must be validated when applied to other localities.

Plantation Establishment

Species and Provenance Selection

Previous work in Hawaii guided our species selections for short-rotation intensive culture of biomass plantations. Initial emphasis was placed on fast growing *Eucalyptus saligna*, and then on the closely related *E. grandis*. Desirable criteria for selection of these and other eucalypts include:

•Fast growth and good stem form, providing high biomass production over a range of site conditions.

•The ability to be asexually reproduced using vegetative propagation methods.

•The ability to coppice readily.

•Resistance to serious disease or insect attacks.

•Have other uses besides biomass, for example pulp, lumber, or chemicals.

The quickest and most efficient gains in a tree improvement program are obtained by identifying the best species and the best adapted provenances within a species (Zobel and Talbert 1984). Use of the best provenances (place of seed origin) can make a difference between profit and loss in a forestry enterprise. The relative performance of species or provenances of a given spe-

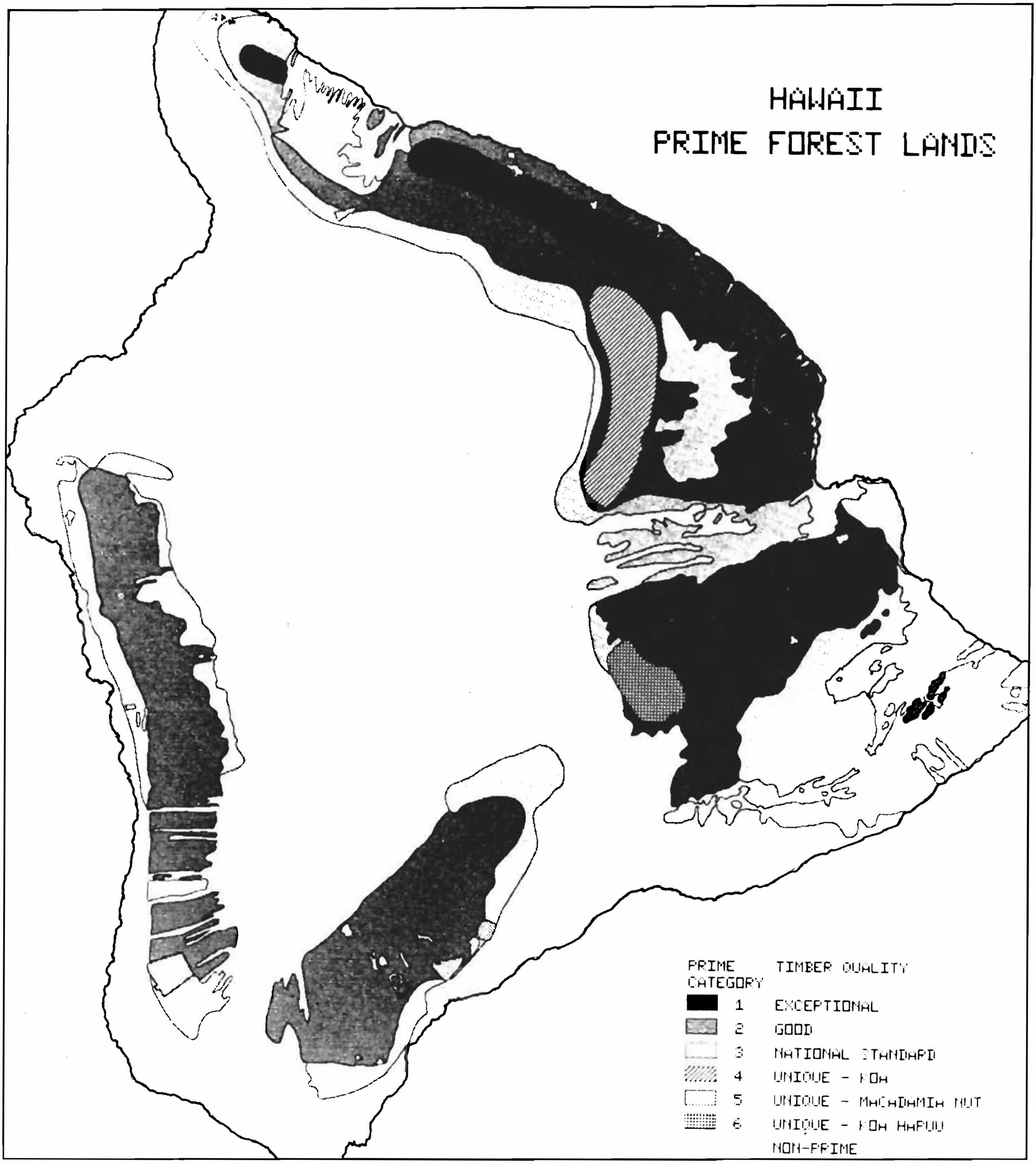


Figure 2—Island of Hawaii prime and unique forest land boundaries (Reprinted with permission of the Division of Forestry and Wildlife, Department of Land and Natural Resources, State of Hawaii)

Figure 3—Typical caneland that could be converted to *Eucalyptus* plantations.

cies is evaluated in field trials, at relatively low cost, considering the potential gains in yields that may be obtained.

Ten species trials were established between 1979 and 1984 (Schubert and Whitesell 1985). The number of species appraised in each trial ranged from three to 15. In these trials a total of 30 species, including 15 eucalypts, were screened to determine their potential *(table 2)*. *Eucalyptus saligna, E. grandis, E. urophylla*, and *E. robusta* consistently outperformed the other species in height, diameter, and survival. Major exceptions to this generality were *Acacia mangium* and *Albizia falcataria*; the former outgrew the aforementioned eucalypts at one location, whereas *Albizia* ranked second or third to the eucalypts at three locations.

The performance of *E. saligna*, planted in 10 species trials, was equal to or better than any other species on eight of 10 sites. However, *E. grandis* outgrew *E. saligna* in two of four species trials and also proved superior in four provenance trials.

Eucalyptus urophylla grew well along the Hamakua Coast and at Ka'u. Of the six sites planted to *E. urophylla*, trees performed satisfactorily on five of them *(table 2)*. This tropical eucalypt is native to Timor and several other Indonesian islands.

Eucalyptus robusta growth was satisfactory in five of six species trials. However, it has not performed as well as *E. grandis* and *E. saligna* in our trials and is not a recommended species for biomass production in Hawaii.

Twelve nitrogen-fixing species were tested. On Hamakua sites on well-drained soils, *Albizia falcataria* performed quite well and increased site fertility through the recycling of its nitrogen-rich foliage. However, on dry sites at Ka'u, its performance was unsatisfactory. *Acacia mangium* performed well on only two of seven sites. The dense foliage of this species contributes to breakage or blowdown in high winds. None of the other nitrogen-fixing species we tested *(table 2)* performed satisfactorily (Whitesell and others 1992a).

Eucalyptus camaldulensis, which is planted world-wide, performed very poorly in a trial of eight Australian provenances planted at Kamae on the Hamakua Coast (Whitesell and others 1992b). These provenances were collected from widely varying sites ranging from Lat. 17°S to 35°S. The best source, from the Emu River area in Queensland, yielded only 1.8 tons/acre/yr at age four. Apparently, this species is not suitable for biomass production on high rainfall areas on Hawaii Island.

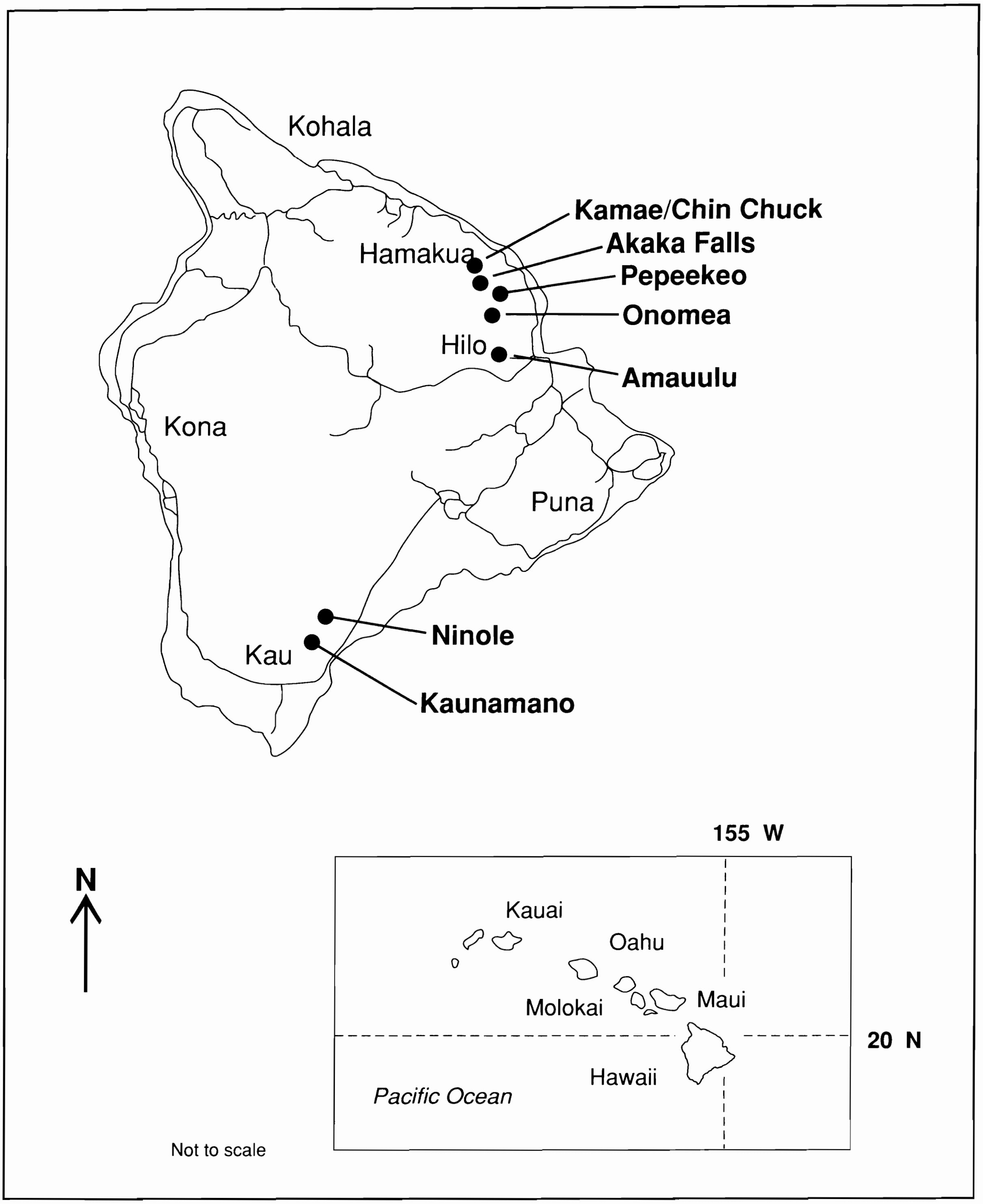


Figure 4—BioEnergy Development Corporation's *Eucalyptus* planting sites on the Island of Hawaii.

Table 1—*Soil nutrient and pH analyses for BioEnergy's planting sites, Island of Hawaii*

Site	Depth	Total N[1]	P	K	Ca	Mg	pH
	in.	*pct*	------------------	*ppm*	------------		
			Hamakua Coast				
Kamae	0-6	0.68	18	52	64	37	5.0
	18-24	0.47	10	43	40	13	5.1
Chin Chuck	0-6	0.60	14	50	459	70	5.8
	18-24	0.47	10	43	181	33	5.7
Akaka Falls	0-6	0.37	7	39	197	39	5.7
	18-24	0.40	7	50	810	83	6.0
Pepeekeo	0-6	0.57	24	88	166	40	4.9
	18-24	0.42	12	38	96	27	5.1
Onomea	0-6	0.54	8	27	93	47	5.3
	18-24	0.48	6	22	54	36	5.3
Amauulu	0-6	0.67	6	48	103	112	4.8
	18-24	0.38	5	30	35	26	5.0
			Ka'u District				
Ninole	0-6	0.41	201	110	510	156	5.6
(Kiloa soil)	18-24	0.36	140	91	696	156	5.7
Ninole	0-6	0.65	104	112	792	201	5.7
(Alapai soil)	18-24	0.34	77	57	894	208	5.9
Kaunamano	0-6	1.07	27	142	1,366	800	5.4
(Alapai soil)	18-24	0.86	6	104	1,669	804	5.5

[1]N - nitrogen, P - phosphorus, K - potassium, Ca - calcium, Mg - magnesium.

Four provenance trials of the *Eucalyptus grandis/saligna* complex were designed and installed by James D. King in 1979 and 1981 (Skolmen 1986). These trials were located along the Hamakua Coast and at Ka'u. Twenty-two seed sources were appraised: 11 *E. grandis* and 10 *E. saligna* from Australia, and one local *E. saligna* provenance. At all four sites *E. grandis* provenances generally outperformed the *E. saligna* provenances. In diameter growth, for example, seven to nine of the top ten provenances were *E. grandis*. Future plantings of *E. grandis* and *E. saligna* should utilize seeds collected from selected provenances in Queensland and New South Wales, Australia, until better provenances are identified *(table 3)*.

A trial of four provenances of *E. urophylla* was established at Kamae in 1982. There were no significant differences in height and diameter growth, survival, or yield at age four years. However, the fastest growing seed source from Mt. Lewotobi, Flores Island, Indonesia, CSIRO Seedlot No. 12896 (CSIRO = Commonwealth Scientific and Industrial Research Organization, Canberra, Australia) produced 8.6 dry tons/acre/yr, 21 percent greater yield than the other sources (Whitesell and others 1992b).

Ten hybrid *Eucalyptus* clones developed in Brazil by the Aracruz Florestal Company were outplanted at Pepeekeo in 1985. These vegetatively propagated trees were selected in Brazil for fast growth, high yields, good coppicing ability, and resistance to diseases. One of the most important characteristics of these clones is their uniform growth, compared to eucalypts raised from seed. The best of these clones grew as well as the best *E. saligna* and *E. grandis* in our species trials at Pepeekeo

Table 2—*Species showing satisfactory and unsatisfactory growth in seven species trials on the Hamakua Coast and two in the Ka'u District, Island of Hawaii*

Satisfactory Growth[1]

Hamakua Coast

Kamae (trial 1)
Acacia mangium[2]
Eucalyptus urophylla
E. grandis

Kamae (trial 2)
E. saligna
Albizia falcataria[2]
E. robusta

Kamae (trial 3)
E. saligna
E. robusta
A. falcataria[2]

Kamae (trial 5)
E. saligna
E. urophylla

Amauulu
E. saligna
E. robusta

Pepeekeo
E. grandis
E. urophylla
E. saligna

Onomea
E. saligna
E. urophylla
A. falcataria[2]
E. robusta
E. grandis

Ka'u District

Ninole (Alapai)
E. saligna
A. mangium[2]

Ninole (Kiloa)
E. saligna

Kaunamano
E. saligna
E. grandis
E. urophylla
E. robusta

Unsatisfactory Growth

Hamakua Coast

E. alba	*Acacia koa*[2]
E. botryoides	*A. melanoxylon*[2]
E. camaldulensis	*Casuarina equisetifolia*[2]
E. citriodora	*Copaifera langsdorfii*
E. dunnii	*Gmelina arborea*
E. globulus	*Leucaena leucocephala*[2]
E. maidenii	*Lippia toressi*
E. microcorys	*Mimosa scabrella*[2]
E. nitens	*Pinus elliottii*
E. tereticornis	*Sesbania grandiflora*[2]
E. viminalis	*S. sesban*[2]

Ka'u District

E. camaldulensis	*Acacia auriculiformis*[2]
E. citriodora	*A. confusa*[2]
E. globulus	*Mimosa scabrella*[2]
E. nitens	
E. tereticornis	
E. viminalis	

[1]Satisfactory: mean annual growth increment equals or exceeds 3.3 ft height and 0.6 in. diameter; survival equals or exceeds 75 pct.
[2]Nitrogen-fixing species.

