Realized Gain from Breeding *Eucalyptus grandis* in Florida[1]

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Abstract: E. grandis is in the fourth generation of selection in southwest Florida. The breeding strategy combines a provenance trial, genetic base population, seedling seed orchard, and progeny test in a single plantation where all families are completely randomized in single-tree plots. That planting configuration closely predicted the magnitude of genetic gain realized through age 2.5 years in a simulated commercial plantation: up to 66 percent gain in tree height, 164 percent gain in stem volume, plus significant gains in stem straightness and freeze tolerance.

A small but intense eucalyptus research effort began in Florida in 1961 with the private, nonprofit Florida Forests Foundation dedicated to investigating the commercial forestry potential of exotic hardwoods in south Florida. By 1965 we had established numerous eucalyptus experiments, including 14 screening trials testing a total of 156 seed sources representing 67 eucalyptus species. The Foundation was absorbed into the Southeastern Forest Experiment Station in 1967. Eucalyptus timber research was suspended until 1971 when a small research cooperative was formed with Federal, State, industrial, and private participants. Operational planting started in 1972 and in 10 years 8.8 million seedlings of Eucalyptus grandis Hill ex Maiden have been planted on 6,475 ha in southwest Florida. Every outplanted seedling was grown from genetically improved seed collected from local seed orchards.

Our tree improvement system had to accommodate two conditions:

(1) Imported seedlots will not produce commercial plantations in Florida. The most we can expect is that the better imported seedlots will produce occasional outstanding individuals which we can select and breed into a locally adapted strain.

(2) In 1972, industrial and private cooperators wanted to start commercial planting "immediately." Instant demand for improved seed dictated that provenance trials, tree selection, seed orchard establishment, and progeny testing be combined and accomplished concurrently instead of in the more conservative stepwise sequence.

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BREEDING METHODS

Grandis trees planted in southwest Florida constitute a landrace developed through three generations of selection and progeny testing in the local environment. Because of recurrent selection for local adaptation, the trees perform better in Florida than progenies of outstanding trees selected in Australia, South Africa, or elsewhere.

The breeding strategy involves importing as many E. grandis seedlots as possible--preferably collected from selected single trees in Australia. But some bulk lots have been included, plus many lots from exotic populations outside Australia. Each seedlot (called a family) contributes about 60 seedlings to a large outplanting called the genetic base population. All individuals of all families and all sources are completely randomized in single-tree plots. Stocking is 1,916 trees/ha in a precise row X column grid, mapped to preserve the location and pedigree of each tree. Trees are measured for growth rate and scored for cold hardiness, stem straightness, branch habit, and general adaptation. At 2.7 years (one-third of rotation age), the best trees are selected and the rest are rogued to convert the base population to a seedling seed orchard. The best families usually contribute three or four selects to the seedling seed orchard; most families contribute only one or two; and about one-third of the families drop out of the breeding population for lack of any worthy candidates.

Select trees exchange pollen in the first general bloom at age 3+ years. The following spring the resultant seed is collected and used to establish the next generation's base population, which is also the progeny test of the seedling seed orchard. Thus a generation is turned, from seed to seed, in 4 years. Progeny test results identify the best commercial seed trees as well as poor seed trees to be rogued from the orchard.

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Each generation of selection enhances the landrace's adaptation to local conditions, but new families must be imported to broaden the genetic base and guard against inbreeding depression. The current grandis population, planted in 1977 (G-POP77), consists of 31,725 trees representing 529 families on 17.3 ha. Nine percent of the families are fourth generation (great grandmothers selected for excellence in a Florida plantation); 24 percent, third generation (grandmothers selected in Florida); 40 percent, second generation (mothers selected in Florida); and 27 percent, first generation (newly imported families). Geographically, 37 percent of the families trace their maternal pedigrees back to New South Wales; 32 percent originate in Queensland; 21 percent from South Africa; 4 percent from many miscellaneous nations; and 6 percent cannot be traced beyond Florida.

The Florida breeding strategy presents two radical departures from usual methods. We combine a provenance trial, a genetic base population, a seedling seed orchard, and a progeny test in a single plantation. We do that simply to compress development time and to concentrate our meager resources of staff and budget.

