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Review Article

History and Status of *Eucalyptus* Improvement in Florida

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The first organized *Eucalyptus* research in Florida was begun by the Florida Forests Foundation in 1959 in southern Florida. This research was absorbed by the USDA Forest Service and the Florida Division of Forestry in 1968. In the early 1970s, the Eucalyptus Research Cooperative formed to provide additional support emphasized *E. grandis*, *E. robusta*, *E. camaldulensis*, and *E. tereticornis* and developed cultural practices for commercial plantations in southern Florida. In 1978, this cooperative united with the Hardwood Research Cooperative at North Carolina State University until 1985 when the 14-year effort ended after three severe freezes from 1983 to 1985. *Eucalyptus* planting and research were continued with a Florida-wide focus by the University of Florida and collaborators starting in 1980. The collective accomplishments in terms of genetic resources and commercial planting are summarized. For example, fast-growing, freeze-resilient *E. grandis* seedlings are produced by advanced generation seed orchards, five *E. grandis* cultivars are commercially available, as are *E. amplifolia* and *Corymbia torelliana* seeds. Genetic improvement of these and other species is ongoing due to beneficial collaborations. Short Rotation Woody Crop systems are promising for increasing productivity and extending uses beyond conventional pulpwood to applications such as windbreaks, dendroremediation, and energy wood.

1. Introduction

Eucalyptus species were introduced in the South as early as 1878, but no significant commercial plantations were established until the late 1960s [1]. Although forestry organizations tested eucalypts in Florida in the 1950s and in Texas in the 1960s, most plantings before 1970 were small scale windbreaks, ornamentals, and shade trees in central and southern Florida and Texas.

In 1959, the Florida Forests Foundation initiated research on eucalypts as a potential source of hardwood pulpwood on rangeland or other low quality sites in southern Florida. The Foundation's research was absorbed by the USDA Forest Service and the Florida Division of Forestry in 1968. In the early 1970s, a eucalyptus research cooperative was formed by seven companies to provide financial and research support to the Forest Service. This effort led to the selection of *E. grandis, E. robusta, E. camaldulensis,* and *E. tereticornis* from 67 species tested and to the development of cultural practices for raising seedlings and establishing commercial plantations in southern Florida [1–13].

In 1971, the Hardwood Research Cooperative at North Carolina State University (NCSU) began a systematic evaluation of species and sources to determine *Eucalyptus* suitability primarily for the Lower Coastal Plain of the South. By 1978, the industrial members of the Florida group joined the Hardwood Cooperative to pursue the *Eucalyptus* dream until 1985 when the 14-year effort ended as the result of severe freezes in December 1983, January 1984, and January 1985.

In Florida, *Eucalyptus* planting and research that started in south Florida in the 1960s were continued with a Florida-wide focus by the University of Florida and collaborators starting in 1980. The USDA Forest Service was a significant and active collaborator until its Lehigh Acres unit closed in 1984.

This paper reviews the history and status of tree improvement research activities with *E. grandis, E. robusta,* *E. camaldulensis*, *E. tereticornis*, *E. amplifolia*, and *Corymbia torelliana* in Florida. In the process, this paper first recognizes significant players in these activities and then highlights accomplishments in terms of genetic resources and commercial and potential uses. This paper also identifies continuing research needs.

2. Significant Players

Numerous institutions, companies, and individuals have contributed to the current status of eucalypts in Florida. The Florida Forests Foundation that initiated research in southern Florida benefitted from the efforts of George F. Meskimen, whose exceptional dedication to *Eucalyptus* research he jokingly once claimed came from being "seduced" by the genus' attributes. The USDA Forest Service had a major role from 1968 to 1984, particularly through the activities of Thomas F. Geary and notably again George F. Meskimen. During this same time, the Florida Division of Forestry, with primary "on the ground" participation by Tim Pitman, facilitated eucalypt commercialization. Starting in the 1960s and continuing to the present, Lykes Bros., through the efforts of Charley Lykes, Ben Swendsen, and Jim Bryan, has been the major planter of eucalypts in Florida and a consistent supporter of related research. The six forestry companies in the Eucalyptus Research Cooperative (Buckeye Cellulose Corporation, Container Corporation of America, Hudson Pulp & Paper Corporation, International Paper Company, ITT Rayonier, and St. Regis Paper Company) provided essential support and impetus for commercialization starting in 1971 [1]. These companies and other members of the Hardwood Research Cooperative at NCSU continued support of *Eucalyptus* research until 1985 [13]. NCSU scientists who made significant contributions during this period included Carlyle Franklin and Bill Dvorak.

