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GENETIC IMPROVEMENT OF *EUCALYPTUS* IN HAWAII

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PHILLIPS, V.D. & ARADHYA, K.M. 1995. Genetic improvement of *Eucalyptus* in Hawaii. The genetic improvement of *Eucalyptus* in Hawaii is largely at the preliminary stage. The evaluation of the performance of various tropical hardwood species, provenances, and progenies in field trials at environmentally diverse sites in Hawaii is in progress. Assessment of the genetic variability within some of the existing germplasm has been completed. This paper describes the initial *Eucalyptus* breeding efforts underway in Hawaii and a recommended strategy for an appropriate long-term tree improvement programme. For the short-term, the establishment of seed production areas from provenance trials is featured as the most cost-effective and time-efficient strategy for achieving tree improvement goals in Hawaii. For long-term sustainable tree production, seed orchards are recommended. To complement the seed orchard strategy, operational clones may be developed through rigorous field testing of selected plus-tree clones in targeted plantation areas to exploit both additive and non-additive genetic potential.

Key words: Tree improvement - short-rotation forestry - seed orchards - *Eucalyptus*- Hawaii.

PHILLIPS, V.D. & ARADHYA, K.M. 1995. Pembaikan genetik bagi *Eucalyptus* di Hawaii. Pembaikan genetik bagi *Eucalyptus* di Hawaii secara besar-besaran di tahap awal. Penilaian sedang dijalankan ke atas performans berbagai jenis spesies kayu keras tropika, provenans dan progeni di ladang-ladang percubaan di tapak pelbagai persekitaran di Hawaii. Taksiran ke atas pembolehubahan genetik di dalam beberapa germplasma telah disiapkan. Kertas ini menerangkan mengenai keupayaan pembiak bakaan awal sedang dijalankan di Hawaii dan strategi yang disyorkan untuk program yang sesuai bagi pembaikan pokok-pokok dalam jangka panjang. Bagi jangka pendek, penubuhan kawasan pengeluaran biji benih daripada percubaan provenans didapati sebagai strategi terbaik dari segi keberkesanan kos dan kecekapan masa untuk mencapai matlamat pembaikan pokok di Hawai. Bagi pengeluaran pokok-pokok kekal jangka panjang, kebun biji benih adalah disyorkan. Bagi melengkapi strategi kebun biji benih, klon-klon perlulah dibesarkan melalui ujian ladang yang ketat melalui pemilihan klon-klon pokok terbaik dari kawasan perladangan yang dikehendaki bagi mengeksploit kedua-dua potensi genetik penambah dan bukan penambah.

Introduction

As the sugarcane and pineapple industries continue to decline in Hawaii, as much as 100 000 hectares of prime agricultural land may become available for alternative land uses, including short-rotation intensive-culture (SRIC) production of tropical hardwoods. SRIC forestry is being considered for the production of utility lumber, woodworking craftwood, laminated wood products, fibreboard, and wood chips for biofuel production or paper manufacture in domestic and export markets (Phillips *et al.* 1995). Because native tree species in Hawaii such as *Metrosideros polymorpha* and *Acacia koa* are unsuitable for SRIC forestry, attention was focused on exotic, fast-growing tropical hardwoods including *Eucalyptus* and *Acacia* spp. from Australia and elsewhere. Much of the current research and development is aimed at identifying the most appropriate tropical hardwood species and provenances for SRIC production. Early field trials in Hawaii demonstrated that *Eucalyptus* spp. are leading candidates for commercial plantations. Also, the interplanting of eucalypts with nitrogen-fixing tree species to provide biological nitrogen appears to be a suitable, cost-effective, and sustainable strategy for achieving targeted SRIC productivity (Whitesell *et al.* 1992). For establishing a sustainable forestry industry in Hawaii, a comprehensive tree improvement programme is needed to maximize genetic gains and economic return in the short term and to provide for continued improvement in the long term, while maintaining a broad base for genetic conservation.

The scope and strategy of such a programme for fast-growing, tropical, exotic hardwoods are presented here. The programme envisaged complements and extends an existing *Eucalyptus* improvement effort initiated by the BioEnergy Development Corporation (BDC), Hilo, Hawaii, and the U.S. Forest Service Institute of Pacific Islands Forestry (IPIF), Honolulu, Hawaii. The BDC/IPIF programme was designed to introduce and evaluate a wide range of germplasm of *Eucalyptus* from Australia and other tropical and subtropical regions, and includes the following elements: (1) introduction and identification of suitable species and provenances for the diverse sites; (2) selection in existing plantations and clonal propagation of superior trees; and (3) expansion of the genetic base to conserve genetic diversity and flexibility to respond to unforeseen changes in environment, technologies, and market needs (Namkoong 1984).

The third element calls for introduction and testing of previously untested species and several other provenances of *E. grandis* and *E. saligna* already identified for a range of potential plantation sites. Introduction and testing of selected material, including *E. urophylla*, some *E. grandis* x *E. urophylla* hybrids and other hybrids from international breeding programmes such as Aracruz Florestal, Ltd. in Brazil and Pointe Noire in the Congo, were also recommended. However, this last element of the existing tree improvement programme has not been implemented fully as it focuses more on the long-term breeding needs of the project.

Selection of species and provenances

On the Hilo/Hamakua coast of the island of Hawaii, as much as 60 000 hectares of former sugarcane land are available for other land uses including commercial forestry. All of the SRIC field trials established by BDC are located along the Hilo/Hamakua coast in windward, northeastern Hawaii and in southern Hawaii's Ka'u district at elevations ranging from 300 to 600 meters (Figure 1). The Hilo/Hamakua coast receives about 5000 to 6000 mm of precipitation annually and the soils are highly weathered silty clay loams developed from the volcanic ash

(Hydrandepts). In contrast, Ka'u receives more sunlight, with more variable rainfall, ranging from about 1000 to 2500 mm annually. The Ka'u soils are classified as Tropofolists, which have low nutrient-retention capacity (Sato *et al.* 1973), but are rich in total mineral nutrients due to relatively younger soils (Whitesell *et al.* 1992).