Our other departure is to plant all the individuals representing a family in completely randomized, single-tree plots. This contrasts with the replicated square plots or row plots used in most tree improvement plantings. Completely randomized, single-tree plots offer several advantages: (1) Each family is maximally dispersed across the planting site, encouraging a thorough sampling of microsites and an accurate estimate of site adaptation. (2) Maximal dispersion promotes random mating of select trees and eliminates the need to choose between outstanding sibling selection candidates standing side by side in the same multitree plot. (3) Different families can be represented by different numbers of individuals with no statistical or operational problems; likewise, mortality causes no problems. (4) Each tree is a replicate of its family and represents a statistical degree of freedom. This efficient, robust design enables us to screen more families with fewer trees.

INDICATED GAINS

In the current base population, G-POP77, comparison of first-, second-, third-, and fourth-generation families shows impressive evidence of genetic gain (fig. 1). At age 2.5 years the average first-generation tree contained 7.5 dm^3 of stem wood and bark from groundline to tip. Second-generation stems grew nearly twice as large, averaging 14.6 dm^3. Third-generation stems show an additional 16 percent increment up to 17.0 dm^3, and fourth-generation yet another 16 percent up to 19.7 dm^3.

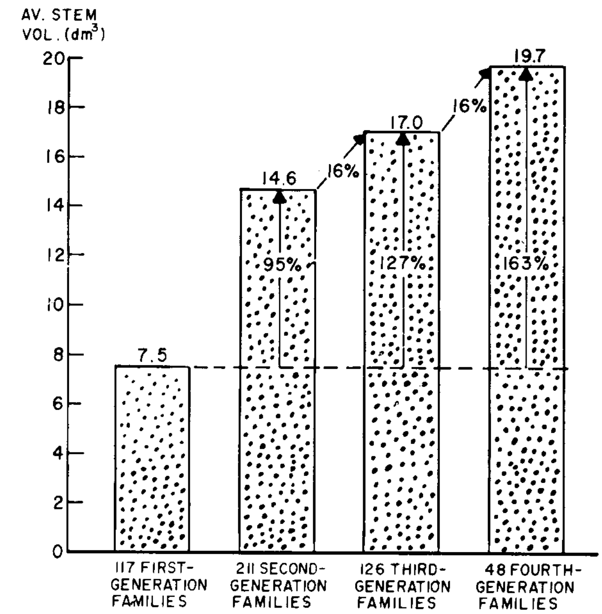

Figure 1--Family mean stem volume at age 2.5 years in G-POP77, the E. grandis base population planted in 1977.

These results imply that at one-third of rotation age, Florida landowners will be producing 2.6 times more wood from planting fourth-generation Florida seedlings instead of stock grown from imported seed. The case for local selection seems compelling considering that a large majority of first-generation families in G-POP77 are offspring of magnificent select trees in Australia and South Africa. But that parental magnificence is rarely reproduced by offspring planted in the Florida environment.

PERPLEXING QUESTIONS

Despite the promise, some thoughtful visitors and cooperators suggest that genetic gains measured in our combination base population-progeny test might seriously overestimate gains realizable in commercial plantations. The concern is that competition among trees might be far more severe in commercial plantations than in our base population.

Our base population-progeny test with its single-tree plots simulates commercial plantations in that offspring of all seed trees are randomly mixed on the planting site. Nevertheless there remains a perplexing difference between our base population and a commercial plantation: the range of genetic quality.

The difference is that our base population includes the entire spectrum of genetic resources ranging from the most advanced families down to new introductions which lack adaptation and compete poorly. In contrast, commercial plantations are the truncated, compressed upper end of the genetic range. For example, G-POP77 consists of 529 families, but the 1979 commercial plantations include only the best 34 of those families--that's skimming just the best 6 percent of the cream off the top of our gene pool. The perplexing question is: What happens when these best families must compete just among themselves over hundreds of hectares? Does the "cream" stay sweet, or does it curdle from the intense heat of best competing against best?

A corollary question is: Can southwest Florida's poor soils, spring droughts, and summer flooding support such intense competition; or do environmental factors become limiting and render the most genetically advanced families no more productive than their ancestral, imported seedlots?

SEEKING ANSWERS

In 1979 we installed a small study called GAIN79 to answer those perplexing questions by measuring realized gain in a commercial plantation setting. This paper reports those gains and compares them with gains forecast by G-POP77.

GAIN79 compares three populations in four replications of 7- X 7-tree plots. The populations are:

Ancestral: Four imported seedlots from which many advanced-generation families descend. All Ancestral trees are first generation.

