OPTIMAL MANAGEMENT AND PRODUCTIVITY OF EUCALYPTUS GRANDIS ON FORMER PHOSPHATE MINED AND CITRUS LANDS IN CENTRAL AND SOUTHERN FLORIDA: INFLUENCE OF GENETICS AND SPACING

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Abstract—*Eucalyptus* short rotation woody crops (SRWC) with superior genotypes are promising in central and south Florida due to their fast growth, freeze resilience, coppicing ability, and site tolerance. Four *Eucalyptus grandis* cultivars, E.nergy™ G1, G2, G3, and/or G5, were established in 2009 at varying planting densities on a reclaimed clay settling area (CSA) in phosphate mined land in central Florida and a bedded former citrus site in southern Florida. Planting densities were 1025, 2050, and 3416 trees/acre on the CSA, and 581, 869, 1162, 1452, and 1742 trees/acre on the citrus site. Modified land expectation values (LEV) for coppicing species are reported for G2, G3, and/or G5 SRWCs on CSAs and citrus land. Optimal coppice stage and cycle lengths to the nearest 1/10th year were estimated for each cultivar × spacing × land scenario, assuming a range of coppice yields, cultural treatments (weed control and fertilization), plantation establishment and maintenance costs, stumpage prices, and real discount rates of 6, 8, and 10 percent. For example, at a 10 percent discount rate, stumpage price of $14 green/ton, costs of $250, 50, 974, 55, 90, and 10/acre for land preparation, bedding, planting, pre– and post–establishment weeding, fertilization, and annual management, respectively, and expected coppice yields, the LEV of CSAs under G3 at 1025 trees/acre was $561/acre or an equal annual equivalent of ~$56/acre/year. Currently, *Eucalyptus* is primarily harvested for landscape mulch, but markets are likely to expand into bioenergy and pulpwood applications.

INTRODUCTION

SRWC production is a potential land-use alternative for undeveloped CSAs and citrus lands affected by citrus greening in central and southern Florida. CSAs and overburden sites in central Florida are a potential SRWC land base of ~200,000 acres (Rockwood and others 2006), and citrus greening has been confirmed in all citrus-growing counties in Florida. *Eucalyptus* species are ideal SRWCs because of their fast growth, site tolerance, coppicing ability, and uses ranging from landscape mulch to biofuel production (Rockwood and others 2008). Furthermore, high-density eucalypt plantations can provide ecosystem services on CSAs by shortening the dewatering time, increasing soil organic matter, and excluding invasive, non-native vegetation, such as cogongrass (*Imperata cylindrica*), and facilitating the reintroduction of native understory vegetation (Tamang and others 2005). *E. grandis* is now grown commercially in southern Florida for mulchwood and can be deployed in central Florida if freeze resilient stock is used. Demand for *E. grandis* mulchwood is likely to increase if cypress availability decreases (Rockwood 2012). Though not a native species, *E. grandis* is non–invasive in Florida and has been planted commercially in south central Florida since the 1960s without spreading (Rockwood 1996).

Much SRWC emphasis in Florida has been on *Eucalyptus* tree improvement for adaptability to damaging freezes, infertile soils, and pest resistance [notably the blue gum chalcid (*Leptocybe invasa*)]. Advanced-generation breeding and the ongoing development of seedling and clonal seed orchards can increase genetic gains in these traits, but significant improvements are possible with clonal forestry. Produced through four generations of *E. grandis* genetic improvement for Florida conditions, including three “1-in-100 year” freezes, cultivars E.nergy™ G1, G2, G3, G4, and G5 were released by the University of Florida in 2009 for commercial planting (Rockwood 2012). Selected based on 18 tests throughout Florida on widely representative site/soil types including flatwoods spodosols, sandhills, dredged bay soil, muck soil, and CSAs, these cultivars have fast growth, excellent stem form, tolerance to various site conditions, coppicing ability, freeze resilience, and ease of propagation compared to 4th generation *E. grandis* seedlings (Rockwood and others 2012).

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Langholtz and others (2007) reported the value of phosphate mined land in central Florida under *E. amplifolia* SRWCs, but our analysis describes 1) the field performance since 2009 of *E. grandis* cultivars G1, G2, G3, and/or G5 on CSAs and former citrus lands and 2) their associated economics under current operational costs and stumpage prices.