Table 3—*Best seed sources of* **Eucalyptus grandis** *and* **E. saligna** *in provenance trials on the Island of Hawaii (Skolmen 1986)*

Species and CSIRO[1] seedlot no.	Seed source location	Latitude	Elevation
			ft
E. grandis			
12423	Tinaroo Falls Dam, Qld.[2]	17°11'S	2,624
12409	Ravenshoe, Qld.	17°42'S	3,083
10774	E. of Gympie, Qld.	26°14'S	1,312
7823	Coffs Harbor, NSW[3]	30°10'S	59
7810	Bulahdelah, NSW	32°20'S	394
E. saligna			
11025	W. of Rockhampton, Qld.	23°49'S	2,821
12064	S. of Calliope, Qld.	24°23'S	2,624
12145	Connondale, Qld.	26°44'S	1,968
11756	Clifford, Qld.	28°30'S	787

[1]Commonwealth Scientific and Industrial Research Organization, Australia
[2]QLD = Queensland, Australia
[3]NSW = New South Wales, Australia

(68 ft in height and 5.0 in. in diameter after 6 years vs. 52 ft and 5.3 in). If these clones continue to perform well, they could form a component of genetically improved material in future trials.

Site Selection and Relative Productivity

Productivity of *Eucalyptus* plantations along the Hamakua Coast is positively correlated with total soil N (nitrogen) and soil depth; it is negatively related to soil erosion and poor drainage (Strand and Cole 1992). Soil profile examinations and productivity determinations from 60 locations in *Eucalyptus* plantations showed that poorly to somewhat poorly drained soils produced low biomass yields, as did sites with shallow soils (<24 in. deep). Soils that had experienced substantial erosion also generally had low productivity.

Low productivity related to low total soil N can be remedied with frequent applications of nitrogen fertilizer (Strand and others 1992). Low productivity associated with shallow or poorly drained soils or both, however, is unlikely to be substantially increased by fertilization. Trees should not be planted on these sites, unless the area is small or too intermingled with adjacent soil types for practical exclusion.

Although no research on soil and site productivity was conducted at Ka'u, we expect that limitations on plantation growth would arise primarily from shallow soils and insufficient or poorly distributed rainfall. Annual rainfall at Ka'u varies from 40 to 90 inches, and 4 or more dry months are common. A survey of world literature on *E. saligna* and *E. grandis* plantations suggested that minimum rainfall is 30 to 40 inches and that the dry season should be no more than 3 to 4 months (FAO 1979). The lower rainfall limit for *E. saligna* stands sampled on the island of Hawaii by Pickford and LeBarron (1960) was 45 inches per year.

Wind damage may be an important consideration in certain locations. Plantations at Ninole valley in Ka'u were destroyed by windstorms in February 1982 and January 1985; however, stands at Kaunamano, a few miles south of Ninole, suffered little damage in either storm. The damage at Ninole appears to be associated with wind velocity caused by the funneling action of closely adjacent hills. Areas that may be subject to such wind funneling should not be planted. Some blowdown and broken tops also occurred at several Hamakua sites in February 1986, destroying one trial and slightly damaging another in two widely separated locations. Wind does not appear to be a serious concern for short-rotation plantations along the Hamakua Coast as it is in the Ka'u District. However, strong winds have caused losses in mature *Eucalyptus* stands along this coast.

Planting Stock Production

Our planting stock production is based on a containerized nursery system using plastic dibble tubes and racks. Most *Eucalyptus* plantation programs utilize container-raised stock (FAO 1979), and the dibble-tube system has been shown to be more reliable and less costly than bare-root stock for *Eucalyptus* and other species in Hawaii (Walters 1981). BioEnergy Development Corporation's system, described below, was labor intensive because the size of the operation did not justify investment in an automated system. About 450,000 seedlings per year were produced in three 4-month cycles of 150,000 each. This time period could conceivably be shortened to 3 months, producing 600,000 seedlings per year. Automated dibble-tube systems for larger scale reforestation programs in Hawaii have been described by Skolmen and others (1982) and by Walters (1983).

BioEnergy's system was developed from previous experience with *Eucalyptus* in Hawaii, and by our nursery practice experiments carried out between 1979 and 1983. Our system used plastic dibble tubes called "Ray Leach Cone-tainer Pine Cells"[1] which have a volume of 4 $in.^3$ The tubes have interior ribs to prevent root spiraling and a hole in the bottom for drainage and air pruning of the roots. The tubes are placed in racks that hold 200 dibble tubes.

The potting medium used is a 2:1 mix of vermiculite and peat moss. Two bales of vermiculite (3.2 ft^3/bale) are thoroughly mixed with one bale of peat moss (4 ft^3/bale). Osmocote[1] (14-14-14), dolomite, and Micromax[1] (micronutrients) are added at 37, 25, and 7-oz. respectively, per batch (one batch fills about 5,400 tubes). The mixture is moistened so that it will stick together in the tubes. Racks of tubes are filled manually, then jarred on a table to settle the mixture in the tubes. A plexiglas plate with protrusions for each tube is pressed on top of each rack of filled tubes to make an indentation for the seeds. Seeding is done manually with a mixture of seeds and chaff, the amount depending on germination tests of each seed lot. The seeds are then covered lightly with a layer of fine gravel.

[1]Trade names or commercial brands are mentioned solely for information. No endorsement by the U.S. Department of Agriculture is implied.

Every other row of tubes is removed and placed in another rack to give a density of 100 tubes per rack. The racks are then moved to benches in a roofed shadehouse *(fig. 5)* and watered by an overhead automated sprinkler system several times a day, depending on weather conditions. Germination occurs within 5 to 7 days. Thinning to one plant per tube is done manually when the seedlings have two pairs of true leaves, about 3 to 4 weeks after sowing. The extra seedlings are then used to fill tubes lacking seedlings.

The seedlings are moved from the shadehouse to outside areas to harden off, under full sunlight *(fig. 6)*, when they are 3 to 4 in. tall, usually 4 to 6 weeks after sowing. Irrigation is provided as needed by an automated sprinkler system. The annual rainfall at BioEnergy's nursery is about 200 in.; therefore, it is not possible to harden (acclimatize) the seedlings by withholding water. The seedlings do, however, gradually lose their succulence and height growth slows, presumably because they use up the nutrients in the potting medium. They are ready for outplanting 3.5 to 4 months after sowing, when they are 12 to 15 in. tall.

Additional fertilization in the hardening area is not recommended so that the seedlings will harden-off, but small amounts of supplemental Osmocote are sometimes added if the foliage shows symptoms of nutrient deficiency. Top pruning is necessary when seedlings are to be held in the nursery longer than 4 months. Several pairs of leaves must be left on the stem below the cut.

An alternative method of producing planting stock is to use rooted cuttings from selected outstanding trees in existing plantations. This method was developed for *Eucalyptus* in Brazil by the Aracruz Florestal Company (Campinhos and Ikemori 1983). Our present system could be adapted to these techniques, but the cost per plant would be higher, and several years' lead time would be needed to build up clone banks of superior material. A substantial improvement in yield, however, may be obtained via selection and propagation of superior clones (Brandao and others 1984).

There have been few problems with nursery diseases or insects in Hawaii. Damping off is only a problem when the seedlings are watered too frequently. Proper irrigation schedules and close monitoring of weather conditions will control damping off. Occasional attacks of aphids or rose beetles are handled by using an appropriate insecticide. Continuous monitoring of the nursery stock is the key to discovering and dealing with problems before they become serious.

Problems caused by lack of or incompatible mycorrhizal species have not been reported for *Eucalyptus grandis, E. saligna,* and *E. urophylla,* the three species of major interest to us (FAO 1979, Le Tacon and others 1988). No increased growth occurred in the field when we inoculated a portion of our nursery stock with spores from fruiting bodies collected from older established plantations in Hawaii. Presumably suitable mycorrhizae-form-

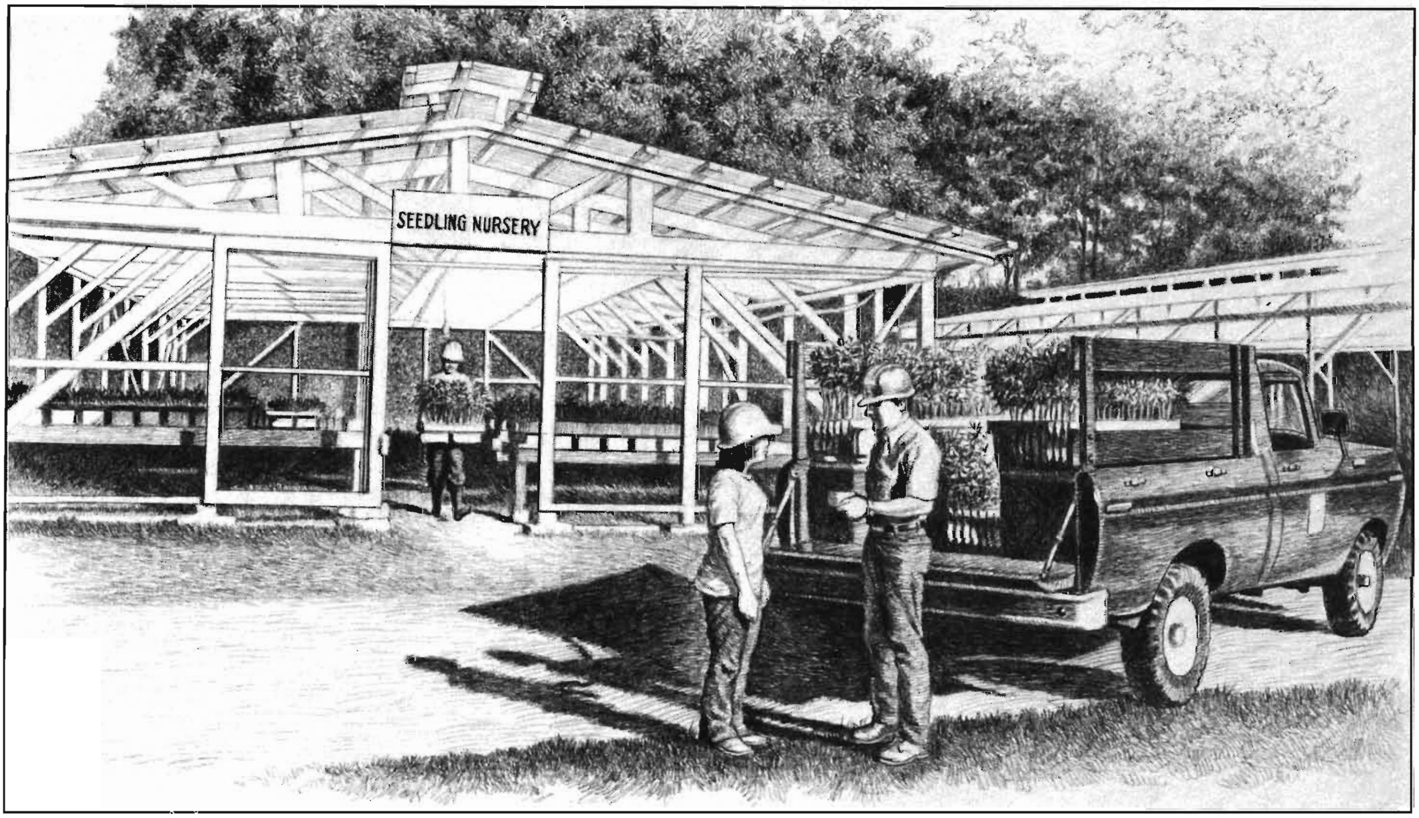


Figure 5—BioEnergy's shadehouses, with racks of seedlings being loaded on truck.

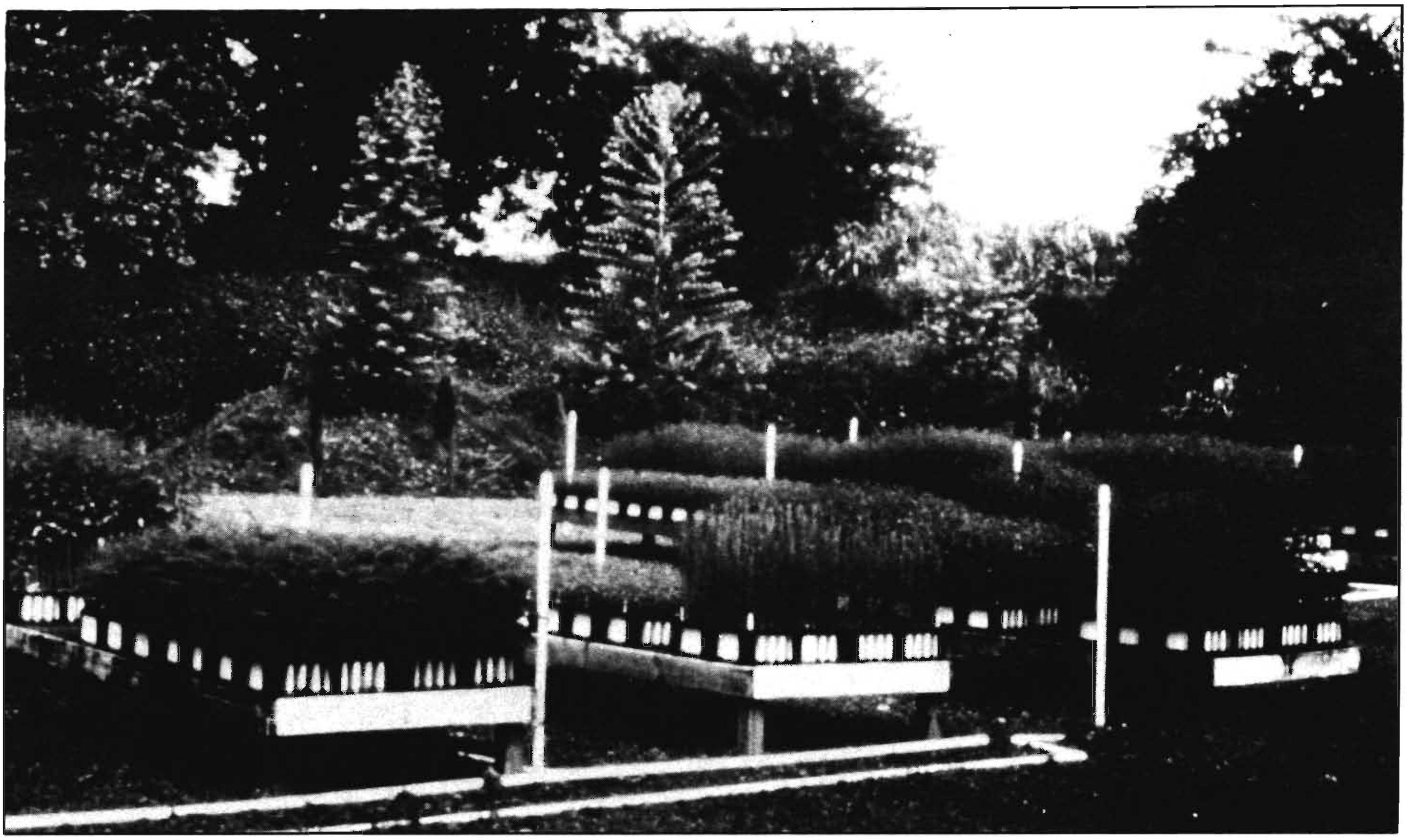


Figure 6—*Eucalyptus* (on right) and *Albizia* (on left) seedlings in hardening area ready for outplanting.

ing fungi are in Hawaiian soils as a result of more than 100 years of *Eucalyptus* culture, or because the native ohia *(Metrosideros polymorpha)* is in the same family as *Eucalyptus* and may harbor compatible mycorrhizal species. Wind-disseminated spores apparently provide adequate inoculation of container seedlings.

Site Preparation

Most of our eucalypt plantations were planted on lands that can be placed into one of three categories: recently harvested caneland, abandoned caneland, or wasteland. On recently harvested caneland the crop had been cleared no longer than 2 to 3 months before tree planting. Abandoned caneland had been out of crop production for periods ranging from 3 months to more than 25 years. Wasteland consisted of areas that had never been in cane production because of steep terrain, poor drainage, or rocky conditions. We also did some clearing and planting in secondary forest on land zoned for agriculture, but the costs for clearing the dense vegetation and building access roads for establishing plantations on such land are very high.

On recently harvested caneland, the volunteer cane and weeds are allowed to regrow for 6 to 8 weeks. When the vegetation is no more than 2 feet tall and 50 percent or more of the soil is still bare, the area is sprayed with a mixture of one gallon of glyphosate[2] and 2.5 lbs a.i. simazine[2] per acre (a.i. = active ingredient). Glyphosate is a contact herbicide, whereas simazine is a pre-emergent herbicide. The herbicide is applied with a tractor-drawn spray rig, and application requires about 0.2 hour per acre.