Commercial: The commercial seed mix for the 1979 planting season, composited from 34 advanced-generation families chosen for excellent early performance at G-POP77. Of the 34 commercial families, 22 are descended from Ancestral seedlots. The average Commercial tree is generation 2.9.

Premier: Six advanced-generation families, top ranked for the combined traits of volume production, cold hardiness, form, and coppicing. All six Premier families descend from Ancestral seedlots, and five Premier families are also among the Commercial families. The average Premier tree is generation 3.5.

GAIN79 simulates a commercial plantation as closely as possible. It was planted in the commercial site-preparation area at the same spacing employed by the landowner.

The G-POP77 and GAIN79 sites are located about 23 km apart in Glades County on a landtype known locally as palmetto prairie, a flat, naturally treeless expanse of saw-palmetto, wiregrass, runer oak, and wax myrtle. Soils are infertile, poorly drained acid fine sands underlain by spodic hardpans. We hand planted both studies in July (G-POP77 in 1977, GAIN79 in 1979) on sites prepared in the spring by burning, broadcasting with 1,120 kg/ha of ground rock phosphate, double chopping (GAIN79) or triple chopping (G-POP77), then bedding. A major difference is planting density: 1,204 trees/ha at GAIN79; 1,916 trees/ha (59 percent more) at G-POP77. Our commercial recommendation is 1,495 trees/ha. The shortfall at GAIN79 is unfortunate but was dictated by the spacing of the commercially prepared beds.

We measured growth in both studies at 0.5, 1, 1.5, and 2.5 years and also scored tree form at 2.5 years. Additionally, GAIN79 was scored for damage following freezes at 1.5 and 2.5 years, and remeasured at 3.5 years.

EARLY GAINS

Growth Traits

GAIN79 demonstrates impressive early growth gains similar to those forecast by G-POP77. Improved trees rapidly expressed superiority at both sites. Analysis of variance first detected highly significant gains for height growth at age 6 months in G-POP77 and at 1 year in GAIN79, and at 1.5 years for diameter and volume growth at both sites. At the oldest common measuring age, 2.5 years, Commercial and Premier trees stand a quarter to half again as tall as Ancestral trees with over twice as much wood in their stems (fig. 2).

Gains illustrated in figure 2 for GAIN79 amount to the following returns from breeding imported seedlots up to a Premier population: an average tree 2.3 m taller at age 2.5 years with 7.2 dm^3 of additional stem volume or 3.3 kg more dry energy fuel; and an average hectare carrying 8 m^3 more volume or 3.7 tons of additional dry energy fuel.[3] Figure 3 characterizes breeding gains per stem, and figure 4 on a stand basis.

Figure 2 depicted percentage gains of comparable magnitude in both studies. The similar percentages are reassuring because they are based on markedly different growth rates at the two sites. The site difference is so extreme that the shortest population at G-POP77, Ancestral, averages taller at 2.5 years than the tallest trees, Premier, at GAIN79 (fig. 3). The pooled 2.5-year height of all three populations is 7.1 m at G-POP77 slipping to 4.8 m at GAIN79, a 32 percent reduction.

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[3]Volume of stem wood and bark from groundline to tip; dry weight of wood and bark in stems and branches from ground to tip (formulas on file with Forest Service, USDA, Ft. Myers, Fla.).