MATERIALS AND METHODS

Experimental Design and Inventory

Cultivars G1, G2, and G3 were planted in September 2009 on a bedded CSA near Ft. Meade, FL, in 15 rows spaced 8.5 feet apart with 126 trees/row at three spacings: 66, 40, and 20 trees at 1.5, 2.5, and 5 feet, respectively (3416, 2050, and 1025 trees/acre, respectively). Single cultivar blocks of three or six rows (including a three row buffer) were systematically assigned within spacing blocks. The interior measurement plots for each cultivar contained 99 and 60 trees within 0.029 acres under planting densities 3416 and 2050 trees/acre, respectively, and 33 trees within 0.032 acres at 1025 trees/acre. Measurements of tree height, diameter at breast height (DBH), form, and survival were recorded at ages 7, 15, 23, 33, 49, and 60 months. At 41 months in February 2013, all trees in rows 1, 2, 14, and 15 and all trees at 1.5 feet spacing in rows 3-13 were felled to 1) initiate coppicing and 2) provide 20 sample trees to determine wood properties.

On former citrus beds near Ft. Pierce, FL, cultivars G1, G2, G3, and G5 were planted in July 2009 with four replications of two to six row wide, 30 feet long single cultivar block (measurement) plots centered on 60 feet wide citrus beds with 3 feet spacing between trees in a row and 5 feet between rows, resulting in five planting densities (581, 869, 1162, 1452, and 1742 trees/acre). Half (reps 1 and 2) of the 3200 trees received 113.4 g of slow release Osmocote fertilizer near the planting hole at planting. Height and survival were recorded at 9 months, and height, DBH, form, and survival were recorded at 15, 23, 39, 52, and 64 months.

Based on a subset of tree heights, the remaining trees' heights were predicted from site, cultivar, and treatment specific height versus DBH relationships (Equation 1):

$$\log(HT) = a \times \log(DBH) + b \quad (1)$$

where: HT = total tree height, and a and b are estimated parameters. Data from cultivars destructively sampled in October 2014 were used to generate cultivar-specific coefficients for a whole stem green weight regression equation (Equation 2) (R^2 >.98):

$$GW = b_0 + b_1 D^2H \quad (2)$$

where: GW = individual tree whole stem green weight, D = diameter at breast height, H = total tree height, and b_0 and b_1 are estimated parameters. For D^2H values below the lower limits of observed D^2Hs, Equation 3 with previously defined variables and a cultivar-specific dry weight to green weight ratio (R) was used to estimate individual tree whole stem green weight.

$$GW = \frac{-0.364 + 0.0163 \times D^2H}{R} \quad (3)$$

Growth Projections

Yield data were fit to Equation 4 using nonlinear regression (Langholtz and others 2007):

$$B(t) = e^{[b + c \times \ln(t) - d \times t]} \quad (4)$$

where: B(t) = whole stem green weight (green tons/acre), t = stand age (years), and b, c, d are estimated parameters. Regression parameters were generated for each land scenario × cultivar × planting density × fertilization (citrus site) combinatin (table 1).

Economic analyses used the terminology of Smart and Burgess (2000), where stage length is defined as the time between coppice harvests and cycle length is the total number of stages or years between replanting. Improved and expected coppice factors were applied to each growth function (Langholtz and others 2007), with a maximum of five stages per cycle (the original planted stand plus four coppice stages). Improved coppice scenarios assumed coppice factors of 120, 100, 80, and 60 percent of the original growth function for stages 2, 3, 4, and 5 (first, second, third, and fourth coppice, respectively). Expected coppice scenarios assumed coppice factors of 80, 60, 40, and 20 percent of the original growth function for stages 2, 3, 4, and 5, respectively.

Financial Optimization Model

An optimization model utilized Palisade's @RISK® Optimizer solver function to estimate the optimal number of stages and stage lengths. The objective function maximized land expectation value (LEV), which is defined by Equation 5 (Langholtz and others 2007, Medema and Lyon 1985) and occurs at the financial rotation age (t^*) where the marginal revenue product of letting the stand grow an additional year is no longer greater than but equals the opportunity cost of holding the growing stock and the cost of delaying future rotations (known as the marginal input cost) (Chang, 1984):

Table 1—Yield function parameters for G Series cultivars under three planting densities on a CSA and the most productive (fertilized) cultivar × spacing treatments on a former citrus site (R^2 >.99)