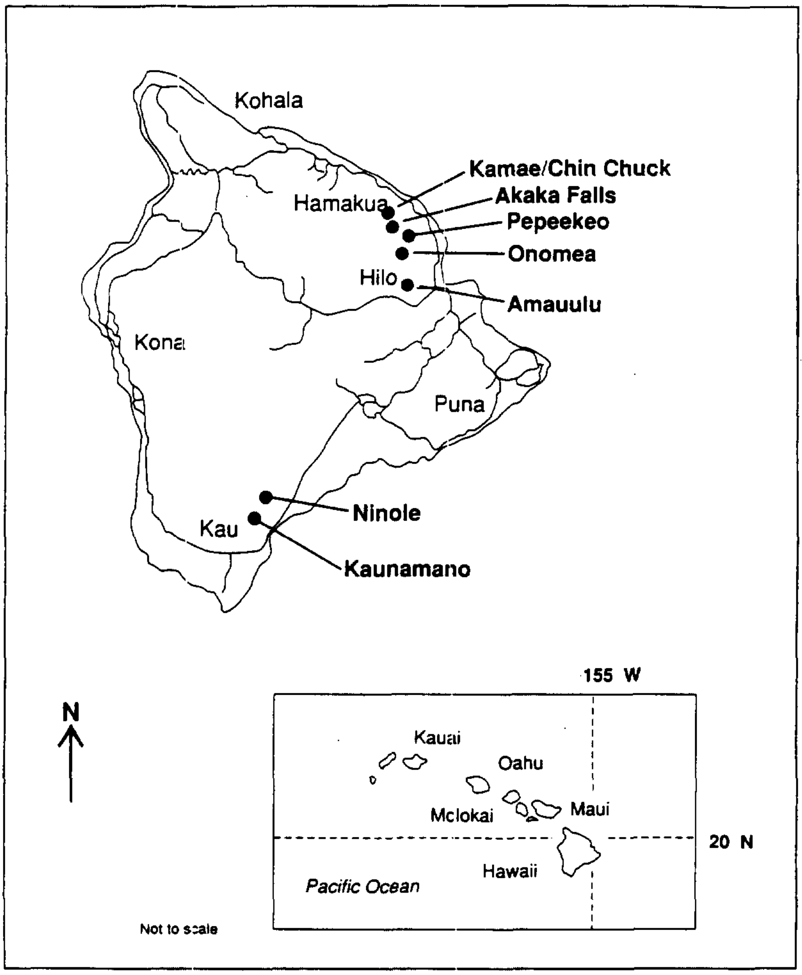

Figure 1. BioEnergy Development Corporation's *Eucalyptus* planting sites on the island of Hawaii (Source: Whitesell *et al.* 1992)

Identification and selection of fast-growing, high-yielding species suited to Hawaii's diverse geological and climatic conditions are the primary challenge to the tree improvement programme in the state. Some plantings of eucalypts, consisting mainly of *E. robusta*, *E. globulus* and other introduced species, began as early as the 1870s in Hawaii primarily to protect denuded watersheds and to provide fuel for sugarcane plantations (LeBarron 1962, Metcalf *et al.* 1978). Some of the later plantings with *E. saligna* completed between 1932 and 1960 have given impressive results (Pickford & LeBarron 1960, Walters 1980).

In 1978, BDC and IPIF launched a joint collaborative research project to systematically evaluate tropical hardwood species, primarily *Eucalyptus*, for their potential as energy crops. The funding for this project was provided largely by the U.S. Department of Energy, administered through the Oak Ridge National Laboratory's Short-Rotation Woody Crops Program. Over 250 hectares of experimental plantations containing both short- and long-term studies were established on the island of Hawaii (Schubert & Whitesell 1985, Whitesell *et al.* 1992). The above studies have resulted in the identification of species suited to some of the targeted plantation sites on the island of Hawaii (Tables 1, 2, and 3). *Eucalyptus saligna* and *E. grandis* have exhibited a wide range of adaptability and have performed better than other species of eucalypts and leguminous trees in the project.

Thirty-seven provenances of *E. grandis*, 25 provenances of *E. saligna*, 17 provenances of *E. robusta*, 6 provenances of *E. urophylla*, 8 provenances of *E. camaldulensis*, and several superior tree progenies of *E. globulus* selected from earlier introductions were tested along the Hilo/Hamakua coast and in the Ka'u district on the island of Hawaii (BioEnergy Development Corporation 1984). Mean volume growth rates of some selected provenances of *E. grandis* and *E. saligna* tested are presented in Tables 4 and 5. Several superior seed sources of *E. grandis* and *E. saligna* have been identified from provenance trials on the island of Hawaii (Table 6). In the Hilo/Hamakua coast trials, the growth rates among *E. grandis* provenances at 4.5 y after planting varied from 11 m^3 ha^{-1} y^1 to 32 m^3 ha^{-1} y^1, with an overall mean of 20 m^3 ha^{-1} y^1. For *E. saligna* provenances in the Hilo/Hamakua coast sites, growth rates ranged from 8 to 22 m^3 ha^{-1} y^1, with an overall mean of 13 m^3 ha^{-1} y^{-1} along the Hilo/Hamakua coast. In general, both species grew more rapidly in Ka'u than on the Hilo/Hamakua coast, and average volume growth rates in Ka'u were more than twice of those at the other sites. In Ka'u, growth rates among *E. grandis* provenances at 4.5 years after planting varied from 37 to 82 m^3 ha^{-1} y^{-1}, with an overall mean of 56 m^3 ha^{-1} y^1. For *E. saligna* provenances in Ka'u, growth rates ranged from 27 to 47 m^3 ha^{-1} y^1, with an overall mean of 36 m^3 ha^{-1} y^1. On the average, *E. grandis* performed better than *E. saligna* in both locations. Two possible explanations for higher volume growth rates at Ka'u are the greater abundance of sunlight and the higher total mineral nutrient level of the younger volcanic soils.