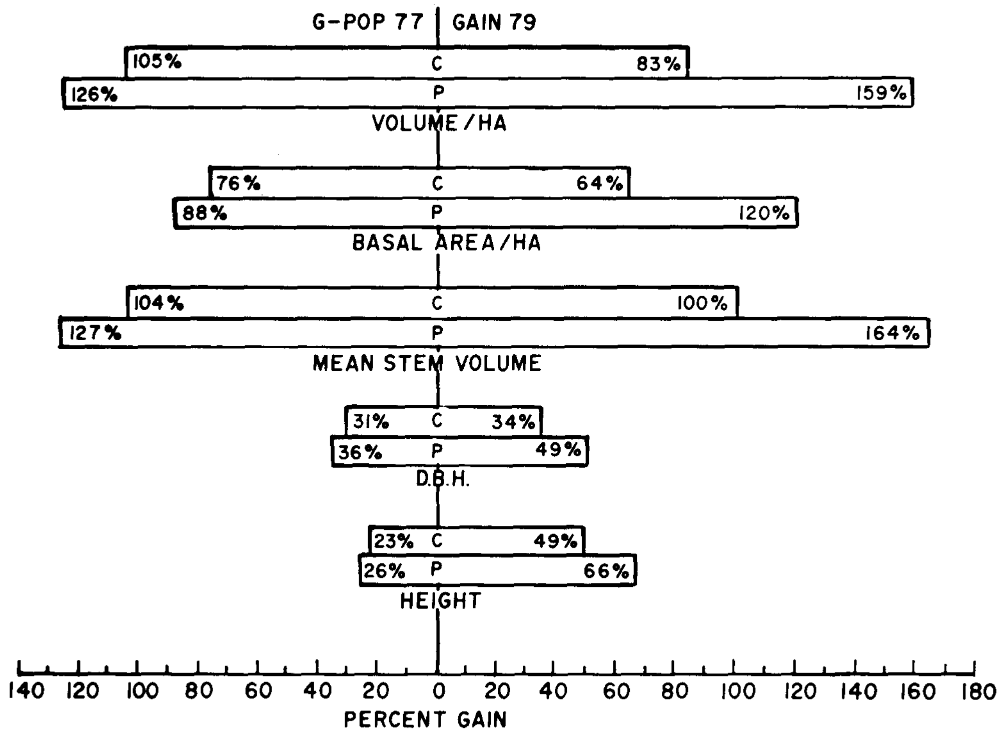

Figure 2--Percentage gains in growth traits at age 2.5 year: for Commercial (C) and Premier (P) trees over Ancestral trees as predicted at G-POP77 and realized at GAIN79. All bars represent statistically significant gains.

Four factors could conceivably contribute to the site-growth differential: (1) inherent differences in site quality; (2) different stocking levels; (3) partially different growing years, July 1977-January 1980 at G-POP77 versus July 1979-January 1982 at GAIN79; or (4) the effects of competition within populations at GAIN79 versus competition among populations at G-POP77. Competition among populations would seem to disadvantage the unimproved Ancestral trees. Yet Ancestral trees grew 79 percent as tall as Premier trees while competing with them at G-POP77, but only 60 percent as tall while not competing with them at GAIN79. Empirically, stocking levels may play a large role in the site-growth differential. G-POP77, planted at 1,916 trees/ha had eliminated herbaceous competition by age 1.5 year; but GAIN79, with 1,204 trees/ha, still competes with a heavy ground cover after 3.5 years.

Whatever the adversities at GAIN79, improved trees coped better than unimproved trees. Ancestral trees grew only 55 percent as tall at GAIN79 as they had at G-POP77, but Commercial trees achieved 70 percent and Premier trees 76 percent of their G-POP77 performance. Our base population-progeny tests cannot be expected to predict actual growth on all sites. Nevertheless, in this case G-POP77 seems a reliable predictor of the magnitude of gains that improved populations will express in commercial plantations.

Tree Form

We evaluated tree form at age 2.5 years using the following scoring systems:

Stem straightness: 0 = too crooked for pulpwood, 1 = acceptable for pulpwood, 2 = good straightness, 3 = excellent straightness.

Branch habit: 0 = too limby for pulpwood, 1 = acceptable for pulpwood, 2 = good natural pruning and small branched, 3 = good natural pruning and fine branched.

G-POP77 forecast highly significant gains in stem straightness which were realized in GAIN79. G-POP77 also forecast highly significant gains in branch habit, but these were not realized in GAIN79 (fig. 5). The contradiction in the two traits is not surprising viewed in the context of tree selection.

As we search our base populations for selection candidates, the first trait we look for is vigor--candidates must be conspicuously larger than their neighbors or their siblings. We notice repeatedly that grandis stem straightness is independent of bigness, but branch habit is not. It is just as easy to find straight big trees as crooked big trees, and there is no need to compromise selection standards for either trait.

