Yields in High Density, Short Rotation Intensive Culture (SRIC)—Plantations of *Eucalyptus* and Other Hardwood Species[1,2]

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Abstract: Initial high density (17,200 trees ha^{-1}, 6961 trees a^{-1}) plantations of Eucalyptus grandis yielded up to 22 oven dry tons (ODT) ha^{-1} yr^{-1} (10 ta^{-1} yr^{-1}) on an approximate 6 month rotation. Border effects could not be eliminated from the small sized plots used. Also within 4 years of planting there were substantial differences in tree vigor and survival such that the effective density was reduced by half. Subsequent plantations of several hardwood species at 5000 trees a^{-1} and with somewhat better border protection were harvested 2 years after planting; tree survival was greater and in some E. camaldulensis plantings yields were in excess of 37 ODT h^{-a} $1yr^{-1}$ (16.5 ta^{-1} yr^{-1}). Accounting for border pct. E. camaldulensis and E. cam x rudis outyielded Salix, Acacia, Populus and Ailanthus sp. tested. Current trials are with greater border thickness and compare seedling and clonal plantations of some fast growing eucalyptus selections at planting densities from about 1900 trees a^{-1} down to 600 trees a^{-1}.

From the outset the major goal of our research has been to determine the feasibility of growing fuelwood as an alternate crop on underutilized but otherwise high valued farmlands (say \$1500 a^{-1}). An economic analysis, which has essentially driven our studies on yields, revealed that profitability of fuelwood plantations depended upon production rats grater than 15 tons per acre per year (t a^{-1} yr^{-1}) of oven dried wood.

Methods

The parameters used in the analysis are listed in table 1. The costs assumed are those applicable for well-managed farmlands in the Central Valley of California. Budget generators, available from the department of Agricultural Economics, University of California, Davis, have many more line items from detailed studies with several field crops. A goal of our research was to verify or alter the assumed costs that we have used in our analysis, using input data from cooperators wherever possible. Keeping the limitations in mind, the break-even, farm-gate price for wood chips, with a 15 t a^{-1} yr^{-1} yield, is about \$43 t^{-1} for the first harvest and \$20 t^{-1} for subsequent harvests. These prices are competitive with wood chip prices quoted in the Sacramento area for March 1983.

Results

Survey Studies

Small E. grandis plantations at Santa Ana, Calif., with over 6900 seedlings per acre (on 30 in. centers) and harvested twice annually yielded about 10 t a^{-1} yr^{-1} in the third year following planting out (table 2), and the 4th year from seeding (Sachs and others 1980). Although at the time this yield was considered high for plantations at this latitude and climate, we realized that it was probably substantially below what could be achieved with altered management practices and better selection of planting material (Skolmen, 1983). (Many herbaceous crops, C_4 plants well-adapted to the Central Valley, could outyield the eucalypts, although higher cultural costs may be required annually raising the breakeven price for biomass above that for perennial species. These herbaceous species could well be utilized as primary fuel crops under certain economic and fuel delivery systems). The E. grandis seedlings were from a non-selected seed lot in which some of the individuals were quite vigorous, but also in which variability was extremely high. (Seed from collection of A. Leiser, Professor of Environmental Horticulture, University of California, Davis, Calif.). The plots were self-thinning in that weak individuals could not compete and large holes developed in the borders as well as sampling areas. In 1982 the blocks were thinned with trees on approximately 5-ft centers, to about 1700 trees a^{-1}. These plots can no longer be used to obtain accurate estimates of yields for large-scale plantations because the borders are not sufficiently dense. They will show, however, what is to be expected from wind-break plantings of moderate height. Based on current growth rates we estimate harvest rotations of three to four years and yields approaching 20 t a^{-1} yr^{-1}.

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[2]Useful conversion factors:
T ha^{-1} = 2.24 x t a^{-1}
a = 0.4047 ha

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Table 1--Economic Analysis for Woody Biomass (Cordwood and Chips) in Short Rotation, Intensive Culture Plantations in California

Estimated Woody Biomass Costs

Calculations based on:
- Planting approximately 1000 trees per acre for cordwood or 1200 trees per acre for chips.
- 4-year harvest cycle.
- Cost of land, labor, and operations.