The Florida-wide *Eucalyptus* research conducted by the University of Florida (UF) since 1980 similarly has benefitted from many collaborators. The Short Rotation Woody Crops Program of the US Department of Energy funded research from 1980 to 1988. The Gas Research Institute provided support from 1981 to 1991. Other institutional supporters included the USDA Forest Service, the Florida Institute of Phosphate Research, Southeastern Regional Biomass Energy Program, USDA-SARE, Sumter County, and the Center for Biomass Energy Programs at UF. Buckeye Technology Florida, Mosaic, and Evans Properties are among the industries providing financial support, and many more contributed in kind through research collaboration, site preparation, and management. Among the numerous UF scientists involved in the research were J. B. Huffman, D. R. Dippon, H. Riekerk, G. R. Alker, D. R. Carter, L. Q. Ma, M. P. Ozores-Hampton, P. J. Minogue, J. T. DeValerio, K. V. Reddy, K. R. Roeder, E. I. Warrag, S. M. Pisano, B. Tamang, B. Becker, and M. H. Langholtz.

Collectively, the investments of personnel and resources in developing *Eucalyptus* for Florida are large. Scientist-years associated with the research conservatively exceed 100. Direct financial support to UF alone exceeded $3 million, and in-kind support over nearly 50 years may equal the direct funding.

3. Genetic Resources

A novel cost-efficient tree improvement strategy pioneered for *E. grandis* in Florida was followed for developing seedling seed orchards (SSOs) of all species [1, 4, 9, 14–21]. This inexpensive but effective strategy utilized eucalypts' short generation time and rapid growth by combining provenance and progeny testing in one place at one time with early selection, large infusions of new, primarily single-tree accessions, and use of pedigrees to minimize inbreeding and achieve steady and often great genetic gains.

Five generations of *E. grandis* SSOs in southern Florida (Table 1) were started in 1961 by the Florida Forests Foundation using block plots of a limited number of accessions. The 1st-generation genetic base population of 4,352 trees from only 13 accessions was quickly thinned to an SSO of just eight trees from three accessions, which in turn were carried forward into the 2nd-generation genetic base population planted in 1964. While this population had 11,000 trees from 18 accessions, the resulting SSO had only 33 trees from 12 accessions.

To expand this narrow genetic base, the 3rd- and 4th-generation genetic base populations received major infusions of new accessions, primarily individual tree seedlots. When planted in 1973, over 13,000 trees from 285 accessions were deployed as single-tree plots in a completely randomized design. Based on 1.5-year tree size data, the 3rd-generation SSO (GO73) was then created with 431 trees of 191 accessions unequally distributed across the SSO (Figure 1).

The 4th-generation genetic base population (GP77) established nearby in 1977 with a worldwide representation of *E. grandis* of over 31,000 trees from 529 accessions was again completely randomized in single-tree plots across more than 12 ha (Figure 1) [1, 7–9, 14, 16, 17]. At 1.5 years, nearly half of the trees were felled to evaluate wood properties and coppicing. From the resulting data, area selects (the best tree in 4 rows of 5 trees) were made to constitute the 4th-generation SSO (GO77) (Figure 1). The final GO77 composition created in 1985 also utilized individual tree responses to severe freezes from 1983 to 1985. These 1,500 orchard trees have produced seed for many commercial plantings in Florida and elsewhere.

The effectiveness of this tree improvement strategy was evident in comparisons across generations in GP77 for tree volume (Figure 2). The comparison of 1st-generation *E. grandis* with *E. saligna* supported dropping *E. saligna* from the research program. A near doubling of tree size in 2nd-generation *E. grandis* demonstrated the payoff in selecting for adaptability to the infertile soils and seasonal rainfall of southern Florida. The 16% gains in tree volume in successive generations illustrate the benefit of continued selection and orchard establishment.

Including the genetic base populations that served as large open-pollinated progeny tests, some 25 smaller progeny tests of *E. grandis* in GO73 and GO77 were planted in

Table 1: Numbers of trees and accessions in Florida *Eucalyptus grandis*, *E. robusta*, *E. camaldulensis*/*E. tereticornis*, *E. amplifolia*, and *Corymbia torelliana* genetic base populations and derived seedling or clonal (C) seed orchards by generation and year of establishment.