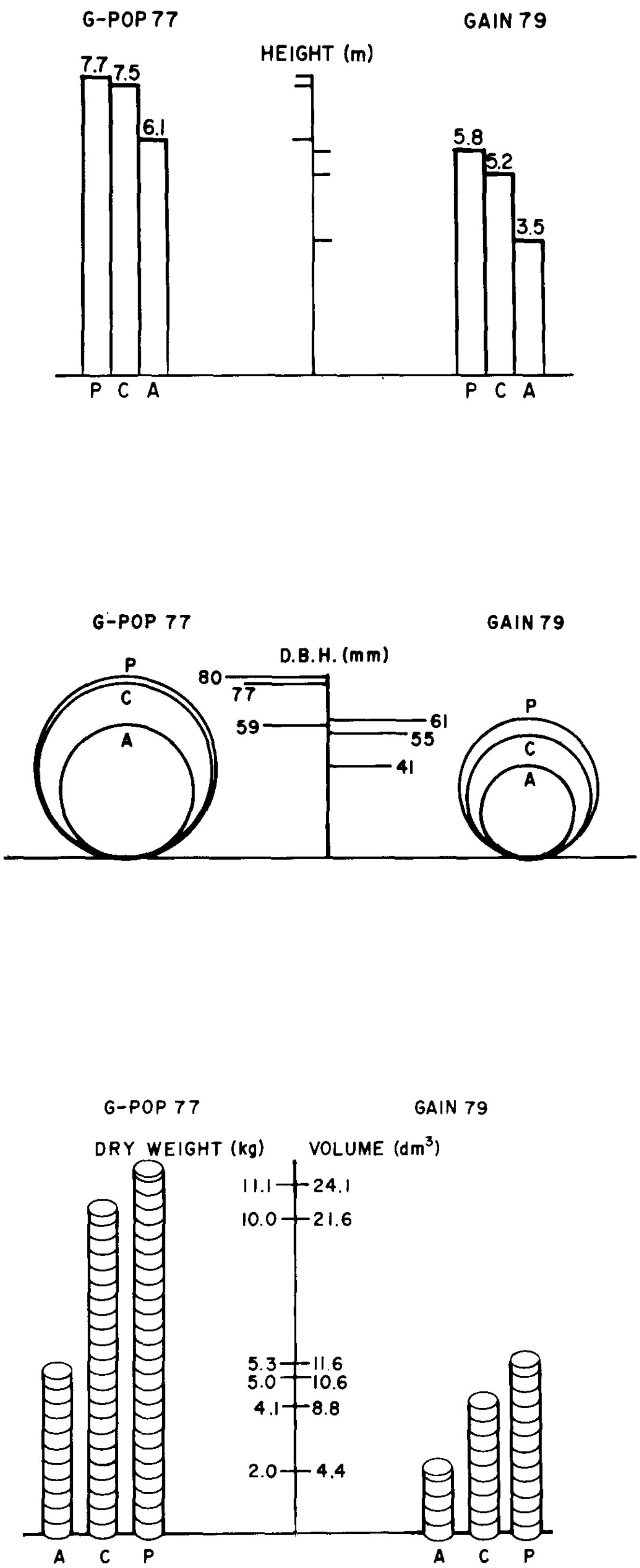

Figure 3--Mean stem values at age 2.5 years for Ancestral (A), Commercial (C), and Premier (P) trees.

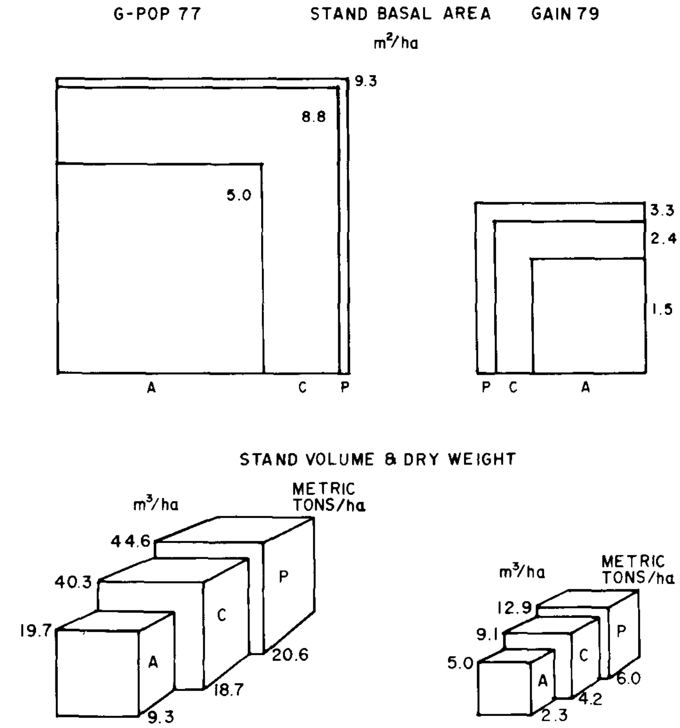

Figure 4--Stand basal area, volume of stem wood and bark from ground to tip, and dry weight of wood and bark in stems and branches for Ancestral (A), Commercial (C), and Premier (P) populations at age 2.5 years.