On abandoned caneland and wasteland, a low ground-pressure D-6 tractor equipped with wide-gauge shoes is used to pull a heavy-duty off-set cutaway harrow *(fig. 7)*. This requires about 0.3 tractor hour/acre. On very rocky soils such as those at Ka'u, a heavy Krajewski roller is used to cut and crush the cane and other vegetation, which requires 2 hours/acre on rocky soils. If the area is covered with particularly heavy vegetation and brush, as when it has been abandoned for many years, a tractor equipped with a bulldozer blade is used. The blade is positioned about one

[2]This paper neither recommends the pesticide uses reported nor implies that the pesticides have been registered by the appropriate governmental agencies. Pesticides should be utilized in accordance with label instructions for their use. Surplus materials and containers should be disposed of properly.

Figure 7—D-6 tractor pulling cutaway harrow to clear abandoned caneland.

foot above the ground to knock down the brush so that the harrow or roller can then crush it. This requires about 3 tractor hours/acre.

After clearing, the vegetation is allowed to regrow for 6 to 8 weeks before spraying. If 50 percent or more bare soil is showing, the same glyphosate/simazine mixture is used for weed control. However, if the soil is mostly covered with a mulch of cut-up and crushed cane and other vegetation, only glyphosate is used, at 0.5 gallon/acre, because simazine is effective only when sprayed on bare soil. About 0.2 tractor hours/acre are required for this treatment.

The *Eucalyptus* seedlings are planted from 3 to 4 weeks after the herbicide spraying. If simazine was used, care should be exercised during the planting operation to not disturb the soil any more than necessary.

Planting Procedures

Racks of seedlings in dibble tubes are transported to the field in enclosed trucks or trailers to avoid exposure to the wind. The racks are hand-carried to the planting site; the tubed seedlings are then transferred to planting bags and the seedling removed from the tube just before it is placed in the ground. Planting is done manually by a 2-person crew, with one worker opening holes with a metal dibble bar *(fig. 8)* and the other following behind to place a seedling in each hole and to stamp the soil around the hole to close and firm the soil around the root mass. About 600 seedlings can be planted per person-day under Hamakua site conditions, but only 300 per person-day in the rocky soils at Ka'u where more time is needed to open the planting hole and to scrape together enough soil to close the hole and to firm the soil around the roots.

The empty dibble tubes are replaced in the racks and returned to the nursery where they are reused after washing and sterilizing with a solution of 1 part chlorine bleach to 9 parts water. The tubes (resistant to the effects of ultraviolet light) are good for about four cycles, and the racks are still usable after five years unless they are broken by careless handling.

After initial fertilization, as discussed in a subsequent section, little further care is needed until the first weeding. The plantations should be monitored for areas needing replanting, but survival is usually at least 95 percent. Supplementary watering may be needed if an extended dry period occurs soon after planting.

Our planting operations have not been mechanized because they have been of a relatively small scale. Manual planting has been efficient and, unlike a planting machine, a planting crew can work under quite adverse weather conditions. Tree-planting machines have been used, however, for planting other areas in Hawaii. Moreover, the local sugar companies are developing machines for planting cane plantlets instead of the traditional stem pieces. Such machines could easily be adapted for tubed tree seedlings if large scale operations make this desirable.

Figure 8—Planting with dibble bar; tops of seedlings are sticking out of planting bag.

Initial Spacing

Spacing of trees in short-rotation plantations affects individual tree growth rates and stand productivity as well as the costs of management practices and utilization. Product quality may also be affected. A positive effect of higher planting densities is an increase in wood production at early ages because of the greater number of trees per acre. The corresponding negative effects are a decrease in individual tree growth rates and therefore tree size, and an increase in planting and harvesting costs. Choice of the optimum spacing therefore usually involves a balance between shortening the time to attain trees of some minimum desired size, maximizing production of biomass or wood, and minimizing the costs of management and utilization.

Although numerous plantations of *Eucalyptus saligna, E. grandis*, and other eucalypt species had been established in Hawaii and elsewhere, information to guide decisions on tree spacing for short-rotation eucalypts was limited. Several trials were established to evaluate tree growth and stand development across a range of planting densities from 16 to 172 ft^2 of growing space per tree. Data from these trials have provided a general understanding of relationships between diameter and density, and effects of initial spacing on patterns of tree growth and stand development.

Tentative relationships between quadratic mean stand diameter and stand density for *E. saligna* and the rationale for their development and use were described in an earlier paper (DeBell and Whitesell 1988). In essence, the upper maximum diameter density line in *fig. 9* represents the maximum number of trees that can be grown to any given mean stand diameter. Severe competition occurs, however, before most stands attain this upper limit, resulting in significant numbers of unusable and dead trees. We have therefore defined an operating "maximum" line, which estimates the number of trees to establish for given target diameters *(fig. 9)*. This line represents 70 percent of the total number of trees that could attain a given mean diameter if the stand was allowed to attain the upper asymptote. Using this operating maximum line, we estimated the number of *E. saligna* trees to plant per acre and the effective square spacing for selected target diameters at harvest *(table 4)*. These recommendations assume that no thinning will be done and that mortality due to causes other than competition is minimal. If such assumptions are not appropriate, planting density should be increased accordingly.

Effects of initial stand density on patterns of tree growth and stand development are equally important in spacing decisions because they determine mean tree size and yield per acre at various harvest ages. Composited data from two spacing trials are displayed in *fig. 10*. Note that mean stand diameters exceeded 6 inches at 4, 5, or 6 years, depending on whether stands were initially planted at densities providing growing space per tree of 94, 72, or 65 ft^2. Although a similar mean diameter was reached under these three stand densities, estimated yields at harvest ranged from 28 to 46 tons/acre.

Self-thinning was in progress at ages 5 and 6 years in the plots planted at densities providing 65 ft^2 of growing space per tree. Mortality averaged 11 percent in these plots; thus, effective growing space per surviving tree was about 72 ft^2, nearly identical to that indicated by the operating maximum line developed from diameter-density relationships (DeBell and Whitesell 1988).

Initial Fertilizer Applications

Beneficial effects of nitrogen (N), phosphorus (P), and potassium (K) fertilization on tree growth during the first year have been demonstrated in field trials at Hamakua Coast locations (Strand and others 1992, Whitesell and others 1987, Yost and others 1987). Thus, *Eucalyptus* plantings on the BioEnergy project usually received two applications of commercial fertilizer during the first year. At planting or soon thereafter, 4 ounces of N-P-K (14-14-14) are buried in a dibble hole adjacent to each seedling (*fig. 11*). A second dose is applied in similar fashion 6 months after planting. The fertilizer is buried rather than broadcast in young plantings on the Hamakua Coast in order to decrease the chance of it being washed away by frequent heavy rains, which often cause severe erosion of the bare silty-clay loam soils. At Ka'u early fertilizer applications are broadcast because the lower rainfall intensity causes less surface loss. Also, the extremely stony soil at Ka'u makes digging holes for the fertilizer difficult.

Weed Control

Post-planting weed control is done with manual backpack sprayers. The most critical time is 2 to 3 months after planting, when regrowth of the cane plants and other weeds is competing strongly with the tree seedlings. Glyphosate at a rate of one gallon/acre, with appropriate surfactant and antifoam agents, is used as a directed spray on the weeds. Special care is required to avoid spraying the tree seedlings, because *Eucalyptus* foliage is extremely susceptible to herbicide damage at this stage. About 6 person-hours per acre are needed.

The importance of keeping the young trees free from competition was demonstrated by an experiment comparing herbicide weed control with hand sickling (which provides immediate but very short-term release). After 18 months the trees weeded with

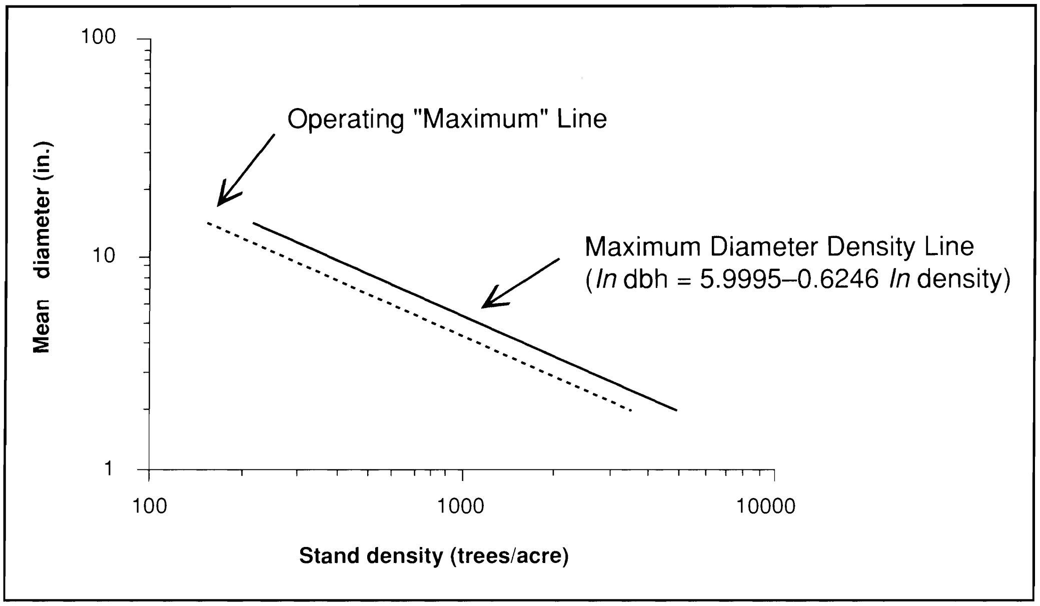


Figure 9—Relationship between stand density and mean stand diameter for *Eucalyptus saligna*, Island of Hawaii (adapted from DeBell and Whitesell 1988).

Table 4—*Recommended planting densities and approximate growing space per tree to achieve mean target stand diameter for* **Eucalyptus saligna**, *Island of Hawaii*

Mean target stand diameter	Trees per acre	Growing space per tree	Approximate spacing
in.	*no.*	ft^2	*ft*
2	3,400	13	3.6 x 3.6
4	1,130	39	6.2 x 6.2
6	590	74	8.6 x 8.6
8	370	117	10.8 x 10.8
10	260	167	12.9 x 12.9
12	200	223	14.9 x 14.9
14	150	287	16.9 x 16.9

herbicides were 70 percent larger in height and diameter than those weeded by hand sickling.

If the first herbicide treatment is done carefully and is applied on schedule (2-3 months), many of the trees will have outgrown the weeds by the end of the first 6 months; the second fertilizer application at this time will maintain their growth rates (see cover illustration). There are always some problem areas, especially where the site preparation spraying was less effective or where vigorous cane regrowth has occurred. A second spot application of herbicide is therefore done 5 to 6 months after planting *(fig. 12)*. Typically only about half of the area will need this spot application. The same formulation of glyphosate, surfactant, and antifoam agents is used. The work should take only about 3 person-hours per acre. The second fertilizer application follows the spraying; the advantage of this timing is that the area has been opened up by the passage of the backpack spray crew.

Most of the plantations in which our weed control practices were developed were established at 5- by 5-ft or 6- by 6-ft spacings. At these densities herbicide spraying covers essentially the entire area, and crown closure by the eucalypts reduces the need for weeding after about one year. When wider spacings are used, the first spraying could be confined to circles around the trees large enough to keep them free of competition. The second spraying might need to be more intensive to control taller vegetation between the rows which could interfere with the trees as they grow larger. Additional spraying may be needed if crown closure occurs at a later age. Mechanized mowing, as in macadamia nut orchards, may be appropriate where spacings are wide.

Competition for moisture between eucalypts and weeds is unlikely to be a problem in the Hamakua area because of the high rainfall. In the Ka'u District, where rank growth of grasses is a problem and spraying is often hampered by windy conditions, there may be some advantage to mowing the weedy vegetation and leaving it on the ground as a mulch to help conserve soil moisture, especially at lower elevations and during dry periods *(fig. 13)*.

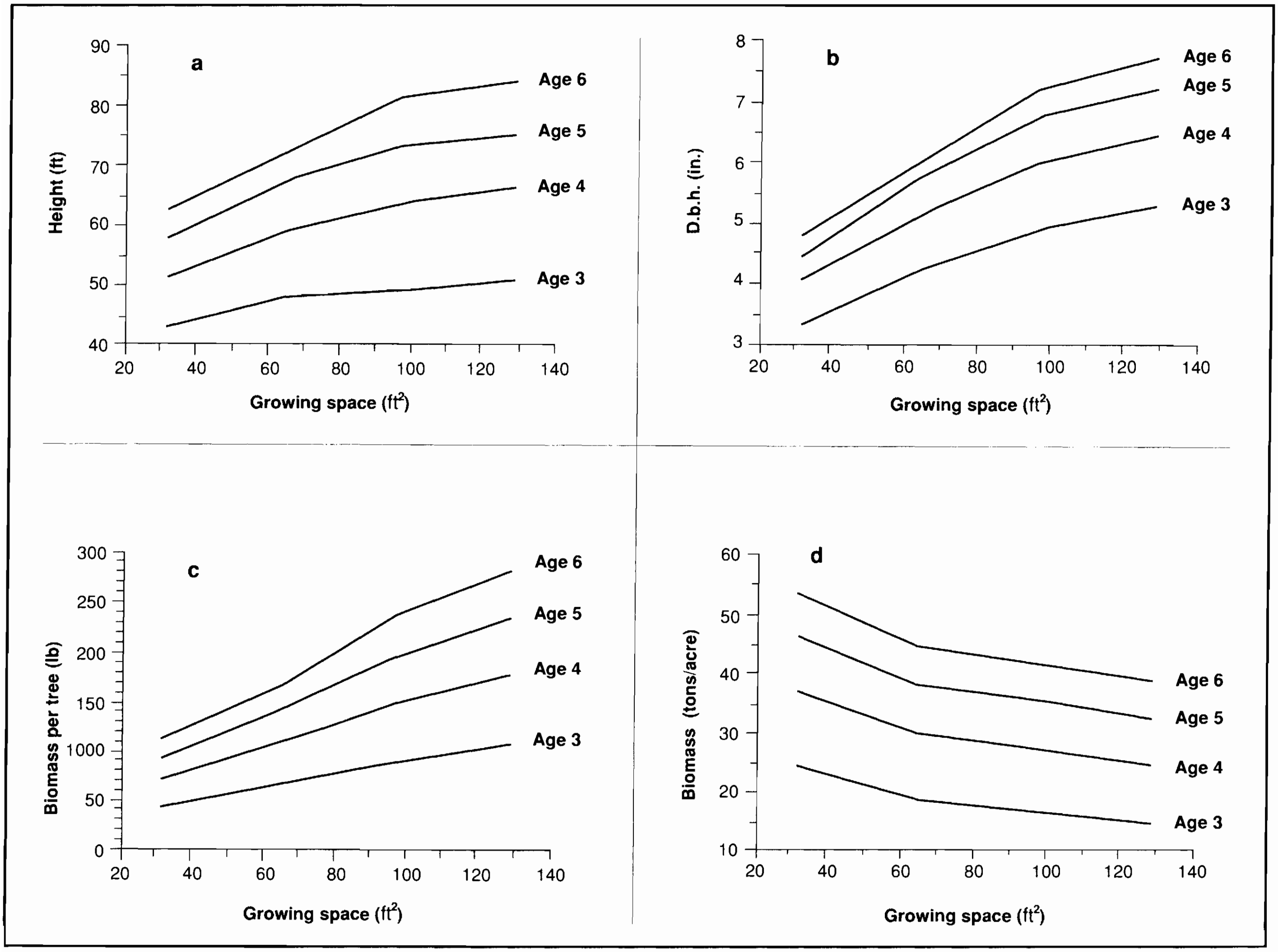


Figure 10—Effects of growing space per tree on height (a), diameter at breast height (b), and biomass (c and d) for *Eucalyptus grandis*, Island of Hawaii.

Figure 11—Initial application of fertilizer placed in dibble hole next to seedling.

Stand Development and Cultural Practices

Influence of Growing Space

Increased growing space had little effect on height growth during the first two years. Greater growing space did, however, result in trees that were substantially taller in later years. Mean heights of trees planted at 130 ft^2 (10 ft by 13 ft) of growing space per tree were approximately one-third taller than mean heights of trees planted at 32 ft^2 (10 ft by 3.2 ft) at 6 years of age *(fig. 10a)*. Diameter growth was more strongly affected than height growth by growing space, and positive effects were seen at younger ages. By age 6, diameters of trees planted at wide spacings were nearly 60 percent larger than those at narrower spacings *(fig. 10b)*. The combined influence of both height and diameter leads to even greater differences in tree biomass. Trees planted with 130 ft^2 of growing space weighed about 2.5 times more than those with 32 ft^2 *(fig. 10c)*, but produced only three-fourths as much biomass per acre *(fig. 10d)* at age 6 years.