Operations	Assumed cost a^{-1} (cordwood)	Assumed cost a^{-1} (chips)
	---- Dollars ---	
Land Rent	150	
Site Preparation	150	
Weed Control	100	
Plant Materials (0.35/tree)	350	420
Irrigation Installation	300	
Planting	75	
Pesticides	50	
Fertilization	50	
Total	1,225	1,295

Annual maintenance	Assumed cost $acre^{-1}$ yr^{-1}
	---- Dollars ---
Land Rent	150
Irrigation	100
Fertilization	50
Subtotal	300
Total for 3 years	900

Harvesting	Cordwood	Chips
	---- Dollars ---	
Cutting and stacking	1,000	400
Total for 4 years (excluding transportation)	3,125	2,595

Estimated Yields for Intensively Cultured Wood Lots

Cordwood
- 7 cords a^{-1} yr^{-1}
- Harvest 700-1000 trees a^{-1} every 4 to 6 years.
- Wood will have approximately 50 pct. moisture content and need one year to air dry.

Wood Chips
- 15 dry tons a^{-1} yr^{-1}
- Harvest 1000 trees a^{-1}.
- Whole tree harvesting.

Break-Even Prices

	---- Dollars ----	
First harvest (4th year)	112/cord	43/ton
Subsequent harvests (every 4 years)	43/cord	20/ton

Table 2--Yield from *Eucalyptus grandis* plots, spacing of 2.5' x 2.5' ft at a density of 7600 trees a^{-1}, Santa Ana, California[1].

Plot	Harvest dates: 11-77	6-78	9-78	6-79	9-79
			$t a^{-1}$		
1	7.5	2.5	2.9	6.9	4.3
2	4.6	5.1	2.5	5.1	3.2
3	3.8	5.5	2.8	6.0	3.6
4	3.3	2.1	1.3	5.8	3.5
Avg.	4.8±1.9	3.8±1.7	2.4±0.7	6±0.7	3.7±0.5

Plot	Annual harvest totals: [2]11-77 to 9-78	6-78 to 6-79	9-78 to 9-79
		$t a^{-1}$	
1	5.4	9.8	11.2
2	7.6	7.6	8.3
3	8.3	8.8	9.9
4	3.5	7.1	9.3
Avg.	6.2±2.2	8.3±1.2	9.7±1.2

[1]Source: Sachs and others (1980).

[2]10-month harvest.

Clonal vs Seedling Plantations

The Santa Ana site is being used to obtain performance data for selected seedling plantations of *E. grandis* and clonal plantations of *E. camaldulensis*. (*E. grandis* seedlings were obtained from the Florida Division of Forestry; *E. camaldulensis* clones C-1 and C-2, Low and others, 1983). No yield estimates are yet available for any of the plantations. For *E. grandis* growth rates are very high for selected individuals, but variance is once again very large (fig. 1). Holes are developing in the plantations in the first year from planting; hence, large variations in yield can be expected depending upon the area sampled. In practice variance of this magnitude will result in lower yields on short rotation cycles simply because part of the land area will not be covered with photosynthesizing tissue.

It is too soon after planting to analyze variance in the clonal plantations of *E. camaldulensis* at Santa Ana, but experimental blocks at Davis of a mixture of four clones of *E. camaldulensis* x *rudis* show greatly reduced variance (fig. 2). For this reason establishing clonal

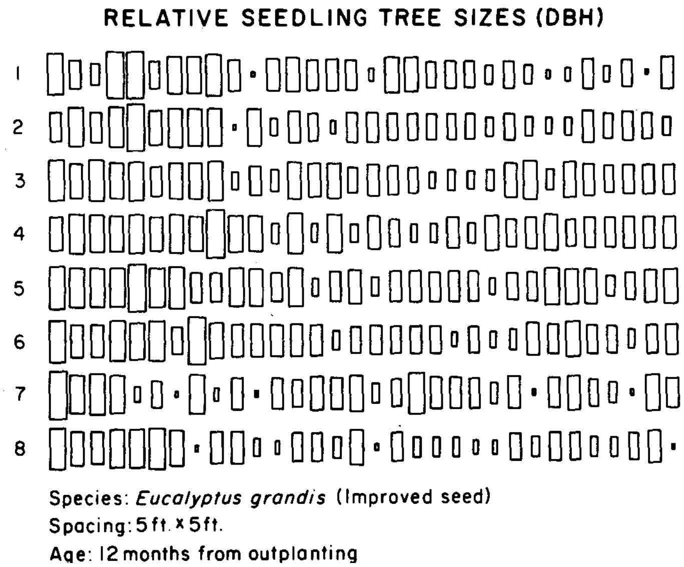

Fig. 1. Schematic computerized diagram of trunk diameters at breast height (dbh) of seedling plantation of E. grandis, 1 year after planting out at Santa Ana, California. Trees are on 5 ft centers in and between 8 rows; dbh is not to the same scale as that of the plantation.