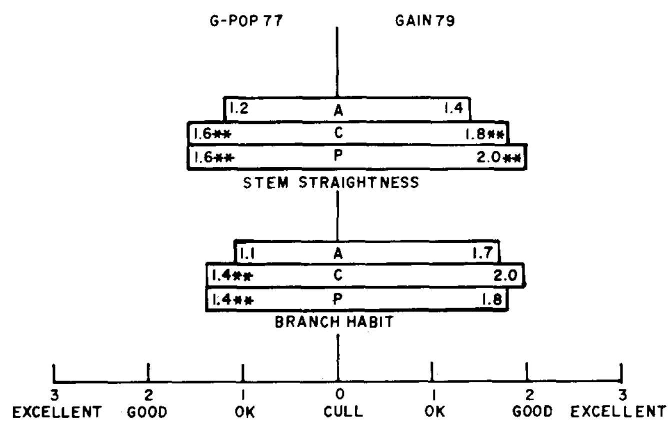

Figure 5--Mean scores for branch habit and stem straightness for Ancestral (A), Commercial (C), and Premier (P) trees, age 2.5 years, at GAIN79 and G-POP77. Asterisks signify significant (0.01 level) gains over Ancestral population.

In contrast, big trees have coarse branches far more commonly than fine branches. We have had to compromise--but never abandon--our standards on branch habit, especially when selecting from first-generation families.

The failure of GAIN79 to demonstrate predicted gains in branch habit may also be attributable to smaller tree size and wider spacing than at G-POP77. At the evaluation age of 2.5 years, trees at GAIN79 averaged 2 m shorter than at G-POP77. It is difficult to infer the mature relationship between branch size and bole size until saplings are quite advanced. Also the natural pruning aspects of branch habit are not evident until growth rate and stocking converge at partial crown closure. The natural expression of branch habit might also have been altered or delayed at GAIN79 by recovery sprouts arising after freeze damage 1 year earlier.

Gains in form may seem miniscule--no more than 0.6 of a scoring unit--but that perception changes if gain is expressed as the percentage of movement along the scale from the score of unimproved trees to the maximum score of 3. A sample calculation follows for Premier stem straightness at GAIN79:

$$\frac{\text{Premier score - Ancestral score}}{\text{3 - Ancestral score}} \times 100 = \text{percent gain}$$

$$\frac{2.0 - 1.4}{3.0 - 1.4} \times 100 = 38 \text{ percent gain}$$

So computed, the Premier and Commercial scores presented in figure 5 translate to the following percentage gains:

	G-POP77	GAIN79
Stem straightness		
Premier	22**	38**
Commercial	22**	25**
Branch habit		
Premier	16**	8
Commercial	16**	23

**Represents gain significant at the 0.01 level, based on ANOVA of actual scores.

Freeze Damage

Severe frost damages grandis even in the recommended planting zone, but the trees rarely die. They may freeze back, but they sprout and regrow vigorously. Frost has cost a season's growth several times but never a plantation. Southwest Florida usually has inversion freezes with temperatures coldest at ground level but moderating dramatically in the first meter or two above ground. Marginally hardy trees like E. grandis can r duce risk simply by growing fast--elevating tender crown tissue above lethal temperatures while building larger stems with thicker, insulative bark close to the ground. Each additional year of growth reduces risk. Since research planting started in 1961, severe damage has been suffered 1 out of 3 years by seedlings in their first winter, 1 out of 4 years by saplings in their second winter, and 1 out of 11 years by trees in their third winter or older. We make freeze tolerance a prime selection criteria--whenever nature "blesses" one of our base populations with a severe freeze.

In its four winters to date, GAIN79 has been statistically unlucky with two significant freezes. A moderately hard freeze occurred January 13, 1981, with low temperatures near -8.5°C (16°F). Damage was moderate to severe at GAIN79, then in its second winter; in contrast, damage was slight at G-POP77 in its fourth winter.

One year later a catastrophic freeze struck with temperatures as low as -11.5°C (11°F), and subfreezing for 8 hours. The 1982 freeze devastated all grandis trees in Glades County, regardless of age or size. The eucalypts were particularly vulnerable to the 1982 freeze because of a total lack of preconditioning. The preceding month included 21 days with afternoon highs above 27°C (80°F,). We scored damage from both freezes at GAIN79. At G-POP77, damage was too light to score in the first freeze, and other priorities precluded scoring the severe freeze.