Cultivar	Trees Per Acre	Estimated Parameters		
		b	*c*	*d*
		----------*CSA*----------		
G1	1025	1.14	3.82	0.68
	2050	2.39	2.76	0.67
	3416	1.76	4.37	1.08
G2	1025	1.99	3.80	0.66
	2050	2.04	2.46	0.23
	3416	2.70	3.35	0.83
G3	1025	1.21	5.44	1.03
	2050	2.41	3.62	0.62
	3416	2.10	4.57	1.07
		----------Former Citrus Site----------		
G3	581	2.14	3.30	0.54
G2	869	1.38	3.67	0.54
G2	1162	2.67	3.96	0.84
G5	1452	2.21	2.74	0.35
G2	1742	2.83	3.00	0.52

$$LEV = \frac{\sum_{s=1}^{n} \left[V(t_s) e^{\left(-r \sum_{j=1}^{s} t_j\right)} - C_s e^{\left(-r \sum_{j=1}^{s} t_{j-1}\right)} \right]}{1 - e^{\left(-r \sum_{j=1}^{n} t_j\right)}} - \left(\frac{C_a}{1 - e^{-r}}\right) - C_r \qquad (5)$$

where: n = number of stages, s; V(t) = stand value at time t within stage s; r = real discount rate; C_s = costs of stage s at the start of the stage; C_a = annual cost; C_r = year zero start–up establishment cost. LEV is the maximum amount that an investor could afford to bid for bare forestland and earn the required interest rate (Davis and others 2001). Harvest schedules are reported to the nearest 1/10th year due to optimum stage lengths that are less than six years; therefore, an annual interest rate was converted to an effective periodic rate.

Because G1 is no longer commercially viable due to its susceptibility to blue gum chalcid, LEVs at 6, 8, and 10 percent real discount rates (net of inflation) were calculated only for G2, G3, and G5.

Summary of Model Inputs

The economic models assumed various timings and costs of management activities and a range of reported mulchwood stumpage prices to assess the sensitivity of LEV to changes in market conditions (table 2). Due to uncertainty associated with *Eucalyptus* markets in central and southern Florida, the operational costs are higher compared to conventional forest plantations in the South. Weed control was assumed to take place at the beginning of each stage to promote rapid growth rates and improve yields. Annual costs were $10 and 35/acre for the CSA and citrus site (includes a $25/acre drainage cost), respectively.

RESULTS AND DISCUSSION

Productivity Estimates

CSA—MAI_{max} for G Series cultivars ranged from 9.2 (G1 at 3416 trees/acre) to 34.9 (G3 at 2050 trees/acre) green tons/acre/year. G3 had the highest yields at all three planting densities (fig. 1), producing 25.9 (4.3 years), 34.9 (4.2 years), and 17.3 (3.4 years) green tons/acre/year at 1025, 2050, and 3416 trees/acre, respectively.

Table 2—Summary of model inputs for CSA and former citrus sites

Activity	Timing	Values
	----------CSA----------	
Land Preparation	One-time start-up cost	$125 and 250/acre
Bedding	Beginning of each cycle	$50/acre (same)
Planting Cost	Beginning of each cycle	$0.10 and 0.25/tree
Planting Densities	N/A	1025, 2050, and 3416 trees/acre
	----------Former Citrus Site----------	
Land Preparation	One-time start-up cost	$400 and 500/acre
Chemical Site Preparation	Beginning of each cycle	$90 and 120/acre
Planting Cost	Beginning of each cycle	$0.25 and 0.40/tree
Planting Densities	N/A	581, 869, 1162, 1452, and 1742 trees/acre
	----------CSA and Former Citrus Site----------	
Fertilization	Beginning of each cycle	$55 (both) and 70 (citrus) or 90/acre (CSA)
Weed Control	Beginning of each stage	$55/acre (same)
Planting Material	Beginning of each cycle	$0.55 and 0.70/propagule
Real Discount Rates	N/A	6, 8, and 10%
Stumpage Prices	N/A	$9, 14, and 19/green ton
Coppice Yields	Duration of each stage	Expected and Improved
Number of Stages	N/A	5 Stages Maximum

G2 achieved a MAI_{max} of 25 (4.2 years), 27 (6.4 years), and 16.4 (2.8 years) green tons/acre/year at 1025, 2050, and 3416 trees/acre, respectively. The pooled average of MAI_{max} at 3416, 2050, and 1025 trees/acre were 14.3, 24.1, and 20.3 green tons/acre/year, respectively. The low productivity at 3416 trees/acre may be due to nutrient limitations (no fertilization at establishment), heavy clay compaction (no subsoiling prior to stand establishment), and stocking levels above the onset of density-dependent mortality, which corresponds to 55 percent of the maximum stand density index of 490 trees/acre for *Eucalyptus* species (Reineke 1933).