The continued acceleration of growth in the wider spacings and accompanying widening of differences in mean tree size and weight at ages 5 and 6 are important considerations in decisions regarding spacing and rotation length, especially if tree size is a significant factor in product value and costs of harvesting or conversion.

No thinnings are envisioned in the short-rotation management of *Eucalyptus* in Hawaii, so no thinning trials were conducted.

Fertilization

Although a complete N-P-K fertilizer is recommended at the time of planting, subsequent fertilizer recommendations involve only N. Frequent applications of this element early in the rotation were beneficial; however, subsequent applications of P and K may also be required on sites that do not have a history of fertilization associated with sugarcane production (Strand and others 1992).

Growth increases associated with increased N supply are clearly demonstrated by comparing the biomass production and soil nutrient content of two spacing studies, one at Kamae and the other at Pepeekeo. Both studies had identical establishment practices, spacing, and fertilization. Biomass production is significantly higher at Kamae than at Pepeekeo at most levels of growing space *(table 5)*. Comparison of soil nutrient levels at time of establishment shows a significantly higher level of topsoil total N at Kamae than at Pepeekeo *(table 6)* although most other elements contributing to soil fertility are better at Pepeekeo than at Kamae. The lower productivity and lower topsoil N at Pepeekeo suggest that a higher rate of N fertilization is required to match the growth achieved at Kamae.

A fertilizer study at Pepeekeo confirms that higher application rates of N fertilizer could have increased biomass production in the spacing study. The highest rate in the fertilizer study is somewhat higher than that used in the spacing study (399 lb vs. 343 lb elemental N/acre), and response throughout the range of application rates is essentially linear *(fig. 14)*. Because the two spacing studies occur at about the same elevation, with approximately the same rainfall and on the same soil series, differences in N supply most likely account for the higher biomass productivity at Kamae.

Results of our field research show that plantation growth is positively correlated with soil N content and that response to N fertilization is greatest on topsoils with the lowest N content (Strand and Cole 1992, Strand and others 1992). Rates and frequency of N fertilization needed to promote growth, therefore, should be linked to topsoil N status (total N concentration in the top 6 inches of soil).

We propose the following three classes of topsoil N status as the basis for such specificity in fertilizer prescriptions:

Good - >0.60 pct N
Average - 0.45 to 0.60 pct N
Poor - <0.45 pct N

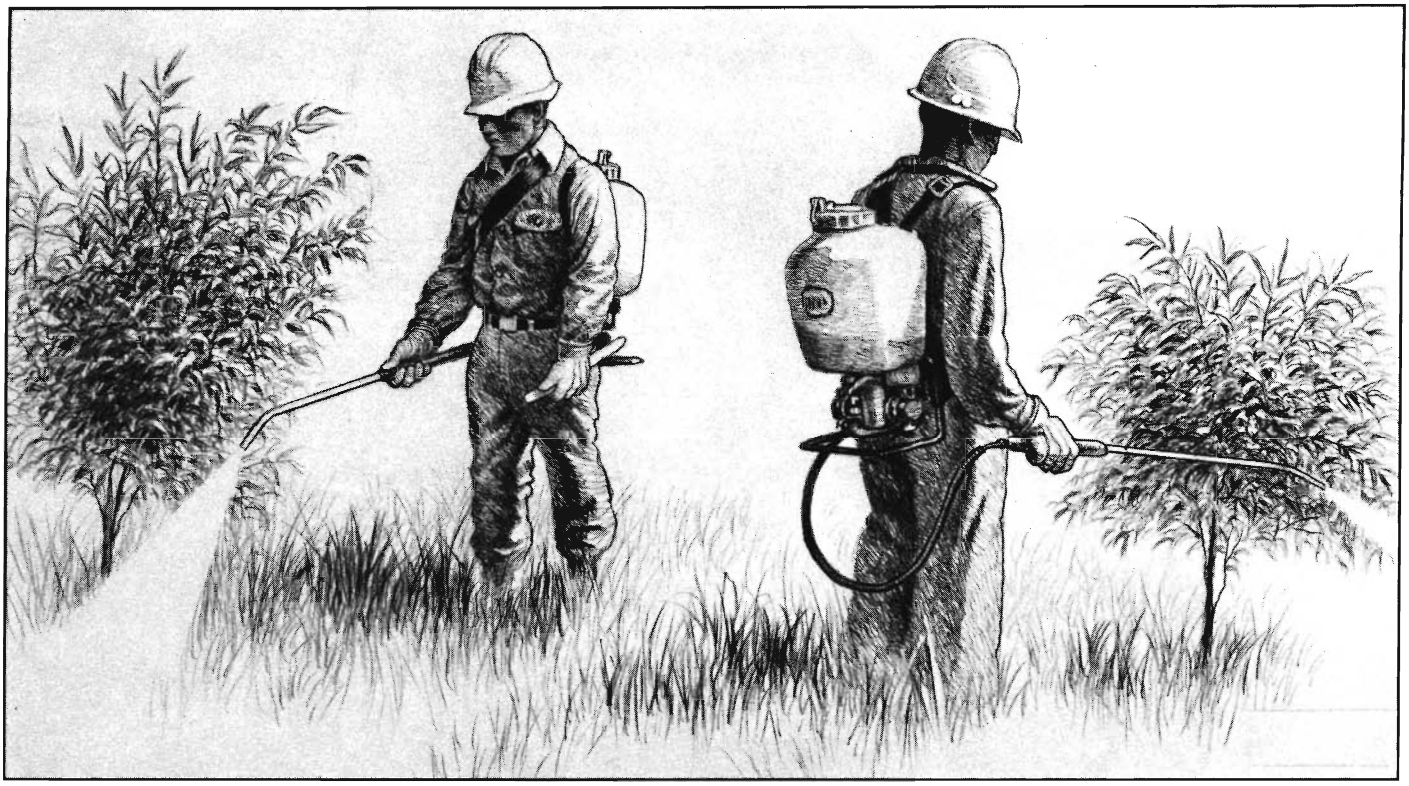


Figure 12—Spraying herbicide for weed control about 6 months after outplanting.

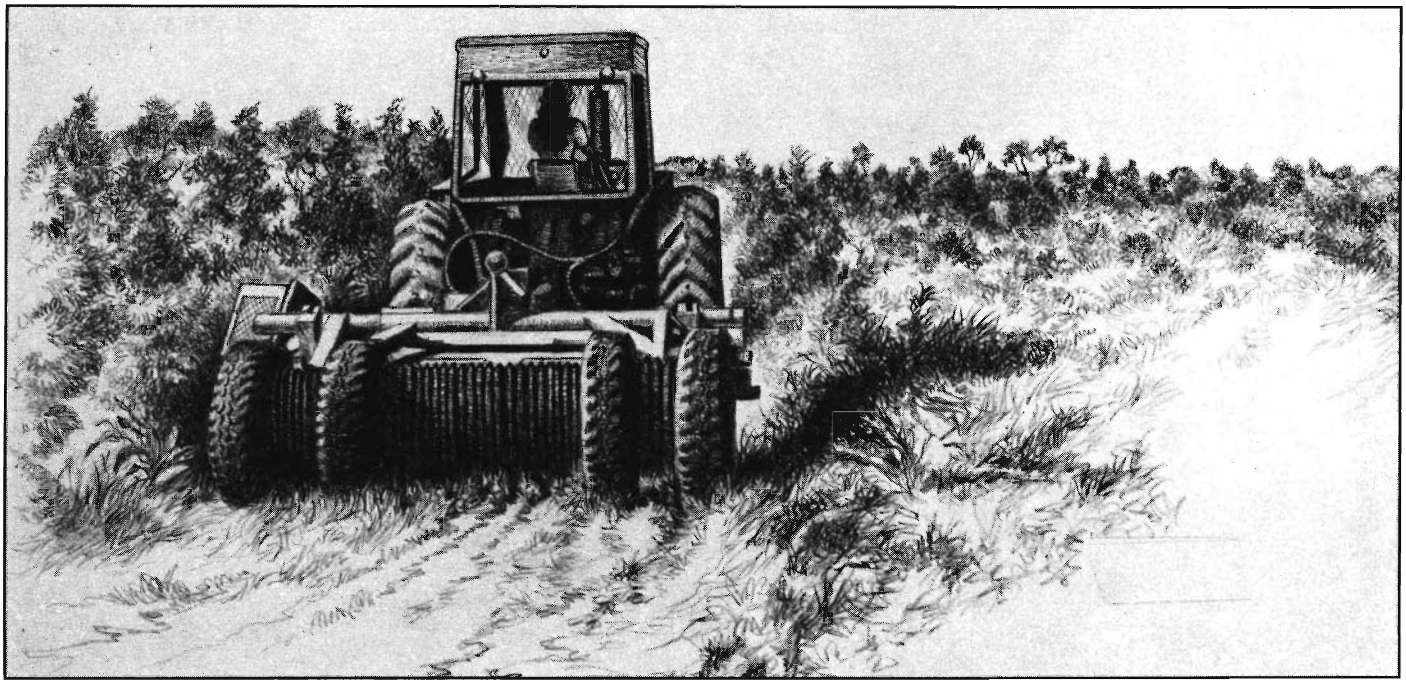


Figure 13—Mowing for weed control in the Ka'u District.

Table 5—*Comparison of biomass production in two* **Eucalyptus grandis** *spacing studies at age 6 years, for identical spacings and fertilization, Hamakua coast, Island of Hawaii*

Location	Initial growing space (ft^2)			
	32	65	100	130
	dry tons/acre/yr			
Kamae	11.7a[1]	8.8a	9.0a	8.3a
Pepeekeo	8.2b	7.6a	6.7b	6.2b

[1]Means in a column not having the same letter are statistically different by Student's "t" test at 0.05 confidence level.

Table 6—*Comparison of soil analyses values for two spacing studies at Kamae and Pepeekeo, Island of Hawaii*

Sample depth	Location (study)	Soil analyses					
		Total N[1]	P	K	Ca	Mg	pH
in.		*pct*	*ppm*				
0-6	Kamae	0.67a[2]	10a	54.7a	10.0a	19.5a	4.2a
0-6	Pepeekeo	0.57b	24b	89.9b	174.3b	40.1a	4.9b
18-24	Kamae	0.51a	8a	43.0a	10.0a	34.0a	4.6a
18-24	Pepeekeo	0.42a	12a	39.1a	134.3b	26.8a	5.1b

[1]N–nitrogen, P–phosphorus, K–potassium, Ca–calcium, Mg–magnesium.
[2]Means in a column (by soil depth) not having the same letter differ significantly by Student's "t" test at the 0.05 confidence level.

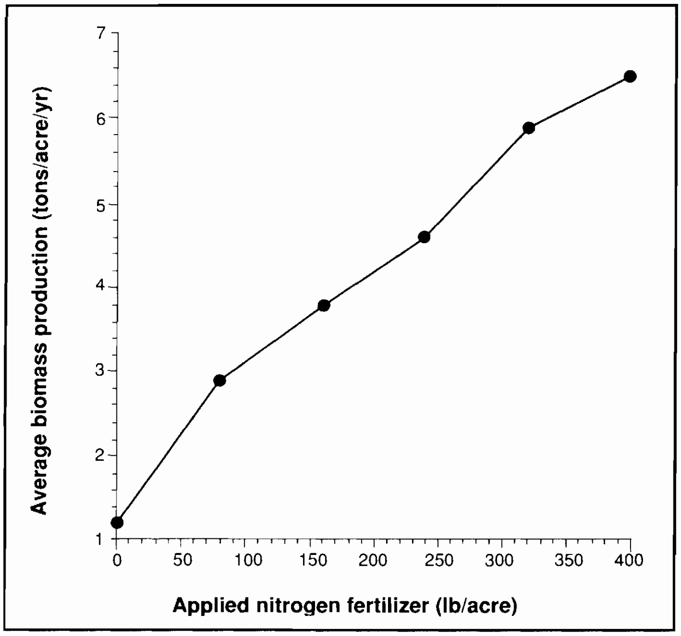


Figure 14—Effect of nitrogen fertilizer treatments on biomass production of 6-year-old *Eucalyptus grandis*, Pepeekeo, Island of Hawaii.

Table 7—*First approximation of nitrogen fertilization regimes for* **Eucalyptus** *plantations on soils of different topsoil nitrogen (N) status classes, Hamakua Coast, Island of Hawaii*

Months after planting	Topsoil N status class[1]		
	Poor	Average	Good
	lb N/acre		
0[2]	20	20	20
6[2]	40	20	20
12[2]	60	30	–
18	100	100	100
24	100	–	–
30	–	100	100
36	100	–	–
42	–	50	–
48	100	–	–
Total applied:	520	320	240
No. of applications:			
Manual	3	3	2
Aerial	4	3	2
Total applications:	7	6	4

[1]N status classes (total N concentration in topsoil [0 - 6 in.]): Poor = <0.45 pct; Average = 0.45 pct - 0.60 pct; Good = >0.60 pct
[2]Subsurface application of fertilizer

Fertilizer regime recommendations for each class *(table 7)* were developed from the results of six fertilizer, one admixture, and three spacing studies, nearly all of which were established on the Hamakua coast. A field trial at Akaka Falls indicated the need for higher amounts of initial N fertilization on poor sites (Whitesell and others 1987). This is reflected in *table 7*.

Mixed Plantings of Eucalyptus *and* Albizia

Because many fertilizer studies in Hawaii and elsewhere (Cromer 1971, McIntyre and Pryor 1974) have demonstrated that *Eucalyptus* growth beyond the establishment phase is markedly enhanced by supplemental N applications, our project designed and evaluated cultural systems in which this supplemental N was supplied by nitrogen-fixing trees (DeBell and others 1985). We found that the need for N fertilizer beyond the initial two applications during the first year could be eliminated on the Hamakua Coast by establishing mixed *Eucalyptus*/*Albizia* plantations. At Ka'u, however, *Albizia falcataria* grew poorly and provided no advantage on this much drier site (DeBell and others 1987).

Our most comprehensive admixture trial was installed at Chin Chuck and has been evaluated for 7 years. A total of seven treatments was established on the basis of different admixtures of *Eucalyptus saligna* and *Albizia falcataria (fig. 15)*. Besides pure *Eucalyptus* and *Albizia* treatments, the five mixed ratios were 11:89, 25:75, 34:66, 50:50, and 66:34 (*Albizia* to *Eucalyptus* percentages). All of the treatments received N-P-K initially, but only the pure *Eucalyptus* plots received additional N fertilization. All treatments had the same initial density of 1,012 trees/acre (43 ft^2 of growing space per tree) and received supplemental applications of P and K.