We score cold damage on an 11-point scale ranging from 10 (undamaged) down to -1 (frozen dead); categories 9 down through 5 denote increasingly severe damage confined to leaves; and categories 4 down through 0 describe increasingly severe wood destruction in branches or bole. Figure 6 details the scoring system. Figure 7 profiles damage suffered by Ancestral, Commercial, and Premier trees at GAIN79.

Figure 7 starkly illustrates that while breeding has made substantial progress toward minimizing damage from moderate freezes, some south Florida freezes are so severe as to probably exceed the natural variation available for selection in the species. In the moderate freeze, Ancestral trees suffered bark splitting and injury to primary branches and main stems, but Commercial trees only lost their leaves, and Premier trees actually retained about 25 percent of their leaves.

If these gains in a moderate freeze are converted to percentages computed in the same manner as for tree form, they amount to a 31 percent gain for Commercial trees and a 53 percent gain for Premier, gains notably similar to the percentage gains for height growth presented in figure 2. We do not think that we are breeding a meaningful improvement in physiological cold resistance, but we do think we are breeding a significant improvement in cold tolerance based primarily on growing big enough, fast enough to avoid lethal temperatures in the inversion layer.

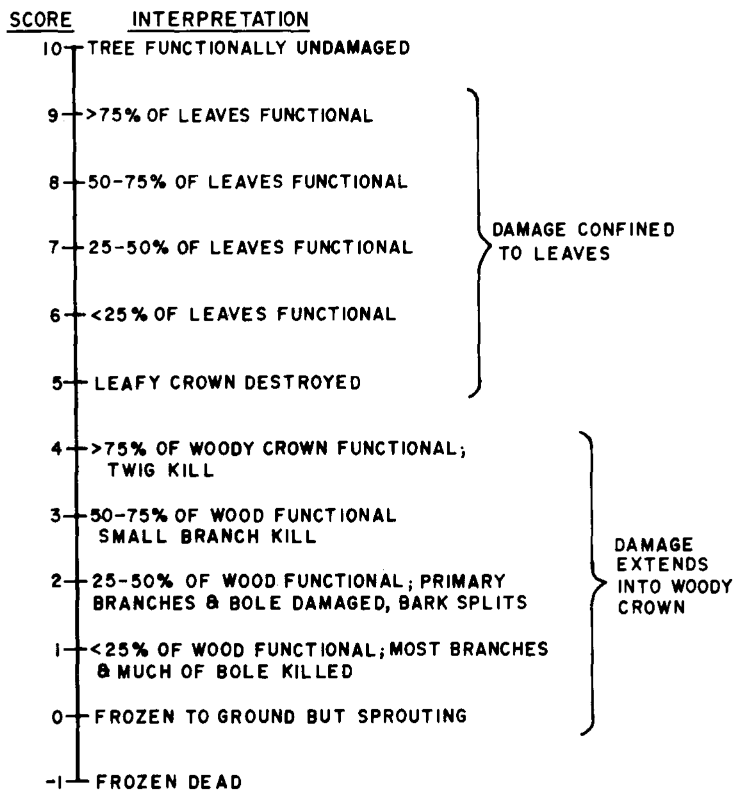

Figure 6--Cold damage scoring system.

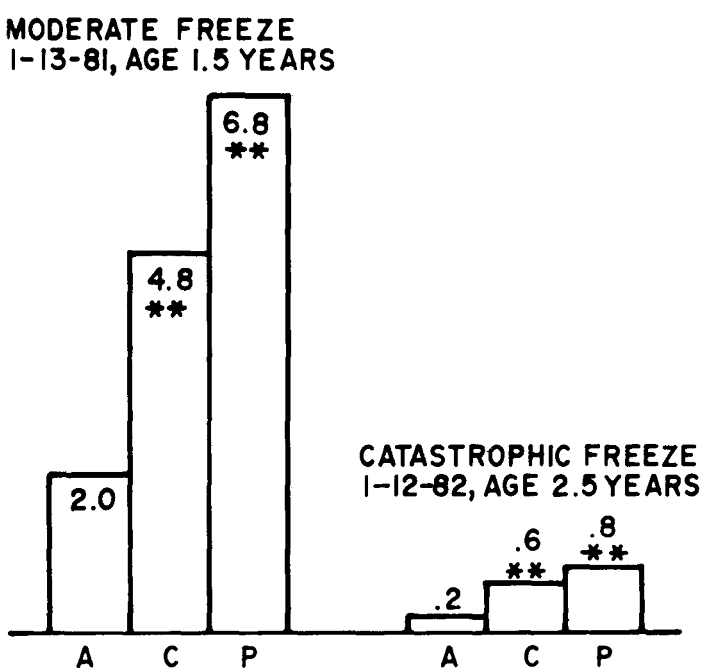

Figure 7--Mean cold damage scores for Ancestral (A), Commercial (C), and Premier (P) populations in two freezes at GAIN79. Asterisks denote scores significantly (0.01 level) above Ancestral score.