Other species of *Eucalyptus* have been identified for specific environments in Hawaii by BDC/IPIF, such as *E. robusta* for poorly-drained, high-rainfall areas and *E. globulus* for high-elevation, drier sites. The wide ranges of variation in topography, rainfall, temperature, and edaphic factors in Hawaii provide significant opportunity for successful introduction of many more new species and provenances. Species introduction and matching with sites should continue as and when new areas become available for plantations. Recently, several Australian *Acacia* spp., such as *A. mangium*, *A. auriculiformis*, *A. crassicarpa*, and *A. cincinnata*, have been identified as promising. However, further testing of species and provenances under diverse environments is required before drawing any conclusions.

Table 1. Relative growth performance of various hardwoods in species trials on the island of Hawaii

Satisfactory growth[1]				
Hilo/Hamakua Coast			Ka'u District	
Kamae (trial 1) *Acacia mangium* *Eucalyptus urophylla* *E.grandis*	Amauulu *E.saligna* *E.robusta*	Kamae (trial 5) *E.saligna* *E.urophylla*	Ninole (Alapai) *E. saligna* *A.mangium*	Kaunamano *E.saligna* *E.grandis* *E.urophylla* *E.robusta*
Kamae (trial 2) *E.saligna* *Albizia falcataria* *E.robusta*	Pepeekeo *E.grandis* *E.urophylla* *E.saligna*		Ninole(Kiloa) *E.saligna*	
Kamae (trial 3) *E.saligna* *E.robusta* *A.falcataria*	Onomea *E.saligna* *E.urophylla* *A.falcataria* *E.robusta* *E.grandis*			
Unsatisfactory growth				
Hilo/Hamakua Coast			Ka'u District	
E.alba *E.botryoides* *E.camaldulensis* *E.citriodora* *E. dunnii* *E.globulus* *E.maidenii* *E.microcorys* *E.nitens* *E.tereticornis* *E.viminalis*	*Acacia koa* *Acacia melanoxylon* *Casuarina equisetifolia* *Copaifera langsdorfii* *Gmelina arborea* *Leucaena leucocephala* *Lippia toressi* *Mimosa scabrella* *Pinus elliottii* *Sesbania grandiflora* *Sesbania sesban*		*E.camaldulensis* *E.citriodora* *E.globulus* *E.nitens* *E.tereticornis* *E.viminalis*	*A. auriculiformis* *Acacia confusa* *Mimosa scabrella*

[1]Satisfactory growth: mean annual growth increment > 1.0 m height & 1.25 cm diameter, and survival > 75%.
Source: After Whitesell *et al.* (1992).

A recommended tree improvement programme

Unlike genetic improvement of annual crops, the impacts of tree breeding programmes are long-lasting and are not easily correctable. Therefore, objectives and methods to achieve those objectives should be clearly established at the outset. In general, the improvement programme should aim at achieving sustainability while maintaining high productivity. The importance of selection and breeding for improvement of qualitative and quantitative performance of trees is well known (Zobel & Talbert 1984, Eldridge *et al.* 1993). Breeding strategies differ considerably with the aims and objectives of the tree improvement programme.

Table 2. *Eucalyptus* species performance along the Hilo/Hamakua coast, Hawaii

Species	Onomea (5.0 y) ht	Onomea (5.0 y) dbh	Kamae (trial 1) (4.5 y) ht	Kamae (trial 1) (4.5 y) dbh	Kamae (trial 3) (3.0 y) ht	Kamae (trial 3) (3.0 y) dbh	Amauulu (3.0 y) ht	Amauulu (3.0 y) dbh	Chin Chuk (2.0 y) ht	Chin Chuk (2.0 y) dbh
E. saligna	13.9	10.0	9.5	7.6	15.9	9.7	10.8	10.2	5.4	4.7
E. grandis	12.6	9.0	12.0	8.1	11.7	7.0				
E. urophylla	12.5	9.6	12.2	7.8					5.0	4.7
E. robusta	12.7	9.1	10.8	7.6	12.5	9.1	9.2	10.2		
E. globulus	12.0	7.0			12.3	8.0				
E. dunnii	8.8	6.8	8.2	5.5						
E. camaldulensis	8.7	4.9							5.0	3.8
E. microcorys			8.1	4.8						
E. botryoides			8.0	6.6						
E. nitens			6.2	5.2						
E. maidenii			8.6	6.0						
E. viminalis			8.9	6.5						

Note: ht = height (m); dbh = diameter at breast height (cm)
Source: Schubert & Whitesell (1985).

Table 3. *Eucalyptus* species performance in the Ka'u district, Hawaii

Species	Ninole-Kiloa soil (4.5 y) ht	Ninole-Kiloa soil (4.5 y) dbh	Ninole-Alapai soil (4.5 y) ht	Ninole-Alapai soil (4.5 y) dbh	Kaunamano (2.0 y) ht	Kaunamano (2.0 y) dbh
E. saligna	10.9	7.4	9.9	6.6	8.1	6.7
E. grandis					7.8	6.7
E. urophylla					6.4	5.6
E. robusta					5.4	5.1
E. globulus					7.3	6.3
E. camaldulensis					5.1	3.8
E. microcorys	11.0	7.2	10.1	6.1		
E. botryoides	10.5	7.6	8.9	5.6		
E. nitens					7.1	7.0
E. viminalis					6.6	5.7
E. tereticornis					5.6	4.5
E. citriodora	10.0	7.1	9.3	6.1	4.6	3.7

Note: ht = height (m); dbh = diameter at breast height (cm).
Source: Schubert & Whitesell (1985).