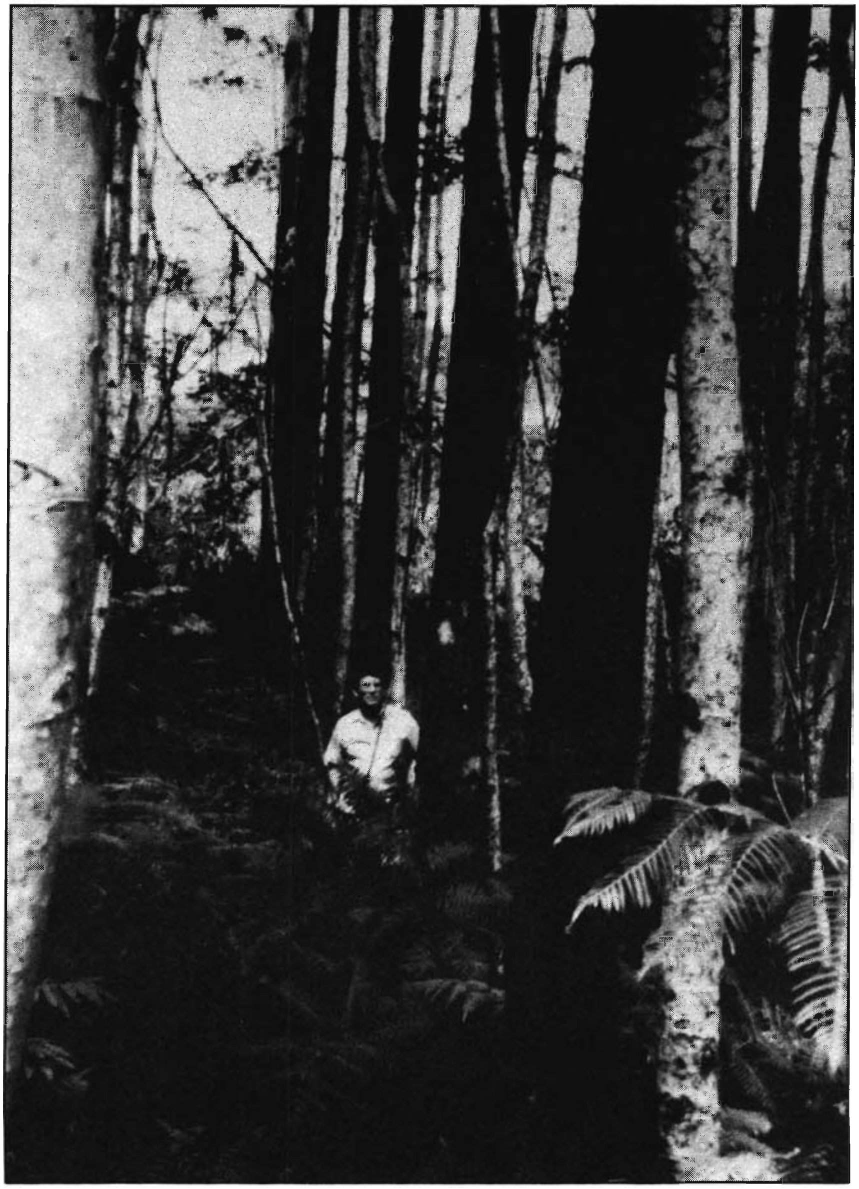


Figure 15—Mixed plantation of *Eucalyptus* and *Albizia*.

Patterns of tree growth and stand development in the trial and adjacent plantings have been very dynamic. Survival and growth of both species through age 4 has been described in detail (DeBell and others 1989a). Additional data illustrating patterns of height and diameter growth through age 7 are displayed in *fig. 16*.

As these stands develop over time, the combinations with *Albizia* look better and better. Height and diameter of the *Eucalyptus* in the 34 percent *Albizia* treatment are comparable to those *Eucalyptus* growing in the pure, fertilized plots. The *Eucalyptus* in the 50- and 66-percent *Albizia* treatments are substantially larger than those in the pure *Eucalyptus* plots, and so much larger than the admixed *Albizia* that a two-storied canopy has developed. The relative importance of improved N status versus increased growing space in these mixtures is unknown, but both factors are undoubtedly influential. *Eucalyptus* crowns in the 50- and 66-percent *Albizia* treatments occur in an environment similar to those with initial densities providing 86 and 130 ft^2 of growing space per tree. Regardless of the relative effect of these factors, these treatments demonstrate the growth potential of *Eucalyptus* at wider spacings and with enhanced N status *(fig. 17)*.

Management Considerations

Biomass Estimation

Production from short-rotation, intensively cultured plantations is usually expressed on an oven-dry weight basis as either stem-only or total above-ground biomass per unit of area. Actual weight can be determined only after harvest; thus estimates based on nondestructive measurements (d.b.h. and height) of standing trees are commonly used. Tree biomass is estimated from these measurements using regression equations developed by destructive sampling of trees from plantations over a range of ages, sites, and stocking conditions. Biomass in plantations is then estimated by measuring trees in sample plots, calculating the weight of each tree from the equations, and summing all the weights to obtain an estimate of biomass per unit area. This estimate is then multiplied by an approximate expansion factor to provide estimated yield per acre.

Biomass equations were developed for seven of the species we planted (Schubert and others 1988, Whitesell and others 1988). For three of these species—*Eucalyptus grandis, E. saligna*, and *Albizia falcataria*—the number of sample trees measured was large enough (n > 25) so that equations using both d.b.h. and height could be derived. For the other four species—*Acacia melanoxylon, Eucalyptus globulus, E. robusta*, and *E. urophylla*—fewer than 25 trees were sampled, and equations that use only diameter measurements were derived. Logarithmic equations were developed for both stem-only and for total above-ground dry biomass *(table 8)*. Diameter and height measurements for these equations are in the metric system, and biomass is expressed in kilograms; this value should be multiplied by 2.2 to convert to dry pounds.

The large sample size for *E. saligna* (n = 286), from 2- to 6-year-old stands, made it possible to derive two sets of equations for this species *(table 9)*. One set is for trees less than 4 years old; the other set is for trees 4 years old and older.

Growth Patterns and Rotation Length

General

A classical concept in forest management holds that the optimal biological rotation age for any given forest crop is attained when mean annual increment of the desired product

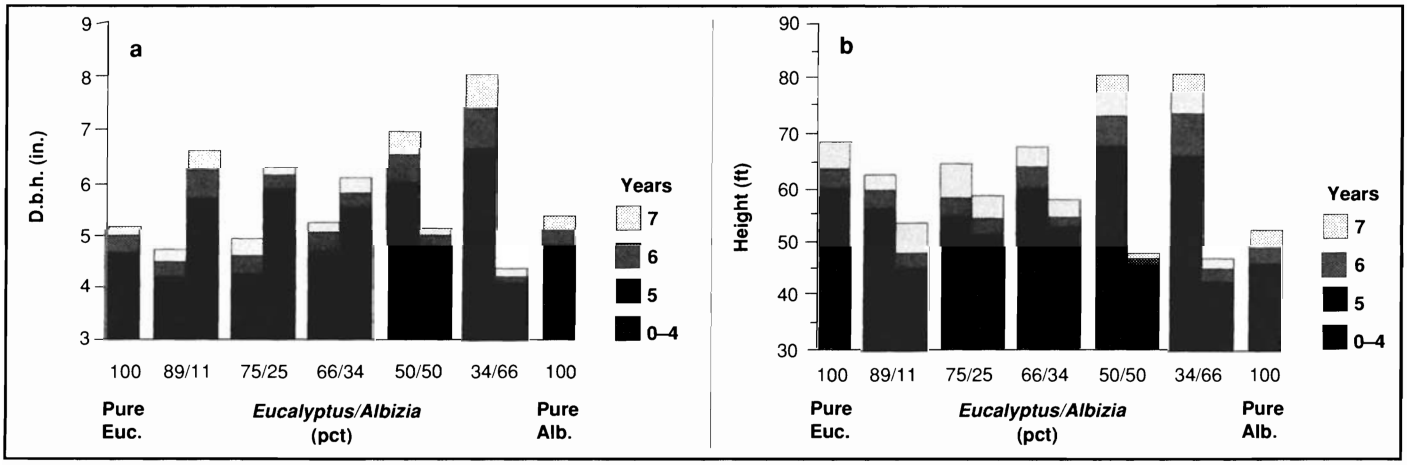


Figure 16—Average diameter (a) and height (b) of *Eucalyptus saligna* trees grown in pure stands with nitrogen fertilizer and those grown in various mixtures with *Albizia falcateria* and without nitrogen fertilizer.

Table 8—***Biomass equations for six species developed from 2- to 6-year-old plantations located on the Island of Hawaii and recommended for prediction of stem-only and total above-ground dry biomass per tree***[1]

Species	Equations[2]
Acacia melanoxylon	$Y_s = 0.087366 * (D^{2.3778})$ $Y_t = 0.150484 * (D^{2.3210})$
Albizia falcataria	$Y_s = 0.017945 * (D^{2.2026}) * (H^{0.6660})$ $Y_t = 0.036207 * (D^{2.3146}) * (H^{0.3600})$
Eucalyptus globulus	$Y_s = 0.076621 * (D^{2.5000})$ $Y_t = 0.082582 * (D^{2.5120})$
Eucalyptus grandis	$Y_s = 0.026084 * (D^{1.7178}) * (H^{0.9824})$ $Y_t = 0.069413 * (D^{2.1472}) * (H^{0.3129})$
Eucalyptus robusta	$Y_s = 0.111171 * (D^{2.2670})$ $Y_t = 0.119339 * (D^{2.3200})$
Eucalyptus urophylla	$Y_s = 0.075360 * (D^{2.4950})$ $Y_t = 0.119931 * (D^{2.3610})$

[1]Schubert and others 1988
[2]Y_s = predicted stem-only dry weight in kilograms
Y_t = predicted total above-ground dry weight in kilograms
D = diameter at breast height (1.3 m) in centimeters
H = total tree height in meters

Table 9—***Biomass equations for* Eucalyptus saligna *plantations on the Island of Hawaii developed from two data bases and recommended for prediction of stem-only and total above-ground dry biomass per tree***[1]

Data base (age)	Equations[2]
	Diameter and height model
Younger (<4 years)	$Y_s = 0.05501 * (D^{1.8942}) * (H^{0.5408})$ $Y_t = 0.12022 * (D^{2.1448}) * (H^{0.1352})$
Older (4 to 6 years)	$Y_s = 0.01444 * (D^{1.7210}) * (H^{1.2347})$ $Y_t = 0.01996 * (D^{1.9144}) * (H^{0.9976})$
	Diameter-only model
Younger (<4 years)	$Y_s = 0.08990 * (D^{2.2494})$ $Y_t = 0.13580 * (D^{2.2336})$
Older (4 to 6 years)	$Y_s = 0.06352 * (D^{2.5412})$ $Y_t = 0.06594 * (D^{2.5772})$

[1]Whitesell and others 1988
[2]Y_s = predicted stem-only dry weight in kilograms
Y_t = predicted total above-ground dry weight in kilograms
D = diameter at breast height (1.3 m) in centimeters
H = total height in meters

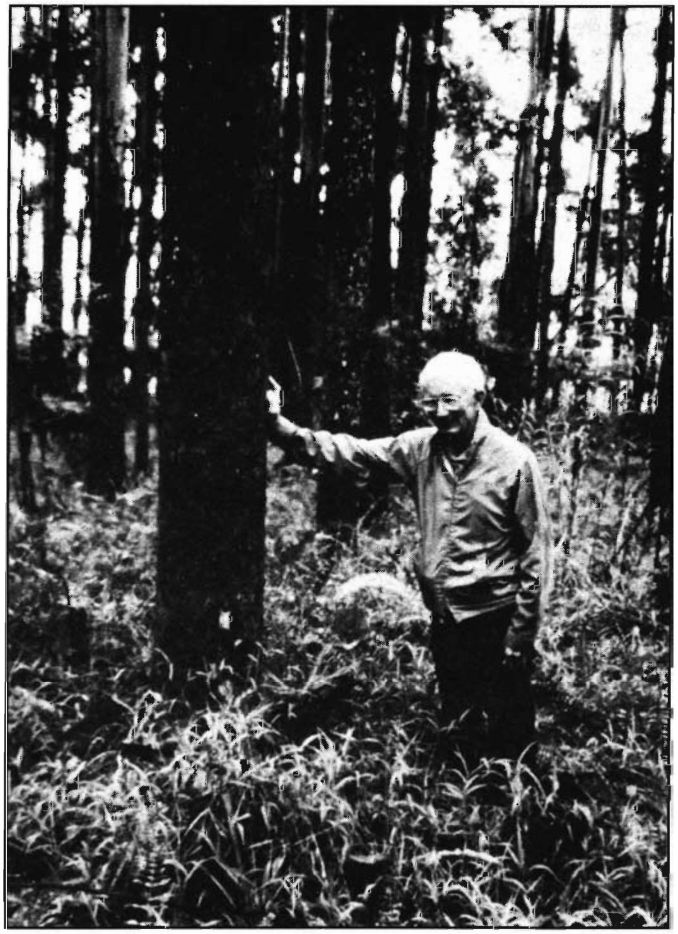


Figure 17—*Eucalyptus saligna* at 10 years showing potential for enhanced growth with wide spacing and regular fertilization.

culminates. The culmination time is defined as the age at which the curve of current annual increment plotted over time crosses that of mean annual increment. Our work on short-rotation management of *Eucalyptus* indicates that peak mean annual increment will not occur before the onset of significant competition-related mortality, somewhat beyond the stage at which stands managed under any short-rotation intensive culture regime are likely to be harvested. Thus, classical theories about stand growth and optimum rotation age developed for more conventionally managed, longer rotation forests have limited application in short-rotation management. In this section, we will discuss general ideas that apply to short-rotation management and may help with decisions regarding optimum spacing and rotation length. These ideas will be illustrated with data on tree and stand characteristics from some plantings established and maintained under conditions approximating those recommended in this report.

Eucalyptus

Data from treatments in two spacing trials and one fertilization trial are presented in *table 10*. The spacing trials were located on average to good sites, and were fertilized regularly. The fertilizer trial was located on an average site, and the treatments included three levels of N application.

The data describes tree and stand characteristics at the end of the year when competition-related mortality became significant (arbitrarily set at approximately 10 percent of initial stem density). Yields in the spacing trials averaged over 9 dry tons/acre/yr. In general, the denser spacings have the higher mean annual production. Although stands planted at densities of 16 ft^2 and 32 ft^2 per tree have the highest production, on the average the trees are small and have not attained the minimum acceptable mean diameter of 6 inches required for cost-effective harvesting (Kluender 1980). Data from the fertilizer trial at Pepeekeo show the effect of increasing amounts of N fertilizer (*fig. 14* and *table 10*). At the same spacing, tree growth and mortality were generally greater, and yields increased linearly with increasing levels of fertilizer. It therefore seems likely that mean annual productivity in the wider spacings of the studies at Kamae and Pepeekeo may be enhanced through additional applications of N fertilizer.

Further evidence to support this conjecture can be seen in data on *Eucalyptus* trees from three treatments in the mixed species trial at Chin Chuck (*fig. 18*). The fertilized *Eucalyptus* was planted at a density of 43 ft^2 per tree. *Eucalyptus* trees in two of the mixed species treatments, 50 and 66 percent *Albizia*, were established at densities equivalent to 86 and 130 ft^2 per tree, respectively. The spacings of *Eucalyptus* ignore the presence of *Albizia* trees because *Eucalyptus* trees in the wider spacings average 33 ft taller than the *Albizia*. It is presumed that in recent years the *Albizia* trees in these treatments have offered little competition for light, that water was not limiting, and that nitrogen levels have been raised to near optimum levels.

The rate at which biomass is being accumulated at Chin Chuck is strongly correlated with the effective spacing. Eucalypts planted at the widest spacing, 130 ft^2 per tree, are growing 99 to 110 lb/yr per tree (since age 4), while trees at the closest spacing, 43 ft^2 per tree, are growing only about 33 lb/yr per tree. Such differences in growth rate are causing the gap in total production among treatments to close rapidly for both total and mean annual biomass per acre (*fig. 18*). These trends suggest that yields in the wider spacings will eventually equal (and may even surpass) those of the denser spacings, provided that rotation length is long enough.

A more conservative view on which to base management decisions would be that if biomass yields at densities from 65 to 130 ft^2 per tree are more or less equal at the onset of competition-related mortality, then the initial spacing will be

Table 10—***Tree and stand characteristics at onset of competition-related mortality in three studies, Island of Hawaii***

Study	Growing space per tree	Age	Survival	Mean d.b.h.[1]	Mean height	Dry biomass per tree	Dry biomass per acre	Dry biomass per acre/yr
	ft²	*yr*	*pct*	*in.*	*ft*	*lb*	---- *tons*	---
Kamae	32	3	90	3.8	50.2	60	36	12
(spacing)	65	4	90	5.4	59.4	124	37	9
	100	4	88	6.7	72.2	207	41	10
	130	4	86	7.2	74.8	240	35	9
Pepeekeo	16	4	83	3.0	41.0	40	45	11
(spacing)	32	4	86	3.7	46.6	60	34	9
Pepeekeo (fertilizer)								
(30)[2]	39	6	89	4.2	53.1	77	38	6
(40)	39	6	91	4.5	58.4	88	46	8
(50)	39	6	84	5.0	62.3	108	51	9

[1]d.b.h. = diameter at breast height
[2]N fertilization rate in parenthesis (g/tree).