Former citrus site—Through 64 months, planting density, cultivar, and fertilization variously influenced productivity, which was as high as 33.6 green tons/acre/year with fertilized G2 in a 3.8-year rotation at 1742 trees/acre (fig. 2). Unfertilized, chalcid susceptible G1 was the least productive with a MAI_{max} of 9.2 green tons/acre/year at 869 trees/acre. Fertilized G3 in a 4.3-year rotation was the most productive at 581 trees/acre with a MAI_{max} of 24.2 green tons/acre/year. Fertilized G2 had the highest yields at 869, 1162, and 1742 trees/acre. The MAI_{max} for fertilized G2 at 869 and 1162 trees/acre were 20.1 and 31.3 green tons/acre/year in 5 and 3.5 years, respectively. Fertilized G5 was superior at 1452 trees/acre with a MAI_{max} of 26.1 green tons/acre/year in a 5-year rotation. The pooled averages of MAI_{max} were 12.8, 14.0, 22.4, 22.5, and 30.9 green tons/acre/year at 581, 869, 1162, 1452, and 1742 trees/acre, respectively. The double-row configuration was established on the apex of a citrus bed, which could explain its low productivity as there may be less plant-available water and residual fertilizer compared to planting rows established on a bed shoulder or back slope (former citrus row locations).

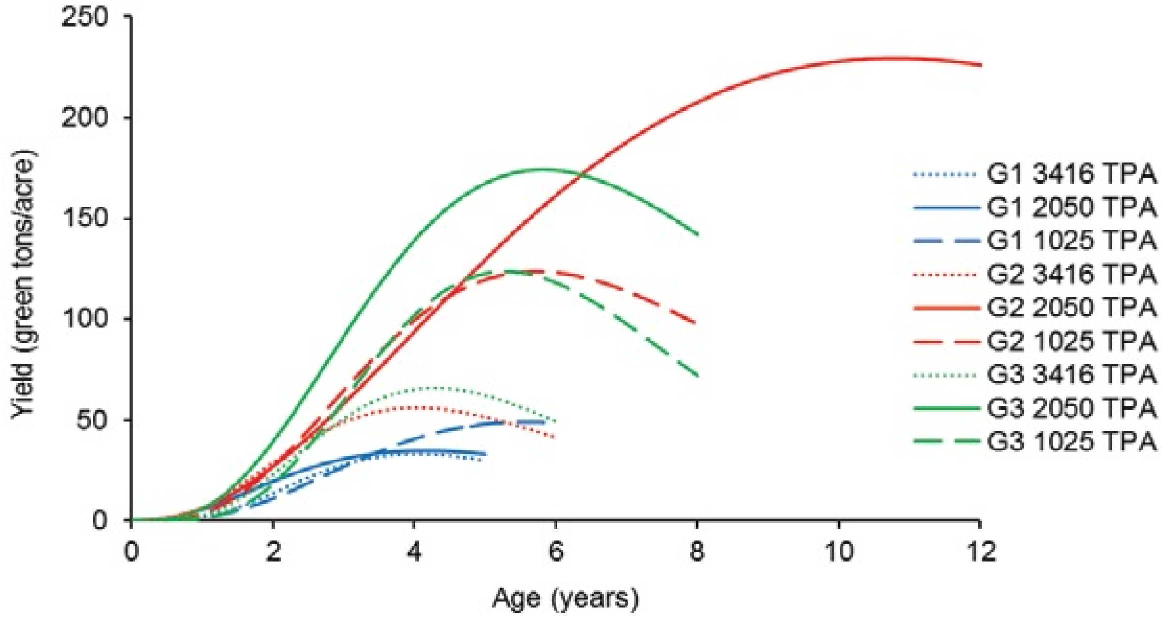

Figure 1—Outside bark yields (green tons/acre) for each cultivar × spacing treatment on a phosphate mined CSA in central Florida.

