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RESEARCH ARTICLE

Irrigation and planting density affect river red gum growth

Stephen T. Cockerham

In a 6-year study, production of river red gum, an excellent fuel-wood source, was evaluated for responses to three levels of irrigation, fertilization and planting density. Irrigation and planting density had the greatest influence on tree growth. Irrigation in the fifth and sixth years produced greater wood volume and weight per tree. Tree size was greatest in the wide spacing of the lower planting density. Fertilizer had no effect on any of the treatments. Per acre volume and weight yields were greater at the higher planting density, while individual tree height, diameter, volume and weight was greater at the low planting density. Growers seeking total wood volume per acre can increase yields with the higher density planting and irrigation.

River red gum, *Eucalyptus camaldulensis* Dehnh., has the widest natural distribution in the world of any eucalypt and has few equals as a fuel-wood source (Chippendale and Wolf 1981). Because of its high heating value, it provides significant biomass use efficiency in cogeneration and small power systems (Jenkins and Ebeing 1985). One of the fastest-growing eucalyptus species in terms of height, diameter and tree volume (King and Krugman 1980), river red gum is well adapted to the inland valleys of Southern California (Standiford et al. 1982; Moore 1983b) and has potential for commercial fuel-wood production.

Eucalypt plantations have traditionally focused on the production of firewood, charcoal and pulpwood, but with genetic improvement are increasingly recognized as a resource for quality, higher value solid and reconstituted wood products. This is being driven by the sustainability of eucalyptus plantations (IUFRO 2000). Over the next 20 years, hardwood demand is expected to increase about 30% due to concerns over protection of the tropical rainforest and preference for wood products from certified sustainable forests. However, global oversupply of pulp and pulpwood in the 1990s kept eucalyptus prices low, limiting plantation establishment so that supply is not expected to keep up with the demand (Apsey and Reed 1996). Production and market opportunities for sustainable eucalyptus plantations will continue to grow for the next couple of decades.

Although the response of various eucalyptus species to nitrogen fertilizer varies (Turnbull and Pryor 1978), river red gum has been shown to respond to nitrogen fertilizer (Meskimen 1971; Crabb et al. 1983). However, because the yield response of river red gum is difficult to predict, commercial nitrogen-fertilization practices have been based on known responses of other tree crops (Moore 1983a). The management of nutrition and irrigation should improve commercial biomass yields for use of eucalyptus as an energy source (Standiford et al. 1982). Growing eucalyptus for fuel-wood could be commercially viable if intensive management to increase yield were both economical and practical.

Planting density can affect stand values because the high harvest cost of small trees produced at high densities may exceed the value of the fuel-wood produced (Hartsough and Nakamura 1990). At a density of about 650 trees per acre in a short-term harvest cycle, high yields may be possible without significantly reducing stem diameter (Moore 1983b).

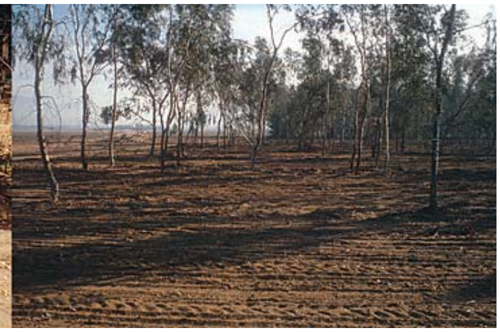
Southern California field trials

In field trials with river red gum, the variables studied were irrigation, nitrogen fertilizer and planting density. The experimental site was in a Southern California inland valley at the UC Riverside Moreno Field Station. The soil was a Ramona fine sandy loam, with a soil moisture holding capacity of 0.11 inches water per inch at 1 to 23 inches soil depth; 0.18 to 0.20 inches water at the 23 to 68 inches depth; and 0.13 to 0.15 inches water at the 68 to 74 inches depth.

Irrigation water contained 550 parts per million (ppm) total dissolved solids, with 0.77 ppm boron. (Boron is toxic to some crops at concentrations over 1.0 ppm.) Previous eucalyptus plantings at the site did not show sensitivity to boron (Moore 1983b). Annual rainfall was 24.3 inches in year 1, 8.6 inches in year 2, 7.6 inches in year 3, 6.9 inches in year 4, 10.0 inches in year 5 and 6.3 inches in year 6. The site's mean annual frost-free growing season is April 15 to Nov. 15, and it is located in *Sunset* western garden climate zone 19.

