Spacing Trials Using the Nelder Wheel[1]

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Abstract: The Nelder Wheel is a single tree systematic experimental design. Its major application is for plantation spacing experiments. The design allows for the testing of a number of spacings in a small area. Data obtained is useful in determining the response of stem diameter and crown diameter to spacing. Data is not compatible with data from conventional plots unless single tree modeling is utilized. The design is sensitive to individual tree losses. Nelder Wheels were planted at Cal Poly, San Luis Obispo with eight species of eucalyptus and a hybrid poplar in 1980. First year growth results are presented.

The productivity of short rotation biomass plantations will vary with many factors including the spacing utilized in the planting. The nature of energy plantations, where productivity is to be maximized in an extremely short rotation, necessitates determination of optimum planting density. The early yield studies dealing with eucalyptus plantations made no attempt to determine what the optimum spacing might be (Metcalf 1924). Most of the yield data for eucalyptus are for relatively long rotations, conventional spacing and merchantable volumes. Many of the early feasibility studies on energy plantations utilized this yield data for determination of the production possible. Spacings in these yield studies varied up to 16 by 16 feet (USDA Forest Service 1975). More recent spacing studies have been conducted using several different spacings, such as 8 by 8 feet, 10 by 10 feet, 12 by 12 feet, and 14 by 14 feet (Walters 1980). When a plantation project was planned at Cal Poly, San Luis Obispo one of the first questions was that of the optimum spacing to use for the species that were being considered. No answers to that question were available. As a result, the Cal Poly plantings were made with one of the goals being to determine optimum spacings for the species, products, and rotations desired.

The plantation area was limited to 17.5 acres. The size limitation forced the utilization of an experimental design that would allow the testing of many spacings in a small area. The Nelder Wheel or fan design was selected.

NELDER WHEEL DESIGN

Concept

Experiments designed to produce specific answers to questions are the best source of data for deriving models of growth. Much of the available data on plantation growth was obtained from the measurement of existing plantations that were planted with a specific objective in mind. Most often that objective was not to maximize total biomass production, but rather to produce a certain product. If the productivity of those plantations is measured for that product, the data is valid. If the plantation is measured for another product, the model may not be applied to a stand planted with other products in mind.

Experiments should be set up to answer specific general questions rather than to select the best of a set of treatments. The Nelder wheel design is a single tree systematic design with the main application toward spacing experiments in a uniform forest. Systematic designs like the Nelder wheel are laid out in a specified pattern to economize on the size and cost of the experiment. Treatment locations are not randomized and data generated cannot be analyzed by analysis of variance. The data is useful, however, in regression parameter estimation. Nelder wheel experiments have most commonly been utilized for modeling of individual tree growth.

Design and Layout

Nelder wheels are circular plots with a variable number of spokes per plot and rings per spoke (fig. 1 & 2). In the examples shown the plots have 24 spokes and 10 rings. This design provides 240 planting spots per plot. In the Nelder wheel design the innermost and outermost rings should not be included in the data because these planting spots do not have a uniform spacing. The design shown in fig. 1 and 2 would have 192 data trees, assuming 100 percent survival. Any time a tree dies in the plot the four trees in the adjacent planting spots must also be eliminated from the data, because their spacing has been changed.

Before the plot is laid out in the field, the spacing trials desired should be determined. The plot design works best if the interval spacing or radial spacing for planting spots on the spoke is approximately the same as the cross spacing between the planting spots on the spokes. The

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cross spacing can be determined from the following formula:

$$C = \sqrt{2a^2(1-\cos\theta)}$$

where C = cross spacing
       a = interval spacing
       θ = angle between spokes

Plot layout in the field takes a great deal of time and requires a high degree of accuracy. The angle between the spokes must be turned accurately or the spacing between the planting spots will not be accurate. This can be checked most easily by measuring the distance between the spokes at the plot perimeter. The interval spacing along the spokes should also be measured with a high degree of accuracy. Planting spots should be staked prior to planting to assure that planting is carried out over a short time interval.