Generation	Year	Base population		Orchard	
		Trees	Accessions	Trees	Accessions
		E. grandis seedling seed orchards			
1	1961	4,352	13	8	3
2	1964	11,000	18	33	12
3	1973	13,234	285	431	191
4	1977	31,725	529	1,500	260
5	2002	1,620	69	73	33
5	2010-11	1,300	26	~260	~20
5	2011-12	5,580	36	~480	~25
		E. grandis clonal seed orchards			
4C	1996			154	41
4C	2007			176	36
		E. robusta seedling seed orchards			
1	1961	2,304	9	119	??
2	1967	6,275	64	94	39
3	1975	24,476	372	706	191
		E. camaldulensis/*E. tereticornis* seedling seed orchards			
1	19??	?	??	??	??
2	1974	13,421	184	243	150
		E. amplifolia seedling seed orchards			
1	1992	1,685	109	139	106
2	1999	1,638	59	40	22
2	2003	216	22	33	12
		C. torelliana seedling seed orchard			
1	2008	960	29	69	25

(a)

(b)

Figure 1: Aerial views of GO73 (front) and GP77 (back) in 1980 (a) and GO73 and GO77 in 1993 (b).

southern Florida since the 1970s [7, 12, 16, 17, 20–25]. GP77 and eight of these smaller tests with appropriate tree size and freeze responses, in combination with the multigeneration pedigrees that have been maintained, have recently contributed to the calculation of breeding values for 2,174 trees for stand basal area and/or freeze resilience (the ability to reestablish vigorous vertical growth after freeze damage).

The severe freezes of the 1980s [11] afforded exceptional opportunities to develop fast growing, freeze resilient clones (Table 2), and several clone banks were established. Most of the early emphasis was on *E. grandis*, with genetic tests distributed widely across sites and climates in Florida. Based on the resulting performance (Table 3), UF has patented and released five cultivars: *E.nergy* series *E. grandis* cultivars G1, G2, G3, G4, G5 [26], which grow well under many circumstances (Figure 3).

Progeny test results, breeding values, convenience, and/or security of multiple orchard locations led to the establishment of additional *E. grandis* orchards (Table 1). Small clonal seed orchards were established in 1996 and 2007 to be closer to facilities and to protect against tree loss due to storms, respectively. For similar reasons, 5th-generation seedling seed orchards have also been developed using multiple-tree row plots in randomized complete block designs.

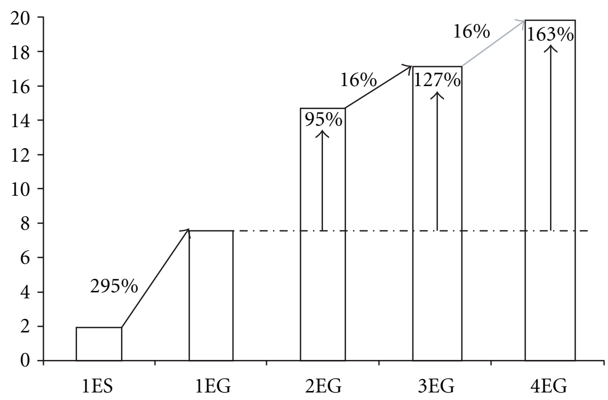


Figure 2: Genetic gains in 2.5-year-old family mean stem volume (dm^3) for 27 1st-generation *E. saligna* (1ES), 117 1st-, 211 2nd-, 126 3rd-, and 48 4th-generation *E. grandis* (1EG, 2EG, 3EG, and 4EG, resp.) families in genetic base population GP77.

Table 2: Numbers of clones selected, tested, and commercialized by species.

Species	Selected	Tested	Commercialized
E. grandis	390	350	5
E. robusta	52	52	0
E. camaldulensis/tereticornis	28	4	4
E. amplifolia	115	35	0
C. torelliana	4	0	0

In the early species comparisons in southern Florida, *E. robusta* appeared to be comparable to *E. grandis*, and hybrids between the two species were promising [1]. Therefore, similar emphasis was given to *E. robusta* seedling seed orchards (Table 1). In 1975, the 3rd-generation orchard RO75 was established using comparable techniques to GO77 [4], but after RO75 was rogued, the top *E. grandis* progenies were interplanted to encourage production of spontaneous hybrids. Following this unproductive effort, RO75 was harvested and is no longer viable.