Irrigation was applied by furrow at 2.0 acre-feet per year (every 4 weeks), 4.0 acre-feet per year (every 2 weeks) and unirrigated control. Nitrogen fertilizer was applied annually as ammonium sulfate (21-0-0) shanked in 4 inches deep on one side of the tree row at 100 pounds per acre, 200 pounds per acre and unfertilized control. The plant density treatment was 302 trees per acre (spaced every 4 feet within row), 454 trees per acre (8 feet within row) and 907 trees per acre (12 feet within row), with 12 feet between all rows. The experimental design was a split plot in a split block, and the treatment design was a three factor-factorial. Irrigation and fertilizer are the





River red gum, an Australian eucalyptus species grown for fuel wood, was tested for response to irrigation, spacing and fertilization over 6 years in Southern California. *Far left,* a furrow-irrigated research plot was planted with 12-foot spacing, and fluorescent paint was used to mark record trees. The next plot has a different spacing, and is separated by eucalyptus guard trees. *Left,* researchers used a fiberglass pole to measure tree height and, *above,* an aluminum caliper to measure diameters. *Above right,* trees were harvested to obtain the final data; guard trees were pulled before the record trees.

two main plot factors, and density as the subplot factor.

The seed source of the river red gum was the Lake Albacutya Provenance of Australia. The treatments were replicated four times. Each plot consisted of 16 trees planted four rows wide by four trees long. The center four trees were record trees used to collect data, with the surrounding 12 trees acting as guard trees. Eight-inch-tall seedlings were planted in summer 1983 and irrigated immediately, with irrigation continued to establishment. Each seedling received one-quarter to one-third ounce of a slow release 21-8-8 fertilizer in the planting hole. Treatments began a year later with the first data collection in the fall, and the experiment was terminated after 6 years. Furrow irrigation began in early April each year and fertilizer was applied in the fall.

There are different calculation methods to estimate tree wood volume. Some require measurement of the trunk diameter at several given points (Skolmen 1983; Pillsbury et al. 1989), or measurement of the height only to the 2-inch-diameter top (Metcalf 1924), which usually requires destruction of the tree. In this study, trees were measured annually in the fall for height in feet and diameter breast height (dbh) in inches at 4.5 feet above the ground. Diameter was measured with a Drescher caliper. Height was measured with a fiberglass telescoping measuring pole from the ground to the tip of the tree.

The equation used assumes each tree is a cylinder from ground level to breast height and a cone from breast height to the tip, allowing an *in vitro* estimate of whole tree volume. The whole tree volume was calculated as $v = d^2(0.001818h + 0.1636)$ in cubic feet, where d = dbh and h = height (Meskimen and Franklin 1978).

At the end of the experiment the trees were cut at 6 inches above the ground. The 6 inches of tree length left in the field as stump was included in the dbh (measured as 4.0 feet from the cut end) and added to the height (length) to be included in the volume calculation, but was not added to the weight measurements. Each tree was pruned of all branches less than 2 inches in diameter and the resulting bole was weighed. The minimum size diameter for firewood is considered 2 inches (Standiford et al. 1982). A cross section approximately 1 inch thick was cut from the butt of a single tree in each treatment in one replication for moisture determination. The mean percent moisture of the green bole was determined as 47.0% with a standard deviation from the mean 3.68% (Meskimen and Franklin 1978).

Factorial analysis of variance was run to test the effects of irrigation, fertilizer, density and all interactions. For the data analysis, means were adjusted for spatial variation in the experimental plot (analysis of covariance). Means in table columns and sections with no letters in common are significantly different with Fisher's protected LSD test at $P = 0.05$. Volumes and weights were transformed to logs to homogenize variances for statistical analysis. (Means were back-transformed from means of log to the base 10 transformed volumes/weights; statistical significance was based on analysis of log-transformed volumes.)

Tree parameters after 6 years

Tree survival was high and not related to treatment effect. Fertilizer had no significant affect on any of the tree parameters measured. In addition, there were no significant interactions between irrigation, fertilizer and planting density on any of the tree parameters measured.

TABLE 1. Mean tree height of river red gum ($n = 16$)

	Year 2	Year 3	Year 4	Year 5	Year 6
	feet				
Irrigation					
Unirrigated	21.1a	25.7a	33.0a	38.8ab	41.4b
2.0 ac-ft	19.5b	25.4a	32.7a	37.8b	42.6ab
4.0 ac-ft	19.9b	26.4a	34.3a	40.1a	44.1a
Significance*	s	ns	ns	s	ss
Fertilizer					
Unfertilized	20.4a	26.3a	33.4a	38.8a	42.5a
100 lb/ac	20.2a	25.7a	33.4a	39.0a	42.8a
200 lb/ac	20.0a	25.6a	33.3a	38.9a	42.7a
Significance	ns	ns	ns	ns	ns
Plant density					
302 trees	19.4a	25.8a	33.7a	39.5a	44.1a
454 trees	20.7a	26.5a	33.9a	40.1a	42.7ab
907 trees	20.0a	25.2a	32.4a	37.1b	41.3b
Significance	ns	ns	ns	sss	ss

* ns = not significant; s = significant at $P < 0.05$; ss = highly significant at $P < 0.01$; sss = very highly significant at $P < 0.001$.