Nelder wheel plots are frequently divided to provide for varied treatments or replications of species tests. Most frequently the plots will be used for from one to three species or for one to three treatments. This type of plot division can present a problem in data interpretation if the species or treatments vary widely in their growth pattern. Edge effects may be created between treatments or species tests.

Another type of systematic design provides square and rectangular spacing trials. In this design the spacing between trees is increased by a constant for each successive planting in both the x and y axis (fig. 3). This results in spacings of all distances in both a square and a rectangular trial.

Figure 1--Nelder wheel layout showing planting spots, cross pacing, ring interval spacing, and average spacing.
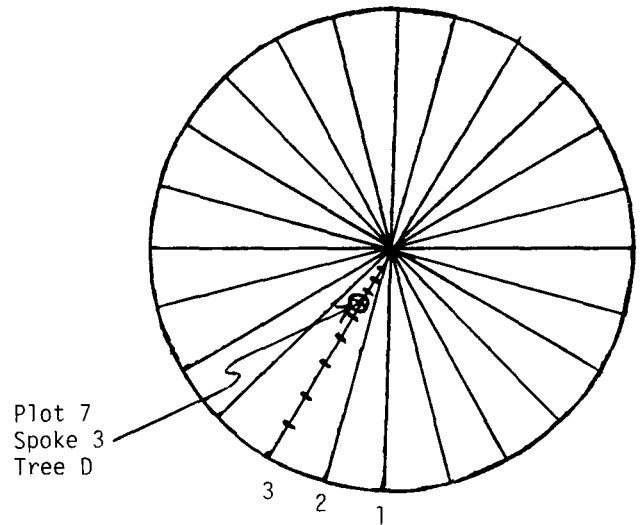

Figure 2--Illustration of labeling of planting spots in Nelder wheels. Planting spot indicated is Plot 7, Spoke 3, Tree D. Tree A is closest to the center.
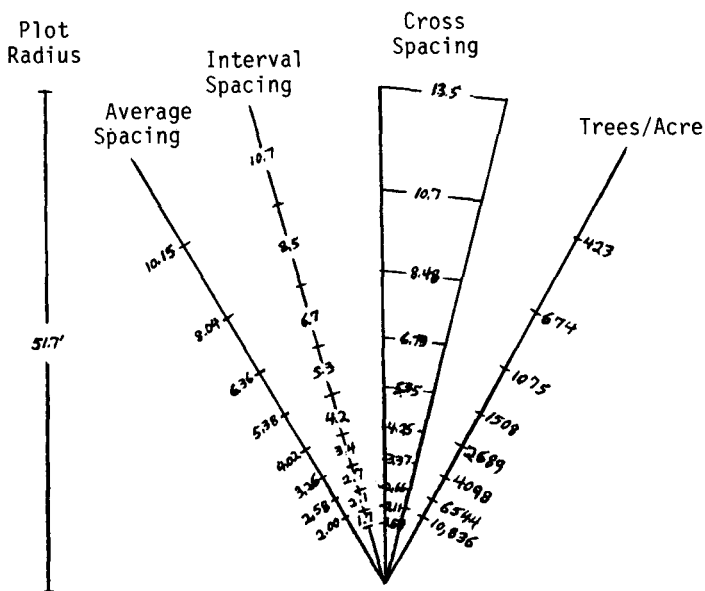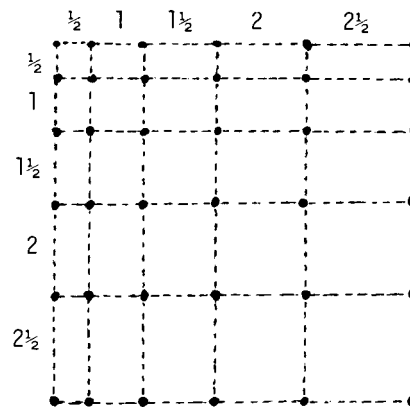

Figure 3--Systematic experiment design using a rectangular design.