Some *E. robusta* candidates were selected and clonally tested in the early 1980s (Table 2). However, the *E. robusta* clones failed to perform well, and none were ever commercialized.

Early species comparisons also showed promise for *E. camaldulensis* and *E. tereticornis*, resulting in a 1st-generation seedling seed orchard (Table 1). A considerable effort in 1974 expanded the genetic base population for these species, and seedling seed orchard CT74 was eventually developed.

Because seed production was problematic, some *E. camaldulensis* and *E. tereticornis* clones were selected (Table 2). A few of these were commercially propagated for use in California in the 1990s [27–29] but are no longer available.

Reevaluation of a number of species [15, 18–20, 23, 25, 30–33] resulted in expanded tree improvement efforts with two species that had been considered of limited potential. For both *E. amplifolia* and *C. torelliana* (formerly *E. torelliana*), the starting germplasm was derived from seed or trees resulting from earlier screening efforts. The Florida Division of Forestry had retained and grown small quantities of *E. amplifolia* and *C. torelliana* because of their ornamental properties.

Two generations of *E. amplifolia* orchards have been established (Table 1) for producing seed for planting in more freeze-frequent northern Florida and similar areas. The 1st-generation genetic base population included many new accessions, particularly individual tree accessions from frost-frequent portions of the species' natural distribution. Most of those accessions were retained in the SSO AO92. The two 2nd-generation orchards (Figure 4) included seedlings from AO92 but were mostly composed of additional new accessions. Commercial seed is available from two of the SSOs, and breeding values will be calculated from all 15 progeny tests that have been established since 1998.

Collectively, over 100 *E. amplifolia* cloning candidates have been identified, with some 35 entered in tests. Since rooting percent in *E. amplifolia* is highly variable but typically half that of *E. grandis* (40% versus 80% [19]), many more candidates may be needed before commercialization.

The *C. torelliana* genetic base population planted in 2008 (Table 1) included seedlots from 29 trees in windbreaks established from Division of Forestry and retained seed of unknown source. Surprisingly, this tropical species has demonstrated tolerance to temperatures as low −5°C, and all 69 orchard trees combine freeze tolerance with good growth and tree form (Figure 5). New Australian accessions have been acquired for inclusion in the 2nd-generation base population.

A few *C. torelliana* cloning candidates have been identified (Table 2). Capture has been by tissue culture, with no trees yet ready for field testing.

Other eucalypts are currently being tested for Florida conditions. One company is testing *E. benthamii*, *E. macarthurii*, and a genetically engineered hybrid of *E. grandis* × *E. urophylla* with genes for cold tolerance, lignin biosynthesis, and/or fertility [34]. Using more recent and broader germplasm than what was represented in earlier tests, NCSU and several collaborators started in 2010 assessing 149 species at 11 locations in the Southeast, including two in Florida, with about 30 species per location [35].

4. Uses

Matching *Eucalyptus* species to Florida's diverse weather and soils is challenging. Historically defined climatic regions based on average low temperatures or numbers of freezes provide some broad guidelines, but annual aberrations such as the three 100-year freezes in the 1980s [11], extended cold periods of the 2010-11 winter, and the abrupt freezes of the "warm" winter of 2011-12 profoundly influence freeze susceptibility of all young eucalypts. Rainfall patterns with unpredictable, extended dry spells make Florida's summer rainfall climate highly variable and difficult for successful planting and early growth. Within climatic regions, soils

(a)

(b)

Figure 3: 13.3-year-old G4 on dredge spoils (a) and 2-year-old G1, G2, G3 on phosphate mined land (b) in central Florida.

Table 3: Characteristics of *E. nergy* series *E. grandis* cultivars G1, G2, G3, G4, and G5.