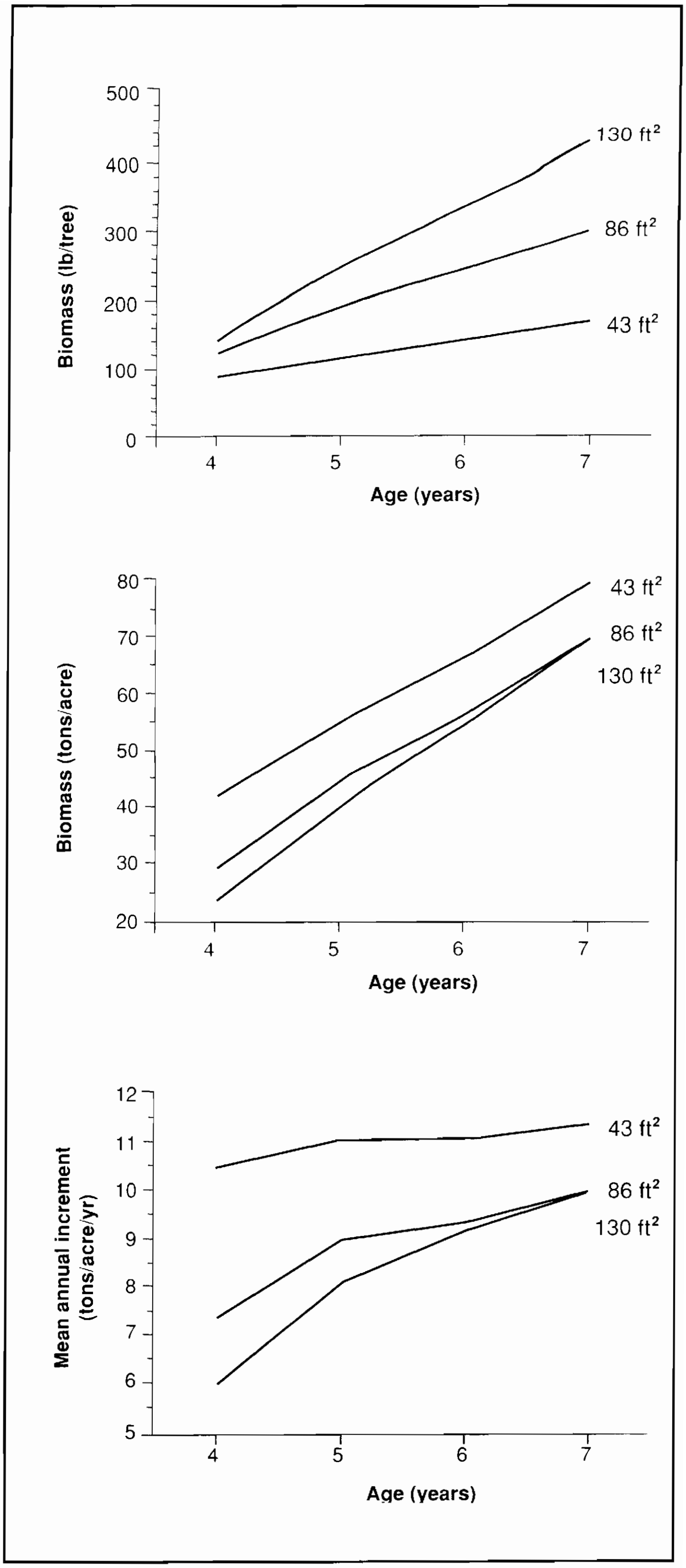


Figure 18—Biomass yields for 4- to 6-year-old *Eucalyptus saligna* as influenced by growing space per tree.

determined by the desired tree diameter at harvest. To achieve a minimum mean acceptable tree d.b.h. of 6 inches, tree spacing must be at least 8.5 by 8.5 ft per tree or a density of 72 ft^2 per tree. Choices among alternative wider spacings and associated rotation lengths can be based primarily on other considerations (discussed in next section).

Mixed Species Planting

In terms of producing large quantities of biomass from trees meeting minimum size limits, certain *Eucalyptus/Albizia* mixtures at Chin Chuck appear promising. Total yields of dry biomass and mean annual increments at ages 5 through 7 are given in *table 11*.

These mixed species plantings are in a very dynamic state. Biomass growth is still accelerating, with *current* annual increments between 6 and 7 years ranging from 10 tons/acre in the 11 percent *Albizia* treatment to 15 and 18 tons/acre in the 50 and 66 percent *Albizia* treatments, respectively. *Mean* annual increments range from 9.3 to 13.4 tons/acre.

An interesting trend has developed in relative production of the two species. The relative contribution of *Albizia* to total yield has increased over time in the 11 percent *Albizia* plots (from 15 to 20 percent). Conversely, in the 66 percent *Albizia* plots, the relative contribution has decreased from 33 to 26 percent *(table 11)*. Presumably this trend results from the capacity of the *Eucalyptus* trees to grow more rapidly than the *Albizia*, using the greater amount of nitrogen-rich mulch provided by the increasing numbers of *Albizia* trees (Dunkin 1989).

From an operational standpoint, it may not be efficient to completely intermix the two species as done in our research design. We suggest that the two species be planted in alternating rows spaced 10 ft apart. Within rows, *Albizia* could be planted 7 ft apart and *Eucalyptus* 10 ft apart. This would provide the *Albizia* trees with an initial growing space of 70 ft^2 (311 trees/acre) and the *Eucalyptus* 100 ft^2 (218 trees/acre) for a total of 529 trees/acre. Of this number, about 58 percent would be *Albizia*.

Eucalyptus growth has been so rapid under such density and composition regimes that their yields (9.9 tons/acre/yr in the 50 and 66 percent *Albizia* treatments) approach those of pure *Eucalyptus* (11.3 tons/acre/yr) that received heavy, periodic applications of fertilizer. No N fertilizers are recommended beyond the first year in the mixed plantings, and additional applications of P and K are probably not necessary. Because the *Eucalyptus* trees were so large (which lowers harvesting costs), mixed treatments may be more economical than pure *Eucalyptus* stands, even if the *Albizia* trees are not utilized.

Table 11—***Total yield and mean annual increment (MAI) of dry biomass at ages 5 through 7 years for various combinations of* Eucalyptus *and* Albizia*, Island of Hawai***

Species combination (pct)		Dry biomass at age (yr)			Mean annual biomass increment at age (yr)		
		5	6	7	5	6	7
		tons/acre			*tons/acre/yr*		
Eucalyptus	(100)	55	66	79	11.0	11.0	11.3
Eucalyptus	(89)	39	46	52	7.8	7.7	7.4
Albizia	(11)	7	9	13	1.4	1.5	1.9
Total		46	55	65	9.2	9.2	9.3
Eucalyptus	(75)	32	41	52	6.4	6.8	7.5
Albizia	(25)	16	17	19	3.1	2.9	2.7
Total		48	58	71	9.5	9.7	10.2
Eucalyptus	(66)	38	47	55	7.6	7.8	7.9
Albizia	(34)	19	22	26	3.8	3.6	3.7
Total		57	69	81	11.4	11.4	11.6
Eucalyptus	(50)	45	56	70	9.0	9.4	9.9
Albizia	(50)	16	18	19	3.2	3.0	2.8
Total		61	74	89	12.2	12.4	12.7
Eucalyptus	(34)	41	54	70	8.1	9.1	9.9
Albizia	(66)	20	22	24	4.0	3.6	3.5
Total		61	76	94	12.1	12.7	13.4
Albizia	(100)	50	58	70	9.9	9.7	9.9

Other Considerations in Rotation Length

Aside from the physical growth patterns of the species under management, a number of other considerations can affect decisions on rotation length. These include economic factors, product characteristics and values, nutritional effects, and environmental and esthetic impacts.

Economic factors can have a profound effect on rotation length. Optimum financial rotations shorten with increasing interest rates. Site preparation, regeneration, and other costs incurred at the beginning of the rotation are, in theory, carried with interest to the processing phase. On the other hand, stand establishment costs occur more frequently with short rotations, and this would somewhat modify effects of interest in determining the optimum rotation length. Costs of stand harvest constitute a major portion of total production costs, and may have effects as important as those of stand establishment costs.

Product characteristics and value, if related to tree size or tree age, can affect rotation length. Utilization of total biomass as fuel does not particularly constrain rotation length because bark and leaves have little adverse effect on this product. Separation and removal of these components as well as limbs are required, however, for production of high quality pulp. Bark, limbs, and foliage could be tolerated in lower quality pulpwood, but chemical costs will increase and total mill production capacity may decrease with increasing quantities of these components (Schmidt and DeBell 1973). Bark and foliage increase as a percentage of the biomass harvest as rotation length decreases, so utilization for high quality pulpwood would tend to increase rotation length of short-rotation plantations.

Nutrient relationships also are affected by rotation length. Shorter rotations result in more frequent and greater removal of nutrients from the site, especially if small branches and foliage are harvested. Furthermore, eucalypts appear to have efficient internal nutrient cycling mechanisms (Florence 1986). With longer rotations this mechanism may assist in husbanding nutrient resources and reducing nutrient drain. Nitrogen, the major limiting factor for eucalypt plantations on the Hamakua Coast, is the element of primary interest. The use of N-fixing species in mixture with eucalypts to supply nitrogen may influence rotation length. Since it takes time for the N-fixers to build up the soil nitrogen, a longer rotation may be required than for regimes with commercial fertilizer applications. If the management strategy is for the N-fixers to be over-topped and suppressed by the eucalypts—the final harvest product—then an even longer rotation may be appropriate.

Frequency of harvest and regeneration activity as determined by rotation length will affect environmental and esthetic considerations. Clearing vegetation in a high-intensity rainfall area increases the probability of significant soil erosion. The more frequently the vegetative cover is removed, the greater the risk of soil erosion and site deterioration. A related productivity concern is the compaction and movement of the soil by harvesting and site preparation equipment. These problems increase in severity as rotation length decreases because the site is disturbed more often. Moreover, such disturbances may be esthetically displeasing to some segments of the public, especially since clearcutting is the normal harvesting method. However, sugar plantations on the Hamakua Coast presently harvest down to bare soil on a 2-year cycle, and soil loss can equal or exceed 1 to 2 inches per rotation. Thus, longer cutting cycles and reduced soil exposure involved in biomass plantations should be more acceptable to most local residents than sugarcane culture.

Harvesting

The financial success of short-rotation, intensive culture systems for most species, particularly those of the temperate zone, hinges on the development of suitable harvesting technology for small stems. In subtropical Hawaii, rapid tree growth may permit use of conventional pulpwood harvesting systems with only minor modifications. Another advantage of short-rotation, intensive culture systems is that equipment and knowledge for sugarcane production can be adapted to develop tree harvesting systems suitable for soil and weather conditions in Hawaii. This situation in Hawaii does not diminish the importance of improving the efficiency of harvesting systems. Harvesting is the largest single cost item in short-rotation, intensively cultured tree crops, and may represent more than 50 percent of the total delivered cost. Several trials were established to analyze and evaluate approaches to harvesting (Crabb and Schubert 1989; Schubert and others 1992).

One of the first systems we studied was cable yarding. The main advantage of this system is that little damage is done to the site or residual stumps. In our test the trees were felled manually with chain saws, with the butts aligned toward the roadside for easy hookup to the yarding equipment. Extraction was with a highline cable system using two boom trucks with winches and cables attached to spar trees within the area. The main problem encountered was that the yarding equipment was undersized and underpowered so that the extractive process was slow and inefficient. Inexperience with cable logging was also a factor.

A second trial in the same area used mechanized equipment, including wheeled Morbark Mark IV[1] and tracked Caterpillar Model 227[1] feller-bunchers, a Timberjack[1] clambunk skidder, and a Morbark Model 30[1] whole tree chipper. A third trial used the same mechanized equipment to harvest three stands on 22 acres. The conventional logging machines were able to handle our trees without difficulty. The tracked Caterpillar Model 227 *(fig. 19)* was designed for considerably larger tree sizes, but seemed to be the best type of machine tested for our conditions. The shearing action of the felling heads caused extensive damage to the stumps, as did the rubber tires of the wheeled machines. This would be a problem only if coppice regeneration is relied upon. The wheeled machines also tended to get bogged down during wet weather. A large capital expenditure is necessary to purchase this type of specialized equipment, and depreciation costs add greatly to the total harvesting costs.

These experiences revealed that logistics as well as tree size are major determinants of the productivity and cost of harvest operations. A balanced system in which all machines work close to capacity, with limited idle time due to delays in other parts of the system, is needed. Smaller, less expensive equipment, a good preventive maintenance system, and an adequate stock of critical spare parts would also help to bring down costs.

Early during the life of the project it was suggested that modification of existing tracked sugarcane harvesting equipment for felling, bunching, and forwarding offered a promising opportunity to conduct harvesting research trials. Unfortunately, financial constraints prevented following up on this suggestion at the time, but it is still a concept that would be worth pursuing. There are also a number of new machines designed for pulpwood harvesting in Australia, North America, and Europe, which might be suited to our conditions.

Regeneration

There are three means of regenerating short-rotation intensive culture stands after harvest: natural regeneration, artificial regeneration, and coppice growth (resprouting of stumps). Natural regeneration by seedfall is not practical for our short 6- to 8-year rotations. *Eucalyptus grandis* requires 4 to 5 years for its first flower production (FAO 1979), whereas *E. saligna* requires 7 to 8 years (Hillis and Brown 1978). In addition, with natural regeneration there is no control over spacing, and risk of establishment failure would be high compared to coppice or planted seedlings.

Artificial regeneration with nursery-grown planting stock requires operations similar to those described earlier for plantation establishment. Planting stock could be either seedlings or rooted cuttings. Herbaceous weeds and stump sprouts must be controlled, probably with herbicides applied before or soon after planting.

Adequate stand regeneration by coppice has been unsuccessful for *E. saligna* in our trials on the Hamakua Coast because of poor resprouting (Bowersox and others 1990). Increased success of coppice regeneration may be possible in the future if the selection of improved, higher yielding stock is based on coppicing ability as well as the potential for higher biomass production rates. Furthermore, any tree improvement program would initially emphasize the planting of superior stock. This would reduce the necessity for coppice regeneration until trees with inherently better coppicing ability are in place.

Diseases and Insects

A stem canker *(Cryphonectria cubensis* [Bruner] Hodges) is the only disease of eucalypts found to date in Hawaii. On Kauai, two adjacent *Eucalyptus saligna* plantations heavily infested with this canker were found more than 10 years ago, but it has not been observed on the other Hawaiian islands. *Eucalyptus*

Figure 19—Harvesting using Caterpillar 227 fitted with feller-buncher head.

saligna was rated as highly susceptible to this disease, *E. grandis* as moderately susceptible, and *E. urophylla* as highly resistant. Variation in susceptibility was considerable among different provenances of *E. grandis* (Hodges and others 1979).

The Australian longhorn beetle *(Phoracantha semipunctata* Fabr.) has been found on *Eucalyptus* on Kauai, Oahu, and Maui, but not on Hawaii Island. A guava moth caterpillar *(Anua indiscriminata* Hampson) was observed feeding on *E. saligna* foliage at Amauulu on Hawaii Island. Neither of these insects was considered a serious threat to the plantations by local entomologists. Ambrosia beetles *(Xylosandrus crassisuculus* Motschulsky) attacked fresh stumps of *Eucalyptus* on the Hamakua Coast just as coppice was beginning to form (Schubert and Markin 1987). Although probably not the primary cause of failure, the attacks seemed to lower the ability of the stumps to coppice. Accidental importation of additional diseases or insects is always a possibility, which must be guarded against by strict observance of plant quarantine regulations and close monitoring of plantations. Over time, however, adaptation of native insects and diseases to exotic plantations is a distinct possibility. The "absolute rule" of Zobel and Talbert (1984) states: "exotic plantations will be attacked by one pest or another."

Environmental Issues

Questions regarding environmental effects of land management practices are being raised with increasing frequency by various interest groups and the general public. It is therefore probable that similar questions will arise regarding short-rotation management of *Eucalyptus*. Because most *Eucalyptus* plantations will likely be established on abandoned sugarcane lands, conflicts are unlikely to be as polarized and volatile as those occurring when native forests are cut and land is converted to intensive agricultural or forestry use. Still, some concerns will surface, and those most likely to be voiced in Hawaii will probably center around soil erosion, nutrient depletion, and use of eucalypt monocultures.

At the outset, it should be recognized that the potentially negative impacts of production plantations of *Eucalyptus*, even with rotations as short as six years, will be substantially smaller in magnitude and will occur less frequently than impacts associated with most agricultural crops. The detrimental effects associated with site preparation, applications of fertilizers and herbicides, and harvesting will be considerably less than those from sugarcane production. In addition, increased establishment of forest cover has beneficial effects, including conservation and improvement of soils, increased habitat diversity for other plants and wildlife, and greater scenic variety throughout the landscape.