It is recognized that trees for SRIC should meet special requirements that are somewhat different from those applicable to tree management under longer rotations. Some of the generally desirable properties of SRIC trees are high growth rate, moderate to high density wood, high coppicing ability, amenability for vegetative propagation, low mortality rate, and high resistance to pests and diseases. Failure to coppice or non-uniform coppicing greatly reduces the yield and value of the tree crop. It is not profitable if replanting is required for each rotation (Standiford & Ledig 1983, Hummel 1988). However, most species exhibit wide variation for this trait and will therefore respond to selection to improve sprouting ability (Ledig 1989). If trees are grown for fibre, wood density is important because pulp yield and many industrial requirements relate to this intrinsic property. At age 5 y, significant variation in specific gravity of wood at the 3 to 7 m height was observed among provenances grown at Upper Ninole in Hawaii (Table 7). In plantations in Hawaii, the mean specific gravity of *E. saligna* is significantly higher than that of *E. grandis*.

Table 4. Performance of different seed sources of *Eucalyptus grandis* and *E.saligna* at 4.5 y after planting along the Hilo/Hamakua coast and in the Ka'u district, Hawaii

Akaka (Hilo/Hamakua)			Upper Ninole (Ka'u)		
Provenance ID No.	Species	Vol. growth* ($m^3 ha^{-1} y^{-1}$)	Provenance ID No.	Species	Vol. growth* ($m^3 ha^{-1} y^{-1}$)
7810	*E.grandis*	32.0a	12409	*E.grandis*	81.7a
12409	*E.grandis*	26.7ab	12423	*E.grandis*	74.9ab
10774	*E.grandis*	25.8ab	11035	*E.grandis*	63.2abc
12461	*E.grandis*	22.2abc	12422	*E.grandis*	55.6abcd
11756	*E.saligna*	21.5abc	7810	*E.grandis*	54.5abcd
7823	*E.grandis*	21.3abc	12381	*E.grandis*	53.7abcd
11243	*E.grandis*	19.8abc	10774	*E.grandis*	49.7abcd
12423	*E.grandis*	19.0abc	12461	*E.grandis*	49.7abcd
11025	*E.saligna*	18.5abc	7823	*E.grandis*	48.6abcd
12064	*E.saligna*	15.6abc	11243	*E.grandis*	47.4bcd
12381	*E.grandis*	15.6abc	12145	*E.saligna*	47.0bcd
12422	*E.grandis*	15.0abc	11756	*E.saligna*	44.1bcd
11605	*E.saligna*	13.5bc	11605	*E.saligna*	42.4bcd
7808	*E.saligna*	13.1bc	11025	*E.saligna*	39.7cd
7786	*E.saligna*	13.0bc	12143	*E.grandis*	37.0cd
12143	*E.grandis*	12.6bc	11894	*E.saligna*	35.7cd
305	*E.saligna*	11.9bc	12064	*E.saligna*	34.5cd
11035	*E.grandis*	11.3bc	7808	*E.saligna*	34.0cd
10225	*E.saligna*	10.9bc	7786	*E.saligna*	33.8cd
12145	*E.saligna*	10.9bc	10225	*E.saligna*	29.9cd
11894	*E.saligna*	10.4bc	305	*E.saligna*	27.6d
10733	*E.saligna*	7.5c	10733	*E.saligna*	26.9d
Mean	*E.grandis*	20.1			56.0
Range		11.3 - 32.0			37.0 - 81.7
Mean	*E.saligna*	13.3			36.0
Range		7.5 - 21.5			26.9 - 47.0

*Means in column with the same letter(s) are not significantly different.
Source: Skolmen (1986).

Tree breeders evaluate the genetic resource available for improvement, and select the genes of greatest utility and economic importance and package these in genotypes that can be used to establish commercial plantations (Libby 1973). Tree breeders also identify superior genotypes in existing provenances and propagate them clonally to tap both additive and non-additive genetic effects governing commercial traits. The important steps involved in a comprehensive tree improvement programme are outlined in Table 8. Depending on the breeding objectives and availability of resources and time, tree breeders may pick and choose the appropriate steps to achieve specific goals. The following major approaches are included in an envisaged long-term tree improvement programme for Hawaii.

Table 5. Performance of different seed sources of *Eucalyptus grandis* and *E. saligna* at 2.5 y after planting along the Hilo/Hamakua coast and in the Ka'u district, Hawaii

Kamae (Hilo/Hamakua)			Lower Ninole (Ka'u)		
Provenance ID No.	Species	Vol. growth* ($m^3 ha^{-1} y^{-1}$)	Provenance ID No.	Species	Vol. growth* ($m^3 ha^{-1} y^{-1}$)
7810	*E.grandis*	30.7a	10774	*E.grandis*	37.1a
7823	*E.grandis*	25.5ab	7823	*E.grandis*	33.8ab
10774	*E.grandis*	23.9ab	12422	*E.grandis*	27.8abc
12409	*E.grandis*	21.1abcd	12409	*E.grandis*	27.6abcd
11025	*E.saligna*	18.7abcde	11025	*E.saligna*	27.6abcd
12422	*E.grandis*	18.2abcde	7810	*E.grandis*	26.9abcd
11035	*E.grandis*	17.1abcde	12381	*E.grandis*	26.9abcd
12381	*E.grandis*	15.2abcde	12423	*E.grandis*	25.3abcd
12145	*E.saligna*	15.1abcde	11243	*E.grandis*	23.7abcd
12064	*E.saligna*	14.8abcde	11035	*E.grandis*	23.2abcd
11894	*E.saligna*	14.6abcde	7808	*E.saligna*	21.1abcd
12422	*E.grandis*	14.1bcde	12143	*E.grandis*	18.5bcd
7786	*E.saligna*	11.7bcde	11756	*E.saligna*	18.4bcd
11243	*E.grandis*	11.0bcde	11894	*E.saligna*	17.6bcd
7808	*E.saligna*	10.7bcde	11605	*E.saligna*	17.3bcd
11605	*E.saligna*	9.0cde	7786	*E.saligna*	16.5cd
12143	*E.grandis*	9.0cde	12064	*E.saligna*	14.6d
10225	*E.saligna*	8.6de	10225	*E.saligna*	14.2d
10733	*E.saligna*	4.5e	12145	*E.saligna*	13.7d
			10733	*E.saligna*	12.3d
Mean	*E.grandis*	18.6			27.6
range		9.0 - 30.7			18.5 - 37.1
Mean	*E.saligna*	12.0			17.3
range		4.5 - 18.7			12.3 - 27.6

*Means in column with the same letter(s) are not significantly different.
Source: Skolmen (1986).