Height. Irrigation at 4 acre-feet increased tree height compared to the unirrigated trees (table 1). The effect of planting density on tree height was significant only in the fifth year in the high-density planting (907 trees per acre), with trees shorter in height than those at the other two spacings.

Diameter. Irrigation increased tree diameters. The trees in the highest irrigation treat-

Left, **record trees were pushed over and pulled up with a skid steer loader, then, *center,* the trunks were cut just above the root mass for measuring. *Right,* final tree heights and diameters were measured with the tree lying on the ground.**

ment (4 acre-feet per year) were significantly greater in diameter than the unirrigated trees (table 2). Diameter was most affected by tree spacing with the greatest diameter at the lowest planting density (302 trees per acre), followed respectively by smaller trunks at the closer spacings and the smallest diameters at the greatest planting density (907 trees per acre).

Whole tree volume per tree. Whole tree volume on a per-tree basis was affected beginning in year 4 due to the affect of irrigation and plant density on tree diameter (table 3). In years 5 and 6 the volume per tree in the highest irrigation treatment was significantly greater than in the unirrigated treatment. The effect of tree planting density was significant, with volume per tree increasing with the wider-spaced, lower planting density of the trees.

Whole tree volume per acre. Irrigation increased the whole tree volume per acre (table 4). In years 5 and 6 the high irrigation rate produced more volume per acre than the unirrigated trees. Volume production at the low irrigation rate was not different from either the high irrigation rate or no irrigation. Whole tree volume per acre was significantly higher with increasing plant density as more trees, even though smaller trees, produced greater total volume.

Weight. Total weight per tree increased with irrigation, while there was no benefit from the high irrigation rate (table 5). With branches smaller than 2 inches removed, the bole weights were not significantly different among the irrigation treatments. Planting density had the greatest effect on tree weight, with the heaviest trees, whole trees and boles produced in the lowest planting density.

Density, irrigation affect growth

Planting density and irrigation had the greatest influence on tree growth. Irrigation made a difference after the trees were well established and into the fifth and sixth years, producing larger trees, as shown by wood volume and weight per tree. Tree size was greatest in the open spacing of the lower planting density.

The planting density of 907 trees per acre yielded a mean tree size of 1.96 cubic feet and weighing 262.2 pounds green weight (139.0 pounds dry weight) per tree, while 302 trees per acre yielded a mean tree size of 4.36 cubic feet weighing 483.9 pounds green weight (256.5 pounds dry weight) per tree, an increase of 122% in size and 85% in weight.

For commercial production, the most wood was produced at the highest planting density per acre. Even though trees grown at the low planting density were bigger and heavier, they were not big enough or heavy enough to exceed the total wood volume produced per acre in the high tree population. Total per acre fuel-wood production was 1,310.5 cubic feet and 73 tons (38.7 tons

TABLE 2. Mean diameter breast height of river red gum (n = 16)

	Year 2	Year 3	Year 4	Year 5	Year 6
			inches		
Irrigation					
Unirrigated	4.1b	3.7b	4.3b	5.1b	5.8b
2.0 ac-ft	4.4a	3.8ab	4.4ab	5.3ab	6.1ab
4.0 ac-ft	4.5a	4.0a	4.6a	5.5a	6.4a
Significance*	ss	s	s	s	s
Fertilizer					
Unfertilized	4.3a	3.8a	4.4a	5.2a	6.1a
100 lb/ac	4.4a	3.8a	4.4a	5.3a	6.1a
200 lb/ac	4.3a	4.0a	4.5a	5.4a	6.1a
Significance	ns	ns	ns	ns	ns
Plant density					
302 trees	4.8a	4.3a	5.0a	6.0a	7.1a
454 trees	4.6b	4.1b	4.6b	5.5b	6.3b
907 trees	3.6c	3.2c	3.8c	4.4c	4.9c
Significance	sss	sss	sss	sss	sss

* ns = not significant; s = significant at $P < 0.05$; ss = highly significant at $P < 0.01$; sss = very highly significant.