Soil Erosion

Site preparation and harvesting activities could increase erosion and thus adversely affect soil productivity. For this reason a cooperative study to evaluate such effects was initiated in 1981 with soil scientists in the Department of Agronomy and Soil Science at the University of Hawaii (Schultz 1988). The study was located at Amauulu on a Kaiwiki silty clay loam soil that receives more than 200 inches of rain annually. Twelve run-off plots were established—with six left bare as control plots, and six planted with *Eucalyptus* seedlings. Litter was periodically removed from half of the *Eucalyptus* plots after cover was established. The trees were cut after 6 years, and regenerated by coppice. Three post-harvest treatments were imposed: minimal disturbance, periodic litter removal, and establishment of a cover crop.

Despite the high rainfall, soil erosion was minimal (Schultz 1988). Annual pre-harvest soil loss on plots where litter was not removed was close to zero after 6 years. Soil loss from plots where the litter was removed periodically by raking was 13 times higher than that from the bare control plots. Apparently water dripping from the tree canopy is more erosive than incident rainfall. Post-harvest soil losses from plots with minimal soil disturbance or with a cover crop were less than 165 lb/acre during the 18 months after cutting. Removing the litter caused more erosion, 251 lb/acre of soil. The worst losses were from those plots that were raked clean both before and after harvest, with 510 lb/acre of soil lost during the 18-month period.

These soil losses are far below the designated maximum tolerable limit of 4.9 tons/acre/yr (Wischmeier and Smith 1978), even when the litter layer was removed under a tall canopy. Along the Hamakua Coast, the litter layer is far more important than the tree canopy in preventing soil losses. Management practices should be designed to develop and preserve this protective cover.

Nutrient Depletion

Questions are frequently asked about nutrient depletion by intensive cropping systems. All of our work has indicated that total N levels in Hamakua Coast soils are inadequate for good growth of *Eucalyptus*. Presumably the decades of intensive sugarcane cropping on the Hamakua Coast and the high temperatures and rainfall increased mineralization and leaching loss of N in the soil. Continuous cropping has also prevented the accumulation of organic matter and recharge of N reserves. There is no doubt that supplemental N will be needed for acceptable growth of *Eucalyptus* plantations established along the Hamakua Coast, and possibly also in the Ka'u District. However, this N deficiency can be overcome with applications of N fertilizer, at substantially lower rates than those used for sugarcane.

There are factors that suggest that N deficiency may be less of a problem when the trees become older, both during the initial rotation and in subsequent rotations:

• Nitrogen concentrations in soils appear related to length of time the land was devoted to cane, and to the length of the fallow period. Total soil N levels in long abandoned canelands and in forest land tend to be higher. Soil N levels after 4 years in one of our most productive *Eucalyptus* plantings were equal to or higher than those when the trees were planted, despite considerable N accumulation in the biomass (DeBell and others 1989a).

• At Chin Chuck, no fertilizer was applied to the pure *Eucalyptus* plots after age 5 years, but yields continued to increase through age 7. Other work also has indicated that *Eucalyptus* is very efficient at internal recycling of nutrients (Florence 1986).

If so, there are two nutrient-related reasons to consider rotations longer than those originally envisioned: (1) to capitalize on internal recycling, and (2) to lower nutrient drain per unit of biomass removed.

• The planting of *Albizia/Eucalyptus* mixtures provides opportunities to enhance productivity by improving N levels and other soil properties. Although our work dealt with *Albizia* mixtures, potential benefits from use of other nitrogen-fixing plants (herbs, shrubs, and trees) and other cultural systems, including crop rotation, should be evaluated.

In addition to rotation length, whole tree or stem-only removal, and use of nitrogen-fixing plants, nutrient management considerations should include protection of the litter layer during harvesting. Such protection not only preserves nutrients contained in the litter, it also reduces erosion of fertile topsoil. Finally, growth and nutrient status of trees should be monitored, and nutrients added as needed.

Monocultures

The desirability of planting large areas with monocultures of single species is often questioned, especially when clonal monocultures are involved. Concerns usually focus on increased susceptibility to insect and disease attacks, diminished habitat diversity for animals and other plants, and esthetics.

Our plantings in Hawaii to date have not encountered any insect or disease pests of consequence. Such problems could appear in the future, and may warrant attention in selecting management regimes and in tree improvement programs. Effects of *Eucalyptus* plantings on biological and visual diversity depend on the setting; in general, the plantings have added diversity to a landscape that has been dominated by another clonal monoculture, sugarcane.

A study of the ecological effects of eucalypts sponsored by the FAO (Poore and Fries 1985) concluded that plantations of these species do not appear to use significantly more water than plantations of other vigorously growing hardwood species. There was no evidence that eucalypt forests caused soil deterioration or irreversible site damage, but short-rotation plantations could lead to nutrient depletion, especially if the whole biomass is harvested. This is true of any rapidly growing, highly productive crop, and can be overcome by appropriate fertilizer treatments and by leaving the nutrient-rich organic material on the site after harvesting. The effects of eucalypts on ground vegetation depend greatly on climate, mostly because of competition for water, and ground vegetation in dry conditions may be greatly reduced. Habitat diversity is obviously less in eucalypt plantations than in native vegetation, but greater than in sugarcane plantations. Diversity can be increased to some extent by leaving patches or corridors of indigenous vegetation.

It should also be recognized that highly productive species or clonal monocultures will require less land to produce wood for current needs, such as the increasing demand for fuelwood in the tropics (Davidson 1987), and thus more land can be managed or preserved in order to provide other needs and values.

Tree Improvement

A substantial increase in biomass yields can be expected from tree improvement programs for *Eucalyptus* in Hawaii. A tree improvement strategy for this purpose has been proposed by F. Thomas Ledig, USDA Forest Service, and is outlined below.

Current Program

The immediate goal is to obtain superior *Eucalyptus grandis* and *E. saligna* seeds for planting stock utilizing the following strategies:

• Import *Eucalyptus grandis* and *E. saligna* seed from Australian provenances that performed well in field trials described by Skolmen (1986).

• Convert provenance trials to seed production areas, removing inferior provenances and poorest phenotypes within the best provenances.

• Collect seed from superior phenotypes in the project's field plantations.

• Inspect all seed, discarding approximately the smallest 20 percent, to decrease self-pollinated seed.

• Upgrade the planting stock by culling the low vigor seedlings.

Short-Term Improvement Program

Select about 120 superior trees from project plantations on the basis of volume, biomass production, including wood density, and tree stem form. About 40 selections of these should be *E. grandis* from the best performing provenances in the trials reported by Skolmen (1986). Scions of selected trees should be collected and grafted into a clone bank to ensure against loss; then selected trees will be semi-girdled to induce epicormic sprouts from their base. Sprouts will be used for rooting. As a last resort, selected trees will be felled to promote sprouting. If stumps fail to sprout, it should be possible to take cuttings off the grafts and root them because grafting rejuvenates the scion.

Scion material for rooting should be treated using techniques of Campinhos and Ikemori (1983). Successfully rooted clones will be multiplied by successive cycles of cutting and rooting until there are sufficient clones with economic rooting potential (at least 70 percent take) for testing over a range of planting sites. At the same time a cutting orchard should be established to multiply selected clones for commercial planting. After 2 years the best 10 to 20 clones should be selected for commercial plantings.

Long-Term Improvement Program

Although 10 to 20 clones may be adequate for a short-term planting program, they are insufficient for a breeding program. The genetic base must be expanded to allow greater scope in selection.

The first step in the long-term tree improvement program is to verify the results of our provenance trials to determine whether the major effort should be placed on *Eucalyptus grandis* or *E. saligna* or on both. The verification will consist of establishing outplanting trials consisting of the best *E. grandis* provenances, the best *E. saligna* provenances, the best of the Aracruz clones, and a Hawaiian seed source of *E. saligna*. These outplanting trials should cover a full range of anticipated future planting sites and should emphasize different locations.

Another collection of provenances of *Eucalyptus grandis* from Australia should be made to expand the base population for a long-term (5- to 20-year) tree improvement program. Seeds should be kept separate by mother tree to allow for establishment of combined provenance-progeny tests on anticipated planting sites in Hawaii. Selection and cloning could begin 3 years after out-planting. The larger the tests, the more gain that will be made by selection.

Selected clones and seed from selected *Eucalyptus grandis* clones should be obtained wherever possible and planting stock from these sources tested under Hawaiian site conditions.

Additional trials of *E. urophylla* should be conducted. Seeds should be acquired from the best available individuals in Timor and Flores, and in other areas where its introduction has been successful. These new test plantations would serve as a base population for future selection and hybridization.

Another *Eucalyptus* species to consider in a Hawaiian tree improvement program is *E. globulus*. This species, more adapted to drier sites than either *E. grandis* or *E. saligna*, grows rapidly, with wood characteristics very suitable for fuel or for pulpwood. It has been widely planted at 2,500- to 5,000-ft elevation in Hawaii. The Forest Service has made seed collections from superior phenotypes in 60- to 70-year-old plantations along the Hamakua Coast. Seedlings were produced and outplanted at Chin Chuck, but all grew poorly at this high-rainfall, low-elevation site. Progeny trials for *E. globulus* should be initiated on drier sites, such as Ka'u, using these seed collections, and seeds from selected trees in Florida, California, and Portugal.

Recommendations for Monitoring and Research

In short-rotation management of plantation forests, stand growth is rapid, and changes develop rapidly in nutrient status and competition for growing space. These changes can be detected by periodic measurements of d.b.h. and height in permanent sample plots. Growth rates of *Eucalyptus saligna* in Hawaii are positively correlated with foliar N, and critical levels for foliar N have been established *(table 12)*. Therefore, concurrent measurement of growth and sampling for foliar nutrient levels can help identify N deficiency and suggest its degree of severity. Abnormal concentrations of other elements can also alert the plantation manager to emerging problems. Periodic adjustments can be made in fertilization regimes based on information obtained in stand monitoring. Frequency of monitoring should be every 6 months through the first two years with another appraisal at 4 years. Size and survival estimates should be obtained from tree and plot measurements at each monitoring examination. Foliar samples should be taken routinely during the first three monitoring periods when collections are easier and nutrient concentrations are changing rapidly. Foliar N concentrations should be determined on all samples, whereas levels of other major and minor elements should be determined in subsamples. Subsequent samples should be taken at locations where tree measurements indicate marked declines in growth rate. The concentration of other nutrient elements should be determined for these samples.

The existence of monitoring trees and plots spread throughout the plantation types permits selection of matching trees and plots in small areas to compare alternative silvicultural treatments. This provides a convenient and low cost method to develop and evaluate new plantation management practices. Existence of the monitoring plot system also tends to build a data base of growth rates, foliar analyses concentrations, and results of research evaluations. This data base would be extremely useful for the continuing development of management practices.

Additional research is needed on a number of points concerning short-rotation management of eucalypts on the island of Hawaii. The most cost-effective rates and frequencies of N fertilization for planting sites with different soil N status need to be determined. Experiments to contrast good versus poor sites should be established, testing varying amounts and frequencies of fertilizer applications, including an accelerated schedule with the total amount applied within the first three years.

Tied in with fertilizer research is the question of nitrogen-fixing species useful for admixture plantings. Further work is needed on optimum mixtures and rotation length. An alternative species with fast growth, dense wood, and a single stem would be useful for Hamakua Coast conditions to replace *Albizia falcataria*. Trials of an N-fixing species with such desirable properties which will grow successfully and enhance the growth of eucalypts are also needed for the drier site conditions at Ka'u.

Continuing research on improved species and provenances in general should be an ongoing component of any large-scale plantation project.

Research should be considered on reliable methods of coppice regeneration. Coppice is an attractive method of regenerating short-rotation tree crops if low mortality and high growth rates can be obtained. Coppice rates in our harvest cuts of eucalypts have been too low and unreliable for regeneration

Table 12—*Levels of foliar nutrients in* **Eucalyptus saligna** *trees from BioEnergy's plantations with biomass yields in the upper 25 percent of all plantings, Island of Hawaii*

Nutrient	Age (months)					
	12	18	24	30	36	48
	pct					
Nitrogen (N)	(2.2)[1]	2.16	2.08	1.96	1.84	(1.8)
Phosphorus (P)	(0.2)	0.19	0.18	(0.2)	0.18	(0.2)
Potassium (K)	(1.2)	1.12	1.08	(1.2)	0.98	1.18
Calcium (Ca)	(0.6)	0.45	(0.5)	0.43	0.38	0.44
Magnesium (Mg)	(0.2)	0.25	0.24	(0.3)	0.27	(0.3)
Sulfur (S)	(0.2)	0.16	0.17	(0.2)	0.16	0.17
	ppm					
Copper (Cu)	(15)	11	11	11	8	7
Zinc (Zn)	(30)	27	27	(25)	22	25
Iron (Fe)	(100)	100	103	98	84	(95)
Manganese (Mn)	(300)	(250)	(250)	(200)	(180)	(180)

[1]Values in parentheses are less reliable than those without parenthesis and were adjusted slightly from the averages upon inspection of the plots of biomass versus nutrient concentrations.

purposes (Bowersox and others 1990). Although we have alternative regeneration methods, the low cost and fast growth of coppice may be worth the cost of research to improve the frequency and reliability of stump sprouting. However, this must be balanced against possible higher harvesting costs because of the need to avoid stump damage, and to handle the two or three smaller diameter stems that remain on coppiced stumps at harvest.

Production Economics

Costs of production are a major factor in decisions regarding investment in short-rotation *Eucalyptus* plantations and in choices among alternative management regimes. Some costs and returns, of course, are specific to the objectives and situations of individual organizations and projects, i.e., land, taxes, administration, insurance, interest rates, and product values. Other costs tend to be relatively similar to all; these include costs related to plantation establishment, maintenance, and harvesting.

We have not performed a financial analysis for inclusion in this paper. Rather we provide estimates of biomass yield and general production costs associated with three management regimes, each of which we believe has potential for use in short-rotation *Eucalyptus* plantations. Also, we provide some of the assumptions underlying the estimated costs, all of which are based on experience in this BioEnergy Development Corporation project. Prospective growers and others involved in decisions on short-rotation *Eucalyptus* plantations can use these data, making adjustments as desired to conduct economic analyses appropriate to their situation and needs.

Regimes listed in *table 13* include three of the most promising alternatives, based on current knowledge. Regime A represents the shortest rotation (5 years) in which minimum acceptable mean tree size (6 inches d.b.h.) is balanced with high productivity. Total biomass yield is estimated at 45 dry tons per acre or 9 tons per acre per year. Periodic fertilization is required on most former sugarcane land to attain this production level. Conceivably, this total yield could be attained in fewer years with genetically improved planting stock or higher fertilizer dosages.

Regime B represents a slightly longer rotation (6 years) and produces a larger average stem size (8 inches d.b.h.). Larger trees may have advantages in quality for some products and generally can be harvested and processed at lower costs. Total biomass yield is estimated at 50 dry tons per acre or 8.3 tons per acre per year. The possibilities for enhancing growth rate and achieving higher productivity with genetic improvement and increased fertilization may be better than with Regime A because growing space is considerably greater (70 percent more space per tree).

Regime C is an alternative developed from our experience with mixed *Eucalyptus-Albizia* planting on the Hamakua Coast. The planting pattern has been described previously in this paper; although the pattern has not been tested specifically, the ratio of *Eucalyptus* to *Albizia* and the density of trees per acre are identical to those in one of our experimental treatments. The main advantages of this 8-year rotation include larger tree size and reduction in costs of and dependence on synthetic nitrogen fertilizer. The biomass yield of *Eucalyptus* alone is 80 dry tons per acre or 10 tons per acre per year; even when excluding the *Albizia*, it is the most productive treatment we have observed. If harvested and utilized, *Albizia* trees might provide another 25 tons per acre, and thus increase annual productivity to 12 or more tons per acre.

Assumptions underlying estimates of production costs are listed in *table 14*. We encountered considerable variation in some of these, such as site preparation, weeding, and harvesting costs. For example, costs of plantation establishment at Ka'u are substantially higher than those on the Hamakua Coast. Tree planting alone costs twice as much in the rocky soils of Ka'u. Existing and competing vegetation also creates changes in clearing and maintenance costs at both locations.