Enhancement of genetic base through further introduction of species and provenances, and matching them with potential planting sites

The major constraints in dealing with exotics are the narrow genetic base that is available for genetic manipulation and the lack of adaptation resulting in substandard performance of newly introduced provenances. Success in using exotic germplasm depends largely on breadth of adaptive gene pools that is available for genetic improvement. Significant genetic gains can be achieved through careful selection of species, provenances, and trees within provenances. Introduced provenances consisting of 40-50 unrelated families would be as near to ideal as practically possible. Identity of families may be maintained in the newly imported seed sources to facilitate simultaneous evaluation of family performances.

Table 6. Most suitable provenances of *Eucalyptus grandis* and *E. saligna* in provenance trials on the island of Hawaii

Species and CSIRO seed lot #	Seed source location	Latitude	Evelation (m)
E.grandis			
12423	Tinaroo Falls Dam, Queensland, Australia	17°11'S	807
12409	Ravenshoe, Queensland, Australia	17°42'S	949
10774	E. of Gympie, Queensland, Australia	26°14'S	404
7823	Coffs Harbor, New South Wales, Australia	30°10'S	18
7810	Bulahdelah, New South Wales, Australia	32°20'S	121
E.saligna			
11025	S.W. of Rockhampton,Queensland, Australia	23°49'S	868
12064	S. of Calliope, Queensland, Australia	24°23'S	807
12145	Connondale, Queensland, Australia	26°44'S	606
11756	Clifford, Queensland, Australia	28°30'S	242

Source: From Skolmen (1986) as reported in Whitesell *et al.* (1992).

Table 7. Specific gravity of wood at 3 to 5 m height and estimated stem dry weight annual increment for provenances of *Eucalyptus grandis* and *E.saligna* at 5.3 y of age at Upper Ninole (Ka'u), Hawaii

Provenance ID No.	Species	Specific gravity [1] kg m^{-3}	Stem[2] (dry tonnes $ha^{-1}y^{-1}$)
11894	*E.saligna*	0.430 a	15.4
12064	*E.saligna*	0.427 ab	14.7
10225	*E.saligna*	0.425 ab	12.7
11605	*E.saligna*	0.414 abc	17.5
12145	*E.saligna*	0.413 abcd	19.5
305	*E.saligna*	0.410 abcd	11.4
7808	*E.saligna*	0.410 abcd	13.9
10733	*E.saligna*	0.404 abcd	10.9
11025	*E.saligna*	0.404 bcde	16.0
7786	*E.saligna*	0.402 bcde	13.6
11756	*E.saligna*	0.397 bcdef	17.5
12143	*E.grandis*	0.393 cdefg	14.5
10774	*E.grandis*	0.387 defg	19.2
12381	*E.grandis*	0.382 defg	20.5
12422	*E.grandis*	0.379 efg	21.0
11243	*E.grandis*	0.378 efg	17.9
12423	*E.grandis*	0.372 fg	27.9
12409	*E.grandis*	0.371 fgh	30.0
7810	*E.grandis*	0.352 hi	19.2
7823	*E.grandis*	0.349 i	17.0
12461	*E.grandis*	0.341 i	16.9
11035	*E.grandis*	0.337 i	21.3
Mean	*E.saligna*	0.413	14.9
Mean	*E.grandis*	0.367	20.5

[1] Means in column with the same letter(s) are not significantly different.
[2] Vol. growth ($m^3ha^{-1}y^{-1}$) (see Tables 4 & 5) × specific gravity × 1000.
Source: Skolmen (1986).

Table 8. Steps in establishing a successful tree improvement programme

Step 1. Identification of appropriate species

Step 2. Determination of appropriate geographic sources or provenances within species

- a) Introduction of provenances
- b) Evaluation for adaptability and productivity
- c) Assessment of genetic variability within and between provenances

Step 3. Identification of best trees within best soures of the best species

Step 4. Exploitation of genetic variabilty

- a) Base population - start with best provenances as far as possible
- b) Selection criteria - identify trait or traits depending on the aims and objectives of improvement programme
- c) Establishment of progeny tests with open-pollinated seed from individual trees of appropriate geographic sources
- d) Estimation of heritability and genetic gain for important traits
  - 1) Analysis of variance using O-P families and estimation of phenotypic coefficient of variation (pcv), genetic coefficient of variation (gcv), narrow-sense heritability, and genetic correlation for important traits
  - 2) Parent-progeny regression - narrow-sense heritability
  - 3) Analysis of variance - half-sib progeny tests
  - 4) Analysis of variance - clonal test
  - 5) Genotype x environment interaction

Step 5. Short-term improvement

- a) Mass selection on a phenotypic basis
  - 1) Thinning to convert provenance trials into seed production areas
  - 2) Unaccompanied seed orchards
- b) Selection of elite trees
  - 1) Half-sib progeny tests
  - 2) Clonal propagation of plus trees