Characteristic	Cultivar				
	G1	G2	G3	G4	G5
Growth	Fast	Fast	Fast	Fast	Fast
Freeze resilience	Average	Good	Excellent	Excellent	Average
Wind firmness	Suscept.	Average	Average	Resistant	—
Coppice	Good	Good	Good	Good	Good
Tissue culture propagation	Readily	Readily	Readily	Good	Good
Pedigree (gen.)	4th	4th	2nd	2nd	3rd
Wood density (kg/m^3)	—	522	470	640	—
Wood moisture content (%, dry wt)	119	104–123	128-129	89	—
Chalcid resistant	No	Yes	Yes	Yes	Yes
Plant in south FL	Yes	Yes	Yes	Yes	Yes
Plant in central FL	No	Yes	Yes	Yes	Yes
Plant in north FL	No	Yes	Yes	Yes	No

available for planting eucalypts can range from sandy, infertile to heavy clay to limestone to organic.

Still, broad climatic regions provide initial guidelines for using the species (Figure 6). From southern into central Florida, *C. torelliana* will tolerate typical winter conditions and grow well across a range of sites, especially when irrigated on deep sands. In peninsular Florida, *E. grandis*, especially hardier cultivars (Table 3), will tolerate most winters and sites even into northeast Florida. While typically tolerant of the colder winters common to northern Florida and similar regions, *E. amplifolia* requires good fertility with pH > 5.6 unless appropriate amendments are added to the infertile, poorly drained soils common to much of the region.

Eucalyptus planting is still largely done in southern Florida. One large landowner maintains a plantation estate of ~8,000 ha of primarily *E. grandis* in southern Florida. Two commercial plantations of ~32 ha of *E. amplifolia* have been established in northern Florida. No traditional plantations of *C. torelliana* have yet been established, but it is widely used for windbreaks in central and southern Florida.

Market opportunities for Florida eucalypts are currently limited but have huge potential. The hardwood pulpwood market forecast for southern Florida grown eucalypts in the 1970s [1] that was made uneconomical by high transportation costs instead became a more local mulch wood market (Figure 7) that supplies *Eucalyptus* mulch widely across the US. As cypress availability decreases, more eucalypt wood may replace it. In areas close to existing pulp mills in northern Florida, specialty pulps may utilize eucalypts.

Other traditional wood markets for eucalypts elsewhere are undeveloped or untapped in Florida. For solid wood products such as lumber and flooring, *E. grandis* grown in longer rotations would be suitable. As medium density fiberboard, *E. grandis* and/or *E. amplifolia* are suitable, as well as for wood-cement boards, plywood, and oriented strand board [36–38].

Eucalyptus energy wood uses in Florida have been demonstrated and are planned [22–24, 39–47]. For cofiring in compatible coal-fired power plants, *E. grandis* is a suitable feedstock. *Eucalyptus* is being considered as the feedstock for energy generation at pulp mills in Florida. It has potential for use in biorefineries even in association with pulp mills [48]. For several stand-alone biomass power plants in the state, *Eucalyptus* is proposed as the primary feedstock [49].

Short Rotation Woody Crop (SRWC) systems can maximize eucalypt productivity for such uses [8, 23, 25, 30, 33, 50–66]. Due to their easy propagation, rapid growth, tolerance to high stand density, response to intensive culture, and coppicing, *E. grandis* (Figure 7) and *E. amplifolia* in SRWCs can produce up to 67 green mt ha^{-1} yr^{-1} in multiple rotations as short as three years in Florida. These species

(a) (b)

Figure 4: *E. amplifolia* seedling seed orchards at 8 years (a) and five years (b).

(a) (b)

Figure 5: 3.4-year-old *C. torelliana* orchard (a) and a tree in the orchard (b).

are very responsive to intensive culture options such as soil amendments, vegetation control, and irrigation.

Eucalyptus grandis, *E. amplifolia*, and *C. torelliana* also have other uses in Florida. While each can be used in windbreaks [33, 67–72], *E. grandis* (Figure 7) and especially *C. torelliana* have been widely planted around citrus groves and vegetable fields in central and southern Florida. For dendroremediation (tree uptake of nutrients, reclaimed water, contaminants, etc.), *E. grandis* (Figure 7) and *E. amplifolia* can be very effective [73–79]. Eucalypts can serve as "bridge crops" to convert lands infested with invasive species such as cogon grass (*Imperata cylindrica*) to agricultural uses [80].