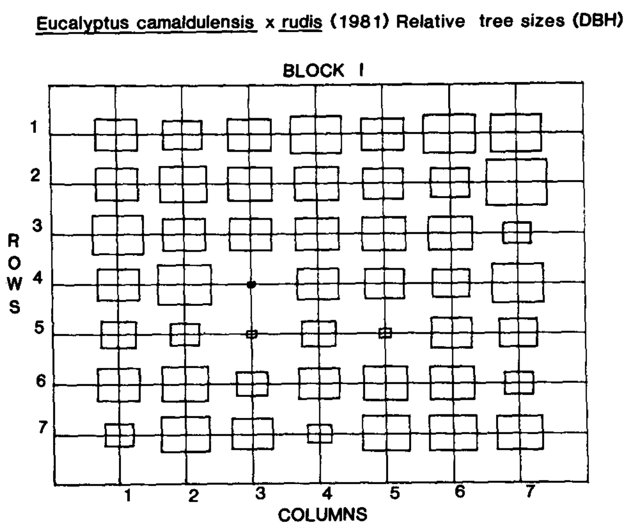

Fig. 2. Schematic diagram of dbh of mixed clonal plantation of E. camaldulensis x rudis, 22 months after planting out at Davis, California. Trees are on 5 ft centers in and between rows; dbh is not to the same scale as that of the plantation.

plantations of selected seedlings has become an important goal in our program. The clones we now use are limited to species that are easy-to-root, (E. camaldulensis and E. cam. x rudis), and from a very limited examination of performance at relatively few trees (ramets) at relatively few sites (Low and others 1983). We are expanding the program to include clonal propagation of E. grandis, cold-tolerant selections of E. gunii x dalrympleana (see papers by Boulay and Chaperon, this proceedings), as well. as improved selections from other eucalyptus species and provenance trials.

Species Selection

There is little question that eucalyptus plantations are very fast-growing, but there is no head-to-head comparative data for yields for other highly touted genera (sequoia, pine, acacia, poplar, willow, etc.) and very little from within the eucalyptus genus (Standiford, 1981; Skolmen, this symposium; Mariani and others, 1981). We made one small study at Davis with high density plantings (3' x 3' ft spacings) of several species (table 3).

Table 3--Species trials of six Eucalyptus species, planted in Oct. 1979 and March 1980, at spacing of 3' x 3' ft and at a density of 5000 trees a University of California--Davis, harvested 1982.

Species	Block [1] A	B	
		ta^{-1}	
Ailanthus altissima	13.05	--	4.36
Acacia melanoxylon	13.40	--	5.09
Salix babylonica	15.11	4.44	7.22
Eucalyptus camaldulensis	16.81	13.28	20.3
E. camaldulensis x rudis	16.94	15.9	7.9
Populus ('Fry' poplar)	16.76	3.06	5.17

[1]Yields include leaves and small branches. In some blocks, yield values in error owing to insufficient border. Overestimate incurred is about 10 pct. Missing values and much of the variation among blocks reflect loss of trees when plantings made in late fall.

Results for a few coniferous species are not shown because their two year growth rates were very far below that for any of the hardwood species. Owing to financial limitations these blocks could not be maintained to evaluate coppice yields, long term border effects, management practices and variability. Nevertheless the comparative growth data were highly instructive and permitted us to narrow our search for species adapted to short rotations. Currently we are comparing selected clones of Populus deltoides and E. cam. x rudis. Plantations of Alnus rhombifolia, established at the same time are considerably slower growing and could not qualify as a candidate species for prime lands. They are maintained to demonstrate comparative performance of a potential N-fixing species. Absence of mycortizal organisms may account for some of the reduced vigor in the olders. The poplar crop may match that of E. cam. x rudis in volume growth, even though we had initial establishment problems. Also, at a waste-water treatment plant in

Davis, this same selection of P. deltoides is out performing all other species in the first year from outplanting.