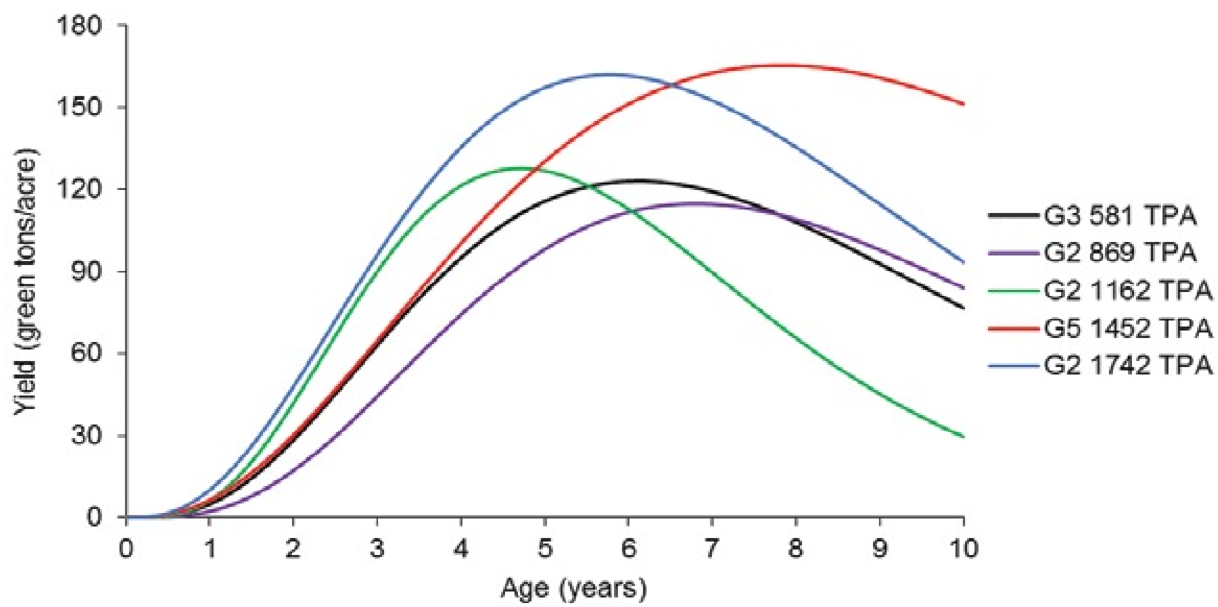

Figure 2—Outside bark yields (green tons/acre) for fertilized cultivar × spacing treatments on a former citrus site in southern Florida.

Financial Results

CSA—Break-even prices were calculated for each genotype at 3416 trees/acre due to low LEV results and the tendency to delay replanting by maximizing the length of the last stage. Since break-even prices exceeded $24/green ton under expected coppice yields and were significantly greater than current *Eucalyptus* mulchwood stumpage prices due to high establishment costs and low productivity, there were no feasible harvest schedules at 3416 trees/acre. For cultivars G2 and G3 at 1025 and 2050 trees/acre, and under all combinations of model inputs, LEVs ranged from -$1168 to 7534/acre. G3 was more profitable than G2 at all three planting densities. Assuming expected coppice yields, G3 generated higher LEVs at 2050 trees/acre compared to 1025 trees/acre under the following inputs: 1) low management costs, $14/green ton, and real discount rates of 6, 8, and 10 percent; 2) low and high management costs, $19/green ton, and real discount rates of 6 and 8 percent; and 3) low management costs, $19/green ton, and 10 percent real discount rate. Table 3 shows the financial results for cultivar G3 at 1025 trees/acre under the least profitable assumptions (high management costs and expected coppice yields) at all three stumpage prices and real discount rates. In addition, assuming improved coppice yields, G3 produced higher LEVs at 2050 trees/acre compared to 1025 trees/acre under the following assumptions: 1) low management costs, $9/green ton, and 6 and 8 percent real discount rates; 2) low and high management costs, $14/green ton, and 6 and 8 percent real discount rates; 3) low management costs, $14/green ton, and 10 percent real discount rate; and 4) low and high management costs, $19/green ton, and 6, 8, and 10 percent real discount rates.

Former citrus site—The most profitable results at each planting density and for all combinations of management costs, stumpage prices, real discount rates, and coppice yields had LEVs ranging from -$1471 to 6193/acre. In general, fertilized stands of G3 at 581 trees/acre and G2 at 1162 trees/acre were the most profitable cultivar × spacing treatments. Assuming high management costs, G3 at 581 trees/acre was the most profitable regime at $9 to 14/green ton, although G2 at 1162 trees/acre generated higher LEVs at $14/green ton and improved coppice yields. At $19/green ton and high management costs, G2 at 1162 trees/acre was the most profitable. However, G3 at 581 trees/acre outperformed G2 at 1162 trees/acre assuming a 10percent real discount rate, $19/green ton, high management costs, and expected coppice yields (table 4). Under low management costs, G2 at 1162 trees/acre was the most profitable for most discount rate, stumpage price, and coppice yield scenarios, but G3 at 581 trees/acre generated higher LEVs under the following assumptions: 1) $9/green ton and expected coppice yields at 6, 8, and 10 percent real discount rates; 2) $9/green ton, improved coppice yields, and 10 percent real discount rate; and 3) $14/green ton, expected coppice yields, and 10 percent real discount rate. Overall, G3 at 581 trees/acre produced higher LEVs under high management costs and low stumpage prices, while G2 at 1162 trees/acre obtained higher LEVs with low management costs and/or high stumpage prices.