CAL POLY NELDER WHEEL EXPERIMENTS

Plot Design

The Nelder wheel design for the Cal Poly spacing trials had 24 spokes with 10 rings on a spoke (fig. 1 & 2) (Kirkley, Pillsbury and Mark 1981). This provided 240 planting spots and 192 data trees per plot. The plot radius to the outermost planting spot was 51.7 feet and each plot occupied 0.23 acres. The average spacing

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distances varied from 2.01 by 2.01 feet to 10.15 by 10.15 feet (Table 1). The angle between the spokes was 15 degrees. These spacings were selected on the assumption that they would bracket the range of optimum spacing for the species being planted.

Plot Layout

Plot layout on the plantation site was complicated by the variable terrain and soils. The plantation site was range land with slopes varying between 5 and 22 percent. The first step was to map the plantation site, including unplantable sites (gullies and rock outcroppings), developments, soils, and topography. This map was utilized in the office to position the plots prior to field location. Once the plot location was determined on the site map, the plot centers were located at the plantation site. The preliminary site preparation, consisting of bi-directional ripping and tilling with a vibrashank, had been done prior to plot location. Plot layout was done using a transit, Clinometer, and steel tape. Spoke angles were turned from the plot center and the outermost planting spot on each spoke was staked. The spoke spacing was checked before staking planting spots along the spokes. Planting spots were determined on the spokes by measuring out the prescribed horizontal distance from the plot center.

Plantings

Eight species of eucalyptus and hybrid poplars were planted in 26 plots. The species of eucalyptus included Eucalyptus camaldulensis (Dehnh.), E. cinerea (F. Muell. ex Benth), E. citriodora (Hook.), E. globulus var. compacta (Labill.), E. polyanthemos (Schau.), E. pulverulenta (Sims), E. stellulata (Sieb. ex DC.), and E. viminalis (Labill.). All the stock was container stock and was obtained from the California Department of Forestry or commercial nurseries.

Prior to planting, the plots were sprayed with "Round-up" to control vegetation which had emerged after the initial site preparation. Plots were not planted within 48 hours of herbicide application. Planting in each plot was finished in the day it was started. Initial planting was completed between February 13 and March 20, 1980. Planting and fertilizing was done using KBC planting bars. Fertilizer treatments included 10 and 21 gram tablets with a 20/10/5 formulation. All plots were planted with one species; however, the plots were split for fertilizer and herbicide treatments.

Pre-emergent herbicide application was started on April 4, 1980. Two herbicides were utilized, "surflan " and "Devrinol". Applications were made on 10 of the 26 plots with each half of the plot treated with a different herbicide. No detrimental effects were recorded from the appli-cation of the pre-emergent herbicide, in fact, the only plot that had no mortality by May 1, 1980 was planted on February 22 and treated. All other weed control was by mechanical means.

RESULTS

The tree growth on the plots was measured in January and February, 1981, approximately one year after planting. The results for six species from the plots of each with the lowest mortality rates are presented in table 2. The tree diameters were measured at the base since the trees had no dbh when planted, and most had none after 1 year of growth. The average height and diameter of the planting stock were as follows:

Species	Height (m)	Diameter (cm)
E. camaldulensis	0.12	0.15
E. cinerea	0.10	0.10
E. citriodora	0.28	0.30
E. globulus var. compacta	0.32	0.29
E. pulverulenta	0.54	0.33
E. viminalis	0.11	0.15

Table 1--Nelder wheel spacing and density as utilized in the Cal Poly, San Luis Obispo spacing plantation

Radius (ft)	Interval Spacing (ft)	Cross Spacing (ft)	Average Spacing (ft)	Trees per acre	Tree Code
51.7	--	13.5	-----	---	I
41.0	10.7	10.7	10.15	423	H
32.5	8.5	8.48	8.04	674	G
25.8	6.7	6.73	6.37	1,075	F
20.5	5.3	5.35	5.38	1,508	E
16.3	4.2	4.25	4.03	2,689	D
12.9	3.4	3.37	3.26	4,099	C
10.2	2.9	2.66	2.58	6,544	B
8.1	2.1	2.11	2.01	10,836	A

Table 2--Height and basal diameter after one year of growth in Nelder wheel plots at Cal Poly, San Luis Obispo.