Step 6. Long-term improvement

- a) Enrichment of germplasm to meet long-term breeding requirements and for sustainable gains
- b) Establishment of seed orchards (exploitation of gca due to additive genetic variation)
  - 1) First generation clonal seed orchards (as applicable) - selection of plus trees from well-adapted provenances
    - a) Accompanied seed orchards - with progeny tests
      - 1) Simultaneous seed orchards
      - 2) Delayed seed orchards
    - b) Unaccompanied seed orchards - without progeny tests
  - 2) First generation seedling seed orchards
    - a) Selection within and between families
    - b) Combined selection
- c) Establishment of clone banks (exploitation of either gca or sca depending on the type of progenies evaluated)
  - 1) Progeny testing of clones
    - a) Half-sib progenies (yield information on gca)
    - b) Full-sib progenies - mating designs (yield information on both gca and sca)
      - 1) Diallele mating
      - 2) Line x tester and other mating designs
  - 2) Establishment of speciality seed orchards
- d) Vegetative propagation (exploitation of both additive and non-additive genetic variability)
  - 1) Clonal propagation of plus trees for mass production
  - 2) Clonal propagation of hybrids for mass production
  - 3) Hedging of plus trees to maintain juvenility
- e) Hybrids (exploitation of sca due to dominance and over-dominance genetic effects)
  - 1) Inter-provenance hybrids
  - 2) Inter-specific hybrids
  - 3) Hedging promising hybrids to maintain juvenility
  - 4) Clonal propagation of hybrids
  - 5) Testing adaptability and performance of hybrids
  - 6) Hybrids versus improved populations

Provenances of *E. grandis* and *E. saligna* currently grown in Hawaii can provide initial stock for short-term genetic gains. For a long-term improvement programme, it is advisable to introduce more provenances of these and other species as soon as possible for field evaluation in diverse environments to identify appropriate seed sources. The selection of provenances should match the environmental conditions of the seed source and target planting areas as closely as possible.

Establishment of seed production areas

The best-performing provenances of *E. grandis*, *E. saligna*, and *E. urophylla* from different testing sites can be rogued and upgraded into seed production areas to meet immediate seed requirements. Alternatively, provenance trials can be designed for direct conversion into seed production areas. In this case, four to eight provenances of a species are planted at one-meter spacing in a randomized, replicated, nested design as shown in Figure 2. This design features 25 m^2 sub-subplots containing 25 trees of each of five provenances randomized and replicated five times within 625 m^2 subplots, which in turn are randomized and replicated five times in an area of approximately 1.5 ha. After two years of growth, a stringent multi-trait selection is applied to rogue the trial. Similarly at the end of the fourth year, another stage of selection is applied to retain only one or two superior trees per sub-subplot. Of the 15 625 trees planted initially, only about 700-800 would remain after the second stage of selection. In this method, the evaluation of provenances, selection within provenances, and establishment of the seed production area are done simultaneously to save time, labor and money.

The superior trees from different provenances are allowed to interbreed to produce seeds that are used for establishing commercial plantations. Genetically, the seeds produced from these superior trees in the seed production area are the products of the combination of superior alleles from different parental stocks. This method is similar to mass selection followed in unaccompanied clonal orchards and relies upon additive genetic effects for silviculturally important traits. The genetic gain accumulates at every stage of selection, and superior alleles recombine to produce genetically superior progenies. The net gains achieved from seed production areas may not exceed gains obtained from seed orchards planted with progeny-tested clones. However, seed production areas can provide seed until permanent seedling or clonal seed orchards are established.

Genetic testing and establishment of seed orchards

Selection of plus trees in best provenances

The correct choice of seed source results in substantial gains, and further improvement can be captured by selecting within the best seed sources and interbreeding them in seed orchards. Response to selection based on phenotypic performance depends largely on the proportion of additive genetic variance governing the traits. Breeders in Florida improved growth 163% in four generations of selection within the local land race of *E. grandis* (Meskimen 1983). In Hawaii, BDC and IPIF scientists have selected about 70 plus trees of *E. grandis* and *E. saligna* on the basis of stem and crown characteristics from the BDC plantations. Subsequently, plus trees with high GCA will be cloned and used to establish clonal seed orchards in target planting areas. The half-sib progeny trials may be subjected to inter- and intra-family selection and converted into seedling seed orchards.

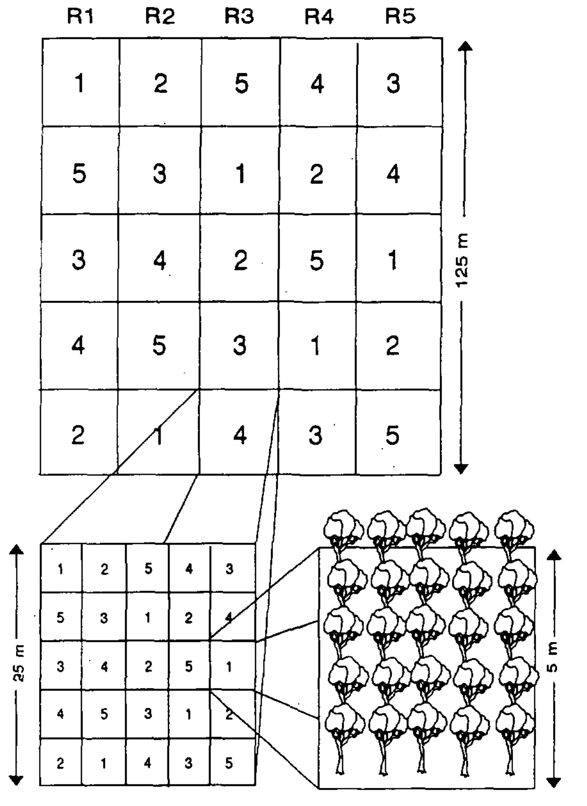

Figure 2. Field design for *Eucalyptus* seed production area derived from a close-spaced provenance trial

Progeny testing of plus trees

Evaluation of open-pollinated progenies of all plus trees should be initiated in all targeted planting areas. The half-sib progenies of the plus trees would be tested in randomized, replicated trials to estimate the GCA for growth rate and volume increment. Index selection involving the important traits should be performed to identify suitable families and trees within families to convert the progeny trials into seedling seed orchards. The plus trees with high GCA could then be cloned for establishing clonal seed orchards. If the orchards (simultaneous seed orchards) are already established, the progeny evaluation results should be used to rogue the orchards to retain only clones with high GCA. Selected plus trees would be involved in a complete diallele or other suitable mating system to generate a number of full-sibs. They would be evaluated in a randomized, replicated design to estimate both GCA and SCA effects. Because gains from full-sib family selection are always greater than those possible from half-sib family selection, the parental clones that generate superior full-sibs would be utilized to produce hybrid seed in a biclonal seed orchard.