Table 13—***Selected management regimes for short-rotation*** **Eucalyptus** ***plantations, Island of Hawaii***

Regime	Description	Rotation length	Fertilization schedule		Biomass yield: Stem	Biomass yield: Total
		yr	*mo.*	*dosage/acre*	*ton/acre*	*ton/acre*
A	Dense planting, pure *Eucalyptus*	5	0, 6	20 lb N,P,K	38	45
	Spacing: 7 ft by 10 ft (620 trees/acre)		12	30 lb N		
	Mean tree size: 6 inches d.b.h.		18, 30	100 lb N		
			42	50 lb N		
B	Wide planting, pure *Eucalyptus*	6	0, 6	13 lb N,P,K	42	50
	Spacing: 10 ft by 12 ft (360 trees/acre)		12	30 lb N		
	Mean tree size: 8 inches d.b.h.		18, 30, 42	100 lb N		
			54	50 lb N		
C	Mixed planting, *Eucalyptus/Albizia*	8	0, 6	18.5 lb N,P,K		
	Species in alternate rows (10 ft apart)					
	Eucalyptus: 10 ft within rows (218 trees/acre)				68	80
	Mean tree size: 9 inches d.b.h.					
	Albizia: 7 feet within rows (311 trees/acre)					25
	Mean tree size: 4.5 inches d.b.h.					

Harvesting costs vary with average tree size, decreasing by one-third as tree size increases from 6 inches d.b.h. to 12 inches d.b.h. Such differences in harvesting costs are taken into account in the production cost estimates given in *table 15* because they are predictable and are directly associated with the regimes. Variation in other costs, however, is not directly related to either tree size or management regimes; thus, costs are based on average values as listed in *table 14*.

Cost estimates in *table 15* indicate considerable differences among the three regimes. Total accumulated costs per dry ton of chipped *Eucalyptus* biomass at the mill range from $54 for the shortest rotation (Regime A) to $35 for the longest rotation involving *Albizia* (Regime C). If *Albizia* were utilized, total biomass produced per acre would increase by about 25 percent, but delivered cost per ton would slightly increase because harvesting cost per ton for the smaller-sized *Albizia* (4 1/2 inches d.b.h.) would be nearly 50 percent greater than the total production cost per ton incurred with utilization of *Eucalyptus* alone. The costs and returns in the three regimes occur at different times; thus, a financial analysis is needed to compare their relative profitability.

Table 14—*Assumptions underlying cost estimates for short-rotation* Eucalyptus *plantations, Island of Hawaii*

Task	Cost (in 1990 $)
- Land clearing	2 hr/acre at $75/hr (range: 0.3 to 3.0 hr)
- Herbicide application (applied before planting)	0.2 hr/acre at $40/hr (tractor) (plus $70/acre for chemicals)
- Planting stock	$0.05/tree
- Hand planting	$0.13/tree on Hamakua coast $0.26/tree on Ka`u District
- Replanting	5 pct of original planting cost
- Herbicide application (applied after planting)	
2-3 month period	6 hr/acre at $8.33/hr (hand labor) (plus $70/acre for chemicals)
5-6 month period	4 hr/acre at $8.33/hr (hand labor) (plus $32/acre for chemicals)
- Mowing between rows (10-ft spacing)	$19/acre (once at 6 mo. or twice at 3 and 6 mo.)
- Fertilizer application (N-P-K[1] applied by hand)	1.2 hr/acre at $8.33 hr (plus $0.04/tree for fertilizer)
- Subsequent fertilization (applied by aircraft)	$10/acre + $0.31/lb N (or $0.14/lb urea)
- Harvesting operations	
Felling and skidding	$22/dry ton (stands averaging 6 in. d.b.h.) $16/dry ton (stands averaging 8 in. d.b.h.) $15/dry ton (stands averaging 9 in. d.b.h.)
Chipping	$10/dry ton (stands averaging 6 in. d.b.h.) $ 9/dry ton (stands averaging 8 in. d.b.h.) $ 8/dry ton (stands averaging 9 in. d.b.h.)
Hauling	$0.24/dry ton/round trip mile.

[1]N - nitrogen, P - phosphorus, K - potassium

Table 15—*Production costs associated with selected management regimes for short-rotation* Eucalyptus *plantations, Island of Hawaii*

Task	Regime A	Regime B	Regime C
	Cost (in 1990 $)		
Establishment (per acre)			
Land clearing	150	150	150
Herbicide application	78	78	78
Planting stock	31	18	26
Hand planting	81	47	69
Replanting	6	3	5
Maintenance (per acre)			
Herbicide application	186	186	186
Mowing	19	38	19
Fertilizer application	201	224	65
Establishment and maintenance costs (per acre)	752	744	598
Harvesting (per dry ton)			
Felling and skidding	22	16	15
Chipping	10	9	8
Hauling	5	5	5
Harvesting cost (per dry ton)	37	30	28
Establishment and maintenance costs (per dry ton)[1]	17	15	7
Total cost (per dry ton)	54	45	35

[1]Assuming a yield/acre of 45-, 50-, and 80-dry ton/acre for regime A, B, and C, respectively (from *table 13*).

References

Bowersox, Todd W.; Schubert, Thomas H.; Strand, Robert F.; Whitesell, Craig D. 1990. **Coppicing success of young *Eucalyptus saligna* in Hawaii.** Biomass 23: 137-148.

Brandao, Leopoldo G.; Ikemori, Yara K.; Campinhos, Edgard. 1984. **The new eucalypt forest.** Falun, Sweden: Marcus Wallenberg Foundation Symposium Proceedings, Falun, Sweden; 1984 September 14; 29 p. plus tables and illustrations.

Campinhos, Edgard; Ikemori, Yara K. 1983. **Production of vegetative propagules of *Eucalyptus* spp. by rooting of cuttings.** In: Proceedings of the 2nd symposium on planted forests in the neotropics: a source of energy. IUFRO Working Party S1.07-09, Vicosa, Brazil; 1983 February 6-13; 60-67.

Carlson, Norman K.; Bryan, L.W. 1959. **Hawaiian timber for the coming generations.** Honolulu, HI: Trustees of the Bernice P. Bishop Estate; 112 p.

Crabb, Thomas B.; Schubert, Thomas H. 1989. **Economics of *Eucalyptus* plantations for biomass in Hawaii.** In: Proceedings, 3rd Pacific Basin biofuels workshop, Waianae, HI; 1989 March 27-28; University of Hawaii at Manoa: Hawaii Natural Energy Institute; 113-123.

Cromer, R.N. 1971. **Fertilizer trials in young plantations of eucalypts.** Australian Forest Research 5(2): 1-10.

Davidson, J. 1987. **Bioenergy tree plantations in the tropics: ecological implications and impacts.** Commission on Ecology Papers No. 9. Gland, Switzerland: International Union for the Conservation of Nature and Natural Resources; 47 p.

DeBell, Dean S.; Harms, William R.; Whitesell, Craig D. 1989b. **Stockability: A major factor in productivity differences between *Pinus taeda* plantations in Hawaii and the Southeastern United States.** Forest Science 35(3): 708-719.

DeBell, Dean S.; Whitesell, Craig D. 1988. **Diameter-density relationships provide tentative spacing guidelines of *Eucalyptus saligna* in Hawaii.** Res. Paper PSW-397. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 3 p.

DeBell, Dean S.; Whitesell, Craig D.; Crabb, Thomas B. 1987. **Benefits of *Eucalyptus-Albizia* mixtures vary by site on Hawaii Island.** Res. Paper PSW-187. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; Revised 1988; 6 p.

DeBell, Dean S.; Whitesell, Craig D.; Schubert, Thomas H. 1985. **Mixed plantations of *Eucalyptus* and leguminous trees enhance biomass production.** Res. Paper PSW-175. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 6 p.

DeBell, Dean S.; Whitesell, Craig D.; Schubert, Thomas H. 1989a. **Using N_2-fixing *Albizia* to increase growth of *Eucalyptus* plantations in Hawaii.** Forest Science 35(1): 64-75.

Dunkin, Kris. 1989. **Nitrogen-fixing albizia increases nitrogen cycling in eucalyptus plantations.** Fort Collins: Department of Forest and Wood Science, Colorado State University; 26 p. Thesis.

FAO. 1979. **Eucalypts for planting.** Forestry Series No. 11. Rome, Italy: Food and Agriculture Organization of the United Nations; 677 p.

Florence, R.G. 1986. **Cultural problems of *Eucalyptus* as exotics.** Commonwealth Forestry Review 65(2): 141-165.

Geary, T.F.; Meskimen, G.F.; Franklin, E.C. 1983. **Growing eucalypts in Florida for industrial wood production.** Gen. Tech. Rep. SE-23. Asheville, NC: Southeastern Forest Experiment Station, Forest Service, U.S. Department of Agriculture; 43 p.

Hawaii State Department of Land and Natural Resources. 1981. **Prime forest lands inventory.** Honolulu: State of Hawaii Department of Land and Natural Resources, Division of Forestry and Wildlife. Prepared for Big Island Resource Conservation & Development Council; 13 p.

Hillis, W.E.; Brown, A.G., eds. 1978. **Eucalypts for wood production.** Canberra: Australia: Commonwealth Scientific and Industrial Research Organization; 434 p.

Hodges, C.S.; Geary, T.F.; Cordell, C.E. 1979. **The occurrence of *Diaporthe cubensis* on *Eucalyptus* in Florida, Hawaii, and Puerto Rico.** Plant Disease Reporter 63(3): 216-220.

Kluender, Richard A. 1980. **Whole tree chipping for fuel: The range of diameter limits.** Tech. Paper 80-A-19. Washington, DC: American Pulpwood Association; 6 p.

LeBarron, Russell K. 1962. **Eucalypts in Hawaii: A survey of practices and research programs.** Misc. Paper No. 64. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 24 p.

Le Tacon, Francois; Garbaye, Jean; Carr, Geoff. 1988. **The use of mycorrhizas in tropical forests.** In: Ng, F.S.P., ed. Trees and mycorrhiza. Proc. of the Asian Seminar, Kuala Lumpur, Malaysia, 1987 April 14-17. Kuala Lumpur, Malaysia: Forest Research Institute Malaysia; 15-32.

McIntyre, D.K.; Pryor, L.D. 1974. **Response of flooded gum in plantations to fertilizers.** Australian Forestry 37(1): 15-23.

Metcalf, Melvin E.; Nelson, Robert E.; Petteys, Edwin Q.P.; Berger, John M. 1978. **Hawaii's timber resources, 1970.** Resour. Bull. PSW-15. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 20 p.

Pickford, G.D.; LeBarron, R.K. 1960. **A study of forest plantations for timber production on the island of Hawaii.** Tech. Paper No. 52. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 17 p.

Poore, M.E.D.; Fries, C. 1985. **The ecological effects of eucalyptus.** FAO Forestry Paper 59. Rome, Italy: Food and Agriculture Organization of the United Nations; 87 p.

Sato, Harry H.; Ikeda, Warren; Paeth, Robert; Smythe, Richard; Takehiro, Minoru, Jr. 1973. **Soil survey of the island of Hawaii, State of Hawaii.** Washington, DC: Soil Conservation Service, U.S. Department of Agriculture; 115 p.

Schmidt, F.L.; DeBell, D.S. 1973. **Wood production and kraft pulping of short-rotation hardwoods in the Pacific Northwest.** In: IUFRO biomass studies, International Union of Forest Research Organizations, S4.01 Mensuration, growth, and yield, Working party on the mensuration of the forest biomass. Orono: College of Life Sciences and Agriculture, Univ. of Maine; 507-516.

Schubert, Thomas H.; Markin, George P. 1987. **Control of ambrosia beetle in *Eucalyptus* stumps, 1984.** Insecticide and Acaricide Tests 12: 351-352.

Schubert, Thomas H.; Strand, Robert F.; Cole, Thomas G.; McDuffie, Katharine E. 1988. **Equations for predicting biomass of six introduced tree species, island of Hawaii.** Res. Note PSW-401. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 6 p.

Schubert, Thomas H.; Whitesell, Craig D. 1985. **Species trials for biomass plantations in Hawaii: a first appraisal.** Res. Paper PSW-176. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 13 p.

Schubert, Thomas H.; Winsauer, Sharon A.; Crabb, Thomas B. 1992. **Biomass harvesting on the island of Hawaii.** Unpublished draft supplied by author.

Schultz, Janet M. 1988. **Erosional relations in a short-rotation *Eucalyptus* plantation on a Typic Hydrandept.** Department of Agronomy and Soil Science, College of Tropical Agriculture and Human Resources, Univ. of Hawaii at Manoa; 205 p. Thesis.

Skolmen, Roger G. 1963. **Plantings on the forest reserves of Hawaii: 1910-1960.** In-house publication: Institute of Pacific Islands Forestry, Honolulu, HI: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 441 p.

Skolmen, Roger G. 1986. **Performance of Australian provenances of *Eucalyptus grandis* and *Eucalyptus saligna* in Hawaii.** Res. Paper PSW-181. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 8 p.

Skolmen, R.G.; King, T.D.; Horiuchi, H.H. 1982. **Nursery: establishment and operation.** In: Hydropyrolysis of biomass to produce liquid hydrocarbon fuels. Honolulu: Hawaii Natural Energy Institute, University of Hawaii; 53-61.

Strand, Robert F.; Cole, Thomas G. 1992. **A preliminary assessment of site, soil, and vegetation factors in relation to productivity of young *Eucalyptus* plantations on the Hamakua coast of the island of Hawaii.** Unpublished draft supplied by author.

Strand, Robert F.; Schubert, Thomas H.; Cole, Thomas G.; Whitesell, Craig D. 1992. **Response to fertilization of short rotation *Eucalyptus* plantations on the Hamakua coast, island of Hawaii.** Unpublished draft supplied by author.

Szego, George C.; Kemp, Clinton C. 1973. **Energy forests and fuel plantations.** Chemtech 3(5): 275-284.

Walters, Gerald A. 1980. **Saligna eucalyptus growth in a 15-year-old spacing study in Hawaii.** Res. Paper PSW-151. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 6 p.

Walters, Gerald A. 1981. **Why Hawaii is changing to the dibble-tube system of reforestation.** Journal of Forestry 79(11): 743-745.

Walters, Gerald A. 1983. **Propagation and planting of containerized *Eucalyptus* seedlings in Hawaii.** In: Proceedings, Workshop on *Eucalyptus* in California. Gen. Tech. Rep. PSW-69. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 98-101.

Whitesell, Craig D.; DeBell, Dean S.; Schubert, Thomas H. 1987. **Six-year growth of *Eucalyptus saligna* plantings as affected by nitrogen and phosphorus fertilizer.** Res. Paper PSW-188. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; Rev. 1988; 5 p.

Whitesell, Craig D.; Miyasaka, Susan C.; Strand, Robert F.; Schubert, Thomas H.; McDuffie, Katherine E. 1988. **Equations for predicting biomass in 2- to 6-year-old *Eucalyptus saligna* in Hawaii.** Res. Note PSW-402, Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 5 p.

Whitesell, Craig D.; Strand, Robert F.; Schubert, Thomas H. (1992a). **Species for biomass production in Hawaii.** Unpublished draft supplied by author.

Whitesell, Craig D.; Strand, Robert F.; Cole, Thomas G. (1992b). **Comparison of three eucalypts for biomass production in Hawaii.** Unpublished draft supplied by author.

Wischmeier, Walter H.; Smith, Dwight D. 1978. **Predicting rainfall-erosion losses: A guide to conservation planning.** Agric. Handbook No. 537. Washington, DC: Soil Conservation Service, U.S. Department of Agriculture; 58 p.

Yost, R.S.; DeBell, D.S.; Whitesell, C.D.; Miyasaka, S.C. 1987. **Early growth and nutrient status of *Eucalyptus saligna* as affected by nitrogen and phosphorus fertilization.** Australian Journal of Forest Research 17: 203-214.

Yost, R.S.; Fox, R.L. 1981. **Partitioning variation in soil chemical properties of some Andepts using soil taxonomy.** Soil Society America Journal 45: 373-377.

Zobel, Bruce; Talbert, John. 1984. **Applied forest tree improvement.** New York: John Wiley and Sons; 505 p.

Conversions (English to Metric)

Length

-inches to millimeters	English × 25.40
-inches to centimeters	English × 2.540
-feet to meters	English × 0.305
-miles to kilometers	English × 1.609

Area

-square inches to square centimeters	English × 6.452
-square feet to square meters	English × 0.093
-acres to hectares	English × 0.405

Weight

-ounces to grams	English × 28.350
-pounds to kilograms	English × 0.454
-tons to tonnes	English × 0.907

Weight as applied to area

-pounds/acre to kilograms/hectare	English × 1.121
-ton/acre to tonne/hectare	English × 2.242

Volume

-cubic inches to cubic centimeters	English × 16.387
-gallons to liters	English × 3.785