Tree Species	Percent Survival	Plot Number	Measurement	Tree Code							
				B	C	D	E	F	G	H	I
E. camaldulensis	91	32	ave hgt m	0.25	0.30	0.29	0.27	0.30	0.28	0.28	0.25
			ave dia cm	0.73	0.82	0.94	0.82	0.84	0.78	0.77	0.79
			max hgt m	0.52	0.45	0.47	0.49	0.52	0.52	0.52	0.36
			max dia cm	1.47	1.52	1.72	1.53	1.56	1.54	1.36	1.39
E. cinerea	73	2	ave hgt m	0.56	0.55	0.53	0.53	0.58	0.54	0.54	0.59
			ave dia cm	0.74	0.78	0.81	0.89	0.94	0.84	0.82	0.91
			max hgt m	0.77	1.20	0.87	0.87	1.19	1.10	0.95	1.46
			max dia cm	1.39	1.80	2.16	1.58	1.80	2.29	1.69	2.18
E. citriodora	71	12	ave hgt m	0.74	0.92	0.67	0.73	0.74	0.63	0.86	0.57
			max hgt cm	1.39	1.44	1.38	1.13	1.19	0.97	1.42	1.20
E. globulus var. compacta	60	6	ave hgt m	0.79	0.63	0.71	0.67	0.58	0.60		
			ave dia cm	0.96	0.69	0.67	0.87	0.74	0.73		
			max hgt m	1.08	0.97	1.05	1.01	0.87	0.87		
			max dia cm	1.78	1.28	1.23	1.46	1.06	1.22		
E. pulverulenta	71	3	ave hgt m	0.61	0.69	0.65	0.68	0.67	0.68	0.68	0.78
			ave dia cm	0.66	0.71	0.67	0.77	0.75	0.76	0.74	0.82
			max hgt m	0.86	1.03	0.91	1.03	1.27	1.21	1.00	1.40
			max dia cm	1.00	1.05	0.96	1.40	1.52	1.24	1.38	1.50
E. viminalis	92	13	ave hgt m	0.94	0.89	0.92	0.93	1.04	0.79	0.86	0.91
			ave dia cm	1.24	1.67	1.71	1.75	1.93	1.65	1.78	1.87
			max hgt m	1.45	1.33	1.36	1.33	1.64	1.28	1.52	1.50
			max dia cm	2.40	3.04	2.80	2.48	2.80	2.65	3.14	3.00

In general the height growth was lowest in the innermost rings, peaked between rings C and F, and dropped off again in the outer rings. Diameter growth generally increased from the innermost rings to the outer rings. This pattern of diameter growth would he expected because of the nearly open-grown status of the trees in the outer rings through the first year. In the Cal Poly unirrigated experiments E. viminalis had the greatest average height and diameter growth (1.04 m and 1.93 cm respectively) of all species tested. The best growth occurred in plot 13 ring F, at an average spacing of 6.37 x 6.37 feet. A few trees were remeasured in October, 1982. By that time E. globulus var. compacta had the best growth with a maximum height of 5.1 m, basal diameter of 10.5 cm, and dbh of 5.7 cm.

The mortality was lowest in plots which had good weed control and which were not on ridgetops. Deer browse was a problem with all the plots planted to Eucalyptus camaldulensis, while all other species were lightly browsed or left alone.

LIMITATIONS AND APPLICATIONS OF THE NELDER WHEEL

The Nelder wheel experimental design is well suited to experimentation to determine the optimum spacing for maximum production at a certain rotation. The data will provide single tree data on diameter and crown growth. This data can be applied to uniformly spaced forest situations provided that a single tree model has been developed. The experimental design is excellent for preliminary testing of newly introduced species or for species that are being tested for new product markets or rotation ages.