Establishment of seed orchards for long-term genetic gains

Because of extremely steep environmental gradients prevailing in Hawaii, there is a necessity for some kind of genetic buffering while planning for large-scale plantations. Clones are likely to be precisely adapted to specific environments. Therefore, large numbers of selected and tested clones may be required to cover the wide range of environments in the potential plantation area as a mosaic over the landscape. Because sexual propagules (seeds) can provide the required homeostasis to adjust to minor changes along these environmental gradients, there is a need for establishing seed orchards of *E. grandis*, *E. saligna* and *E. urophylla*. Interspecific hybrids may offer even broader amplitude for extending site suitability. The strategies for establishing seed orchards are presented in Figure 3.

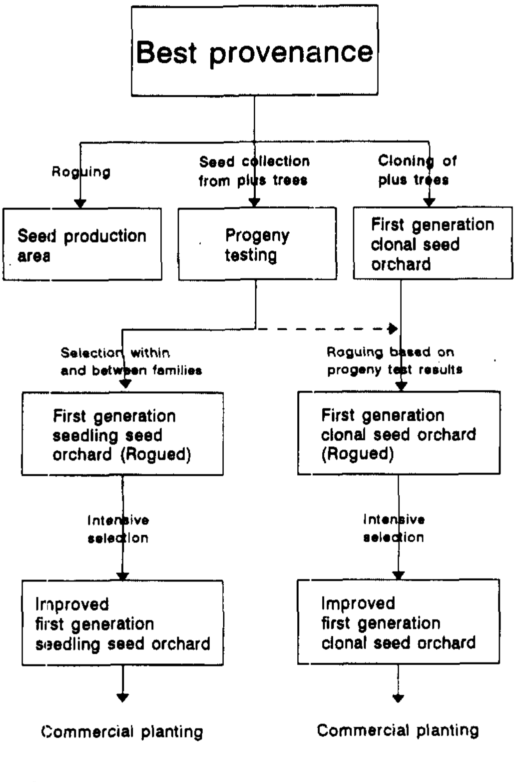

Figure 3. Alternative routes to establishing seed orchards for the production of commercial quality seed

Because eucalypts are hermaphroditic, protandrous and entomophyllous, it is not difficult to produce large quantities of seed from open-pollinated orchards (Griffin 1989). Scarcity of pollen vectors in exotic growing environments may become a major impediment to production of outcrossed seeds. In Hawaii, it may be necessary to rear honey bees in and around seed orchards to facilitate outcrossing and to enhance seed set.

Three to four ramets from each of about 40 selected clones, which are selected based on progeny test results, should be utilized in establishing clonal seed orchards. We suggest establishing at least four orchards, two each in the Hilo/ Hamakua coast area and the Ka'u district, to cover a range of sites throughout the two major targeted planting areas on the island of Hawaii.

Perhaps most importantly, demand for eucalypts seems to be emerging for at least two different products, pulpwood and fibre for particleboard. Requirements for fibreboard and other manufactured products are more stringent than for biomass production as fuelwood. Therefore, divergent selection criteria have to be evolved to screen clones in the orchards to produce seed to grow trees that meet industrial standards. For use of fibre, for example, low-bark volume and anatomical and chemical parameters relating to pulping characteristics will be important selection criteria.

Selections should be made when orchards are at least three years old and the original clones reduced by 50-60% in any single orchard. It should be possible to collect seed capsules one year after selection is completed. Seed can be gathered from felled trees or harvested from standing trees depending on the strategy planned. Seed can be stored to meet needs for a four- to six-year period. If trees are felled, the coppice sprouts would replace the orchards during this four- to six-year period and eventually flower, producing a new crop without interrupting seed supply. Under Hawaii conditions, a one-hectare clonal seed orchard accompanied by progeny testing is estimated to cost $18 500 (Table 9). The profitability is directly influenced by management decisions on its life-span and the intensity of management.

Clonal strategies

Clonal propagation of selected plus trees for large genetic gains

An advantage of clonal forestry is that considerable volume gains can be achieved because a relatively large proportion of the total genetic variability for growth rate is governed by non-additive genetic effects, which can be captured through vegetative propagation (Zobel 1993). Nevertheless, many plus trees do not transfer their phenotypically desirable qualities into their clonal copies when grown in plantations (Zobel 1993). Clones are generally adapted to a narrow range of environments. Therefore, thorough testing of clones in targeted planting environments is required before making final selections for commercial plantations. Clonal propagation is not a breeding method to develop better genotypes. It is only a means for mass propagation of desired genotypes to capture both additive and non-additive genetic effects. Therefore, a long-term clonal forestry programme must be supported by a long-term breeding programme.

Clonal propagation of older trees through stem cuttings often does not result in normal tree form due to slow growth rate, plagiotropic growth, and poor root systems. Large variability in rooting success exists among clones, which seriously reduces the number of clones available for a planting programme. In contrast to sexual propagation, which restores freedom from diseases and pests and imparts vigor to zygotic offsprings, clonal propagation results in an accumulation of diseases and pests within the members of a clone (Libby & Ahuja 1993).