15/Ton/Yr Plantation

At the outset of this paper we stated that approximately 15 dry tons of biomass per acre per year were required to make wood production an economically feasible alternative crop on under-utilized farmland. This yield figure seems achievable with E. camaldulensis and E. cam. x rudis at Davis and probably elsewhere in California's Central Valley. E. camaldulensis plantations in Israel have maintained high yields for more than 80 years and 6 rotations (Kolar 1963) at sites harsher than those typical of farmlands in the Central Valley. Probably higher yields can be expected in the milder winter' climates of southern California (e.g., Santa Ana), but cultural costs will be considerably higher there at these locations. For example, irrigation water is sold above $200 ac. ft^{-1} and at close to $400 ac. ft^{-1} in some locations below the Tehachapi. In all cases that we have examined waste waters will be required for irrigation of plantations in southern California and we have no idea whether or how much the higher salt contents of such waters will depress biomass yield.

Discussion

There is an obvious paucity of comparative data for species performance in short rotation, high density plantations, and there are many other important unanswered questions concerning yields. Our current tests are limited to examining the problem of density and planting pattern (two-row spacings and three within row spacings). Harvest rotation must be established on the basis of growth rate. Non-destructive methods must be developed to establish growth rate (annual volume increment); in collaboration with F. Thomas Ledig and Richard Standiford, we plan to develop volumetric tables for a few eucalyptus species. If we can accurately establish annual volume increments and can use these figures to estimate when growth rate begins to decline, we will have a relatively simple method to determine optimum harvest rotations (and planting densities).

It seems evident from our early studies with very high density E. grandis plantations that yields are depressed with frequent harvest rotations (semiannual in that case). E. grandis should not be treated as a hay crop (an initial goal in our work) if maximum biomass production is desired. Tree establishment time is probably a species specific trait related to development of the root system. This establishment time is probably of no immediate practical significance if one uses volume increment to estimate growth rate and set the harvest cycle accordingly, but it is of theoretical and perhaps, ultimately, practical interest. One would guess that, everything else being equal, species that require less root system development (that is, have a relatively high shoot-to-root ratio) will be among the highest yielding. Reduced root development is, of course, no advantage under non-irrigated, droughty conditions, but our economic model assumes up to 3-acre-feet irrigation during the spring to fall interval. We are using a soil hydroprobe (neutron meter) to determine soil moisture depletion. In this way we will regulate irrigation frequency and amount to make certain that the plantations are not stressed for lack of available soil moisture.

Yields will be dependent upon providing (or returning) to the root depletion zone the minerals extracted at each harvest. Our current goal for the first harvest cycle is to monitor soluble foliar nitrogen and to feed nitrogen at rates sufficient to maintain levels close to that of trees irrigated with half-strength Hoagland's solution. We are far from understanding the nutritional requirements for species (or clones) in our plantations and, as our experimental data improve, expect future modifications of the current practice of adding 100 lbs a^{-1} nitrogen yr^{-1}.

How many clones should we have in a plantation - or in backup gene banks - to protect against catastrophic losses from environmental hazard? For all their advantages in reduction of variance, mono-cultures are particularly susceptible to environmental disease or pest-related losses owing to the absence of genetic-variation, with inherent resistance in at least part of the population. Libby (1980), in addressing the question of the safe number of clones per plantation, concluded that the answer cannot be simple. Monoclonal plantations are frequently the best strategy because they can maximize genetic gain, but some notion must be had of the maximum acceptable economic loss and likely hazards (risk to genotypes) before one can decide to go with only one clone. For eucalyptus in California the most severe hazard has been the infrequent intrusion of polar air with sustained temperatures below freezing. In December 1972, there were 3 days of temperatures below 20° F and in 1932 there were about 7 days with temperatures below 20° F in the San Francisco Bay area and surrounding counties. With the introduction of cold-tolerant clones we should be able to minimize these losses. In coppiced plantations the freeze-induced losses should be limited to the current rotation and only rarely lead to death of entire trees. Diseases and pests of eucalyptus are not unknown, but we have too little information for California to estimate the risk and economic loss.

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