The Nelder wheel design has also been utilized to make genetic selections based on individual tree performance (Namkoong 1966). The design can

be utilized to select trees that will out-perform others at the same spacing distances and can be utilized to choose the maximum performers at varying rotation ages.

CONCLUSIONS AND RECOMMENDATIONS

Application of the Nelder Wheel

The Nelder wheel design is an excellent experimental design for determining the optimum spacing distance for tree species. The design allows for the testing of several different spacings in a relatively small area. The small size of the plots may distort the growth data because of the edge effect that has been observed in small, dense, open sided row plantings of some species (Zavitkovski 1981). The effect has been shown to extend through several rows along the border of small plots. Similar studies have not been conducted on the edge effect in Nelder wheels.

The design should be utilized only for determining optimum spacing distance. It is best applied in situations where the plots are relatively level. If the plots are placed on a slope, the spacing distances do not really represent the distances intended in the design. The plots are laid out using horizontal distance measurements. If the plots are viewed from directly above, they are circular and the crown space is representative of the spacing design. The opportunity for lateral interception of solar radiation is greater and the available rooting zone is larger. If the plot is viewed perpendicular to the slope, the plot will appear elliptical in shape. This distorts growth data because of the varied spacing, especially if the plots are split with different species or treatments. The Nelder wheel design should be applied where the chance for high survival rates are great. Like all single tree experiments the design is highly sensitive to tree mortality. If a single tree dies, not only is the data for that tree lost, but the data on the four adjacent trees is also lost. The death of a tree upsets the arrangement of the design so that the spacing distances are not as planned.

The data must be analyzed using regression analysis. The data is good for predicting regression parameters. The analysis of variance technique should not be applied to the data, since the design is systematic and not randomized.

One common error made in using the Nelder wheel design is to make yield predictions based on an expansion of the growth data obtained. The average growth for a certain spacing is multiplied by the number of trees peg• unit of land area and a yield is predicted. This is not accurate unless single tree modeling has been applied.

For yield prediction a randomized block design is superior to the systematic design. The plot data is applicable to forest stand yield prediction, is not as sensitive to tree mortality, and can be analyzed using the analysis of variance technique. Stand culture is simpler because of the row arrangement and is better suited to mechanization.

LITERATURE CITED

Alder, D. Forest volume estimation and yield prediction: Volume 2-Yield prediction. FAO Forestry Paper 22/2. Food and Agriculture Organization of the United Nations. Rome, Italy. 1980. 10-15.

King, J. P. and S. L. Krugman. Tests of 36 Eucalyptus species in northern California. Res. Pap. PSW-152. Pacific Southwest For. and Range Exp. Stn., Forest Service, U. S. Department of Agriculture. 1980. 6p.

Kirkley, M. L., N. H. Pillsbury, and W. R. Mark. Silvicultural biomass plantation: A renewable fuel source. In Proceedings of the Symposium on Dynamics and Management of Mediterranean-Type Ecosystems, June 22-26, 1981, San Diego, Calif. Gen. Tech. Rep. PSW-58. Forest Service, U. S. Department of Agriculture, Berkeley, Calif. 1982. 609-610.

Metcalf, W. Growth of Eucalyptus in California plantations. Univ. Calif. Agric. Exp. Stn., Bull. 380. Berkeley, Calif.   1924. 61p.

Namkoong. Application of Nelder's designs in tree improvement research. Proceedings of the Eighth Southern Conference on Forest Tree Improvement, Savannah, Georgia. June 16-17, 1965. Georgia For. Res. Council. 1966. 161p.

U. S. Forest Service. Cooperative progress in eucalypt research. Southern Forest Exp. Stn. Forest Service, U. S. Department of Agriculture. 1975.

Walters, G. A. Saligna eucalyptus growth in a 15-year-old spacing study in Hawaii. Res. Pap. PSW-151. Pacific Southwest For. and Range Exp. Stn'., Forest Service, U. S. Department of Agriculture. 1980. 6p.

Zavitkovski, J. Small plots with unplanted plot border can distort data in biomass production studies. Can. J. For. Res. 2(1):9-12. 1981.