TABLE 3. Mean whole tree volume* per tree of river red gum

	Year 2	Year 3	Year 4	Year 5	Year 6
			cubic feet		
Irrigation					
Unirrigated	0.88a	0.83a	1.33b	2.08b	2.79b
2.0 ac-ft	0.95a	0.85a	1.36b	2.16ab	3.13ab
4.0 ac-ft	1.00a	0.95a	1.60a	2.50a	3.50a
Significance†	ns	ns	s	s	s
Fertilizer					
Unfertilized	0.94a	0.87a	1.43a	2.22a	3.14a
100 lb/ac	0.96a	0.85a	1.39a	2.23a	3.05a
200 lb/ac	0.93a	0.91a	1.45a	2.27a	3.17a
Significance	ns	ns	ns	ns	ns
Plant density					
302 trees	1.19a	1.12a	1.86a	3.00a	4.50a
454 trees	1.08a	1.03a	1.57b	2.57a	3.33b
907 trees	0.65b	0.58b	0.99c	1.45b	2.03c
Significance	sss	sss	sss	sss	sss

* Volume = $d^2(0.001818h + 0.01636)$(Meskimen and Franklin 1978).

† ns = not significant; s = significant at $P < 0.05$; ss = highly significant at $P < 0.01$; sss = very highly significant at $P < 0.001$.

Finally, trees were weighed with a forklift and crane scale. The authors found that river red gum trees did best when irrigated with at least 4 acre-feet of water per year and at about 900 trees per acre; fertilizer did not have an effect.

TABLE 4. Mean whole tree volume* per acre of river red gum

	Year 2	Year 3	Year 4	Year 5	Year 6
	cubic feet/acre				
Irrigation					
Unirrigated	441a	412a	664b	1,035b	1,388b
2.0 ac-ft	473a	422a	678b	1,077ab	1,559ab
4.0 ac-ft	497a	475a	796a	1,244a	1,739a
Significance†	ns	ns	s	s	s
Fertilizer					
Unfertilized	470a	434a	712a	1,106a	1,567a
100 lb/ac	479a	421a	694a	1,109a	1,519a
200 lb/ac	460a	452a	724a	1,130a	1,582a
Significance	ns	ns	ns	ns	ns
Plant density					
302 trees	358c	339c	562c	904b	1,359b
454 trees	488b	463b	710b	1,163a	1,505b
907 trees	593a	527a	898a	1,317a	1,840a
Significance	sss	sss	sss	sss	sss

* Volume = $d^2(0.001818h + 0.01636)$(Meskimen and Franklin 1978).

† ns = not significant; s = significant at $P < 0.05$; ss = highly significant at $P < 0.01$; sss = very highly significant at $P < 0.001$.

dry weight) with the widely spaced trees and up to 1,774.3 cubic feet and 118 tons (62.5 tons dry weight) in the closest spacing, an increase of 35% in volume and 63% in weight.

As potential for firewood, the smaller trees of the high-density planting retained 64% of the wood weight after removal of branches smaller than 2 inches, while the larger trees in the low-density planting retained 75%. Still, the high plant population produced, per acre, 76 tons (40.3 tons dry weight) firewood compared with 55 tons (29.2 tons dry weight) in the low density. By year 6, irrigation increased whole tree volume per tree by 25% and whole tree weight by 27%. A similar irrigation effect of 27% increase in bole weight was not statistically significant, an indication of the large sapling variability among the record trees.

Based on our study, irrigation of at least 4.0 acre-feet per year would increase fuel-wood production in planting densities of at least 907 trees per acre in commercial production of river red gum. The cost of water may be a determining factor in the use of irrigation. Nitrogen fertilizer had no effect, and is uneconomical for river red gum production in a short rotation of 6 years.

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TABLE 5. Mean green weight (dry weight) per tree of river red gum after 6 years of irrigation, fertilizer and plant density treatments

	Total	Bole
	lb/tree	
Irrigation		
Unirrigated	326.5(173.0)b	238.2(126.2)a
2.0 ac-ft	383.9(203.5)a	254.7(135.0)a
4.0 ac-ft	413.1(218.9)a	302.3(160.2)a
Significance*	sss	ns
Fertilizer		
Unfertilized	364.5(193.2)a	286.4(151.8)a
100 lb/ac	371.2(196.7)a	249.5(132.2)a
200 lb/ac	382.8(202.9)a	256.7(136.1)a
Significance	ns	ns
Plant density		
302 trees	494.9(262.3)a	366.3(194.1)a
454 trees	398.3(211.1)b	298.8(158.4)a
907 trees	262.7(139.2)c	167.6(88.8)b
Significance	sss	sss

* ns = not significant; s = significant at $P < 0.05$; ss = highly significant at $P < 0.01$; sss = very highly significant at $P < 0.001$.

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