Table 9. Cost estimates for establishing an accompanied clonal seed orchard in Hawaii

Item	Rate	cost (US $)
Selection and cloning		
Selection of plus trees	0.5 man-month	1 250.00
Cloning	1.0 man-month	2 500.00
Seed collection	@$10.00 tree^{-1}	500.00
Seed processing	@$1.00 tree^{-1}	50.00
Nursery expenditures for raising progenies	0.75 man-month	1 875.00
Land preparation and planting		
Progeny evaluation and conversion into seedling seed orchard		
Land clearing (1.0 ha)	6 h @ $75.00 h^{-1}	450.00
Pre-planting herbicide	2 h @ $40.00 h^{-1}	80.00
Tractor hire charges	4 h @ $50.00 h^{-1}	200.00
Planting of progenies (25 plants progeny^{-1})	$0.25 tree^{-1}	315.00
Evaluation of progenies (50 families)	1.0 man-month	2 500.00
Rogue within and between families	$2.00 tree^{-1}	1 250.00
Clonal seed orchard planting		
Land clearing(1.0 ha)	6 h @$75.00 h^{-1}	450.00
Pre-planting herbicide	1-2 h @ $40.00 h^{-1}	80.00
Tractor hire charges	4 h @ $50.00 h^{-1}	200.00
Orchard layout	0.25 man-month	625.00
Hand planting (300 ramets)	$1.50 tree^{-1}(average)	450.00
Re-planting cost	10% of original planting	45.00
Rogue orchard (nearly 50%)	$2.00 tree^{-1}	300.00
General maintenance		
Irrigation	1.5 man-month	3 750.00
Post-planting herbicide		
application (backpack)	10 h ha^{-1} @ $10.00 h^{-1}	100.00
chemicals	$100.00 ha^{-1}	100.00
Mowing between rows (2 ha)	$50.00 ha^{-1} (quarterly)	400.00
Fertilizer application	Hand application of NPK	
0 and 6 months	4 h ha^{-1} @ $9.00 h^{-1}	100.00
fertilizer cost	$0.15 tree^{-1}	150.00
subsequent application(urea)	$50.00 ha^{-1} + $0.15 lb^{-1}	200.00
Inter-cultivation(2 times)	@ $250.00 per job	500.00
Total		18 420.00

Notes: Clonal seed orchard size = 1.0 ha containing 40 to 50 clones; the accompanying progeny test = 1.0 ha; 1 man-month = $2 500.

Micropropagation methods for eucalypts are being standardized by scientists at the Hawaiian Sugar Planters Association. Selected clones of *E. urophylla* have been micropropagated and are in field testing to compare the relative performances of micropropagated and seedling progenies of plus trees. Soon this technology will be used more extensively to micropropagate some of the plus trees of *E. urophylla*, and subsequently initiated in other species such as *E. grandis* and *E. saligna*. Large-scale micropropagation is expensive, time-consuming, and predisposed to somaclonal variation.

We suggest using micropropagated seedlings to create a hedging orchard where the trees are allowed to grow for two years at which time they are evaluated, and superior trees are pruned to delay maturation. The new shoots can be used for macropropagation (rooted cuttings) on an operational scale. A common problem in hedging orchards is that as the donor clones in the hedging orchard mature, they become more difficult to propagate and are eventually unusable. Another drawback is that standardization for rooting ability and growth habit at an earlier stage of maturation of a donor clone may not be applicable at a later stage (Ahuja & Libby 1993). Therefore, clones in the hedging orchards must be replaced periodically with new, juvenile clones.

All rooted clones from *E. grandis*, *E. saligna* and *E. urophylla* will have to be field tested along the Hilo/Hamakua coast and in the Ka'u district, which are the two areas where plantations are being considered, to match the clones with sites and silvicultural practices. Genetic diversity can be maintained effectively in clonal forestry by carefully deploying a sufficient number of unrelated operational clones (Libby 1990). The number of clones sufficient to create a clonal plantation that is as safe as a plantation forest established with seeds is in the range of 7-30 unrelated clones (Libby & Ahuja 1993).

Establishment of clone trials and clone banks for important species

All plus trees, other superior trees, and hybrids will have to be clonally propagated and maintained in clone banks for future use. The plus trees that could be propagated vegetatively must be field tested for their performance in all the different sites to match and deploy the best clones for selection of operational clones. These clones would be maintained in juvenile condition in hedges for future use.

Conservation of genetic diversity

Tree breeding efforts over a period of time will result in the loss of genetic variability for commercially important traits. Eventually, response to selection plateaus and no further gains are possible unless new variability is introduced. For successful long-term tree improvement, it is important to start with a broad genetic base and to follow a breeding programme that conserves genetic potential of the original germplasm. Therefore, it is essential to preserve genetic diversity by saving gene pools such as provenances and progenies, seed orchards, and clone banks to prevent loss of genes, gene complexes, and genotypes.

Conclusion

As the interest in forestry as an alternative land use in Hawaii for both market and non-market values continues to accelerate, landowners, land-use planners, and entrepreneurs will need to base their decisions, in part, on sound strategies of comprehensive tree improvement. We have attempted to provide such information here. The recommended long-term tree improvement programme described in this paper complements the initial BDC/IPIF programme (BDC ceased all operations upon its closure in the Fall, 1994). It concentrates on the effective utilization of existing variability in the species and provenances available to produce genetically improved seed and clones for commercial SRIC tree plantations in Hawaii. Secondly, the establishment of production and research seed production areas and orchards for important species to exploit the genetic variability existing in the gene pools for long-term utilization is recommended. Thirdly, introduction, evaluation, and utilization of more provenances from Australia and elsewhere is required to enrich the gene pool for long-term utilization. Finally, research must be intensified in other complementary areas such as vegetative propagation of plus trees and hybrids, and testing them in target planting sites for their relative performance with genetically improved trees originating from seed.

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