The “rank change” in productivity and profitability between cultivars G2 and G3 across planting sites may suggest a genotype × environment interaction (G×E), which could increase as fewer clones are deployed over widely contrasting soil types. With intensive silviculture, there is a greater likelihood of significant G×E interactions with clonal or full-sib family forestry due to less buffering to environmental conditions compared to genetically diverse open-pollinated families, and G×E is caused by both additive and non-additive genetic effects (McKeand and others 2006).

Sensitivity Analysis—In general, increasing the discount rate slightly decreased optimum stage lengths. Additional growth stages were observed at higher discount rates and lower stumpage prices to delay the cost of replanting. This relationship was consistent with results from Smart and Burgess (2000) and Langholtz and others (2007), who observed for coppicing species that increasing the discount rate does not shorten the cycle (rotation) length as it would with non-coppicing species. This is because the opportunity cost of delaying future rotations is proportionally greater than the opportunity cost of holding the growing stock for SRWC systems compared to non-coppicing species. Improved coppice yields may occur if weeding and/or fertilization is applied at the beginning of each stage, which can significantly increase LEV, lengthen coppice cycles, and favor higher planting densities. Furthermore, assuming expected coppice yields, increasing the planting density of G2 to 1162 trees/acre on former citrus lands and G3 to 2050 trees/acre on CSAs were optimal under low management costs and moderate to high ($14-19/green ton) stumpage prices.

CONCLUSION

Under current market conditions in central and southern Florida, which includes high operational costs and low to moderate mulchwood stumpage prices ($9-14/green ton), *Eucalyptus* SRWCs could generate LEVs that are comparable to, or greater than, Florida agricultural land prices. G Series cultivars can be profitable at real rates of 10 percent on CSAs and former citrus lands, even at moderate stumpage prices, high operational costs, and expected coppice yields. Continued progress in *Eucalyptus* genetic improvement for Florida conditions is essential to increasing growth, freeze resilience, and chalcid resistance, and to meet feedstock demands when bioenergy markets develop.

Table 3—Financial results for cultivar G3 at 1025 trees/acre on a CSA, assuming expected coppice yields, high management costs, three stumpage prices, and three real discount rates

Stumpage Price ($/green ton)	Real Discount Rate	LEV ($/acre)	Stage Lengths (years)
9	6%	301	4.7, 4.7, 4.7, 4.6
	8%	-69	4.6, 4.6, 4.7, 4.7, 4.4
	10%	-292	4.5, 4.6, 4.6, 4.7, 4.7
14	6%	1824	4.6, 4.5, 4.4
	8%	1027	4.5, 4.5, 4.5
	10%	561	4.5, 4.5, 4.5, 4.3
19	6%	3443	4.5, 4.5, 4.3
	8%	2215	4.5, 4.4, 4.3
	10%	1472	4.4, 4.4, 4.3

Table 4—Financial results and optimum stage lengths for the most profitable (fertilized) cultivar × spacing treatments on a former citrus site, assuming expected coppice yields, high management costs, three stumpage prices, and three real discount rates

Stumpage Price ($/green ton)	Real Discount Rate	Cultivar	Trees Per Acre	LEV ($/acre)	Stage Lengths (years)
9	6%			-146	4.9, 4.9, 4.8, 4.4
	8%	G3	581	-422	4.7, 4.8, 4.8, 4.6
	10%			-596	4.6, 4.7, 4.7, 4.7
14	6%			1309	4.7, 4.6, 4.3
	8%	G3	581	627	4.6, 4.5, 4.4
	10%			214	4.5, 4.5, 4.4
19	6%	G2	1162	3043	3.9, 3.8, 3.6
	8%	G2	1162	1800	3.8, 3.8, 3.7
	10%	G3	581	1071	4.4, 4.4, 4.1

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