Whatever the nature of our gains, the catastrophic freeze overwhelmed them. Ancestral, Commercial, and Premier trees averaged respectively 0.2, 0.6, and 0.8 on the damage scale (fig. 7), and no individual tree scored higher than 1. Converted to percentages as before, these miniscule gains amount to 4 percent for Commercial and 6 percent for Premier.

In a freeze of this magnitude, breeding gains need to be expressed in the most basic trait: survival. During the year following the great freeze, 22 percent of Ancestral trees died compared to 7 percent of Commercial trees and 4 percent of Premier trees, significantly heterogeneous mortality ($\bullet^2$ test, 0.01 level). Before the freeze, populations had not differed significantly in survival.

One year after the great freeze, GAIN79 has the following stand characteristics at age 3.5 years:

	Ancestral	Commercial	Premier
Survival (pct)*	73	81	89
Stocking (trees/ha)*	879	975	1,072
Mean height (m)**	3.2	4.7	4.8
Number of persistent freeze-recovery stems per stool	2.7	2.6	2.2

*Trait reflects population differences significant at the 0.05 level ($\bullet^2$ test); **trait reflects population differences significant at the 0.01 level (ANOVA).

The 1982 freeze seems so devastating in the context of this report that we need to view it in broader perspective. The freeze was isolated, almost confined to a single county. Damage was slight to eucalyptus plantations in other suitable growing areas. Freeze damage approaching this severity has not been seen in southwest Florida since 1962. In the interim, two complete rotations could have been planted, grown, harvested, and regenerated. Within the freeze zone the loss of wood inventories depended on age class. Plantations in their first or second winter were frozen to the ground and regenerated from ground level coppice shoots. They will develop as normal coppice stands. Plantations in their fifth, sixth, seventh, or eighth winter suffered severe damage to crown tissues but not to product boles. Those age classes will refoliate and grow on to scheduled harvest with little economic loss. Plantations in their third and fourth winters (GAIN79) suffered profound damage to product boles; stems that recovered are often badly forked or so weakened that subsequent wind breakage seems likely. These age classes, however, would constitute only 25 percent of plantation area in an even distribution of age classes. Freeze damage is an acceptable investment risk that can be ameliorated by adding freeze resilience--swift, graceful recovery--to our tree selection criteria.

CONCLUSIONS

Back-to-back freezes savagely reduced growth and stocking at GAIN79 and converted it from a single-stemmed seedling stand to a multistemmed coppice stand. These transformations are not economically or esthetically pleasing, but they demonstrate graphically that breeding advanced-generation strains from local selections is probably the most important element in managing the investment risk of growing eucalypts in Florida.

Despite great discrepancies in stocking and productivity, G-POP77 either accurately or conservatively forecast the magnitude of genetic gains realized at GAIN79. It seems both efficient and efficacious to breed local landraces in genetic plantings that combine the functions of provenance trial, base population, progeny test, and seed orchard. Completely randomized, single-tree plots seem to be a reliable planting design for ranking populations and predicting the magnitude of realized gains.

ACKNOWLEDGMENT: I thank Lykes Bros., Inc., for experimental sites and land preparation.

Standiford, Richard B; Ledig, F Thomas, technical coordinators. **Proceedings of a workshop on *Eucalyptus* in California, June 14-16, 1983, Sacramento, California.** Gen. Tech. Rep. PSW 69. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1983. 128 p.

To provide up-to-date information on *Eucalyptus* in California, researchers from California, Florida, Hawaii, Oregon, and France presented papers on species selection, products, uses, and economics, growth and yield, cultural requirements, propagation, and breeding programs. This Proceedings of the Workshop should serve as a useful reference for landowners, foresters, nurserymen, horticulturists, and others who are planning to plant *Eucalyptus.*

Retrieval Terms: Eucalyptus, short-rotation trees, biomass, wood energy