5. Research Needs

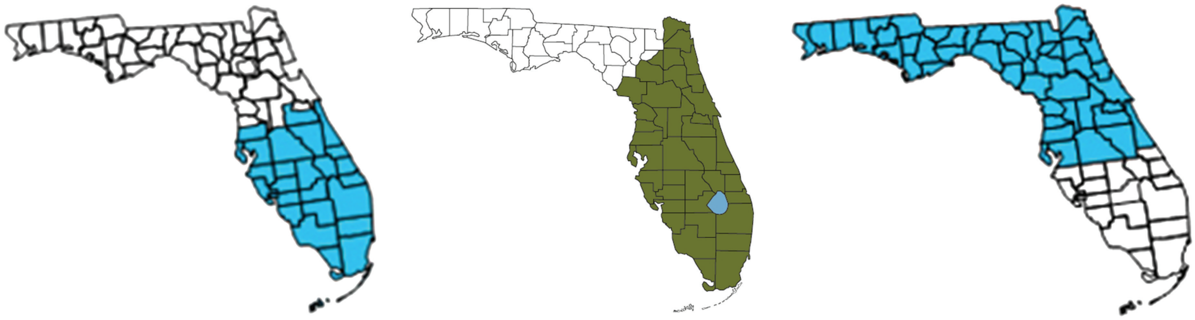
While genetic and silvicultural improvements to date primarily with *E. grandis*, *E. amplifolia*, and *C. torelliana* have dramatically improved *Eucalyptus* productivity in Florida, considerable progress remains to be made through research in several areas. Within the genus, more recently tested species, such as *E. benthamii*, may demonstrate suitability for Florida's demanding climatic and site conditions.

Within the species suitable for Florida, progress is needed in freeze resilience, growth rate, coppicing, pest resistance (e.g., the blue gum chalcid [81]), and propagation. Advanced generation breeding in combination with seedling and clonal seed orchards can continue making gains in these traits, but dramatic improvements are possible with clonal selection and testing. For example, interspecific hybridization and genetic modification, using gene mapping and genomic selection, could produce cloning candidates [82].

With the advent of proven clones, economical and rapid propagation becomes a need. Current vegetative propagules are ~33% more expensive than seedlings. Florida's seasonal planting schedule further necessitates the need for periodic rapid buildups of propagules.

Silvicultural enhancements are needed. Because of the infertility, low pH, and low organic matter of many sites available for planting eucalypts in Florida, appropriate organic fertilizers and water absorbing gels need study. Environmentally friendly applications of inorganic fertilizers need documentation. Weed control treatments are not well developed for eucalypts in Florida. Application of available wastewaters to plantations needs to be commercialized. Growth and yield models reflecting genetic and silvicultural improvements will be needed.

Market expansion for eucalypts in Florida depends on energy project development and technology improvement. The current market for eucalypt mulch wood is met by existing plantations, but the mulch wood market could expand if cypress availability decreases. The number of wood pellet plants and biomass-fueled utility plants currently under construction and proposed for Florida could significantly increase the demand for eucalypts. Improvements in biomass conversion at pulp mills and stand-alone biorefineries would also increase demand.



(a) (b) (c)

Figure 6: Planting regions in Florida for *C. torelliana* (a), *E. grandis* (b), and *E. amplifolia* (c).

(a) (b) (c) (d)

Figure 7: Uses of *E. grandis* in Florida—mulch wood (a), energy wood (b), dendroremediation (c), and windbreaks (d).

6. Conclusions

Fifty years of concerted effort by many players have developed eucalypts of typically satisfactory growth, freeze resilience, and site tolerance in most of peninsular Florida. In southern and into central Florida, *E. grandis* seedlings from advanced generation orchards may be successfully deployed in most years. Five *E. grandis* cultivars (*E. nergy* G1, G2, G3, G4, G5), resulting from freeze resilience screening afforded by extreme winters, may extend the *E. grandis* planting zone into northeast Florida. For southern and central Florida, *C. torelliana* seed is now available from a 1st-generation seedling seed orchard. For northern and into central Florida, improved *E. amplifolia* seed is available. These species may be used for multiple products. Mulch wood is the current market for *E. grandis* and *E. amplifolia*, while *E. grandis* and particularly *C. torelliana* are used for windbreaks. Using SRWC systems, the productivities of these species are high and will be required to meet feedstock demands when energy wood markets develop.

Genetic improvement is ongoing to increase growth and particularly to address freeze resilience and pest resistance needs. Collaboration will be beneficial for continued progress in realizing the attributes of *Eucalyptus* under Florida conditions.

Acknowledgments

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