- *Systematic experimental designs, titled 'Nelder' after their originator, provide an effective means of studying growing space/growth relationships in tree plantations. The designs are also versatile, offering economies of area, plants and time. They can be used over a wide range of site types and species.*
- *This note reviews the Nelder design, and discusses statistical issues associated with analyzing results and describes one such experiment established 40 years ago.*
- *While the systematic nature of Nelder experiments can result in a less robust statistical analysis than conventional designs based on random allocation of treatments, by choosing homogenous sites regression analysis can be used for assessing growth patterns in relation to initial plant spacing.*
- *Forest practitioners and researchers can use the methodology described here to evaluate the impact of growing space in conifer and particularly in broadleaved plantations, where comparatively little field research has been undertaken in this country. As the plots are compact and economic to establish they are particularly suited to small woodlots. Their strong visual impact makes them also suited to demonstration.*
- *The assessment of 1a and 1b designs showed that growing space had a significant effect on all characteristics. All, with the exception of form factor, increased with growing space. Close spacing reduced diameter and height growth. Varying rectangularity had no effect on tree growth.*

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Systematic Spacing Trials for Plantation Research and Demonstration

John Redmond, Gerhardt Gallagher and Máirtín Mac Siúrtáin

Introduction

Research on crop structure in Irish forests has largely depended on field experiments. Spacing and thinning experiments have used randomized complete block designs, which typically comprise up to six treatments and up to four replications. Using this approach the trial area often extends over several hectares, and is costly to establish and maintain. Also associated with such designs are buffer zones, installed to avoid the influence of one treatment on another, thereby further increasing the size of the trial.

Nelder (1962) published a description of compact experimental designs for studying plant growing space and alignment in vegetables at Rothamstead Research Station in the UK. These experiments have been adapted for assessing the impact of growing space on trees and they have been established in a number of countries, including Ireland. The characteristics of the design involve single tree plots where growing space or rectangularity, or both, are varied in a continuous and systematic manner across the experiment.

A Douglas-fir (*Pseudotsuga menziesii* (Mirbel) Franco) Nelder design type 1a in Coastal Oregon.

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Four designs were described:

a) Design 1a where tree growing space is varied;

b) Design 1b where rectangularity[1] of the growing area is varied;

c) Design 1c where growing space changes along the horizontal axis and rectangularity along the vertical;

d) Design 1d where growing space changes along the vertical axis and rectangularity along the horizontal (Figure 1).

The experiments can be set up as circles, half circles or quadrants. The benefit of the circular design is that only outer and inner arcs need to serve as buffer zones. Nelder trials can vary in area from 0.15 ha upwards.

Other forestry applications of the Nelder systematic experiment recorded are: Tree improvement (Namkoong 1966); Inter and intra specific tree competition between Douglas fir and red alder (*Alnus rubra* Bong.) (Cole and Newton 1987); Density and tree growth with maritime pine (*Pinus pinaster* Aiton) (Lemoine 1980) and Ecuador laurel (*Cordia alliodora* Ruiz and Pav.) (Hummel 2000); and Increment and mortality with red alder (Knowe and Hibbs 1996). Nelder designs have been used in Europe, Australia, and in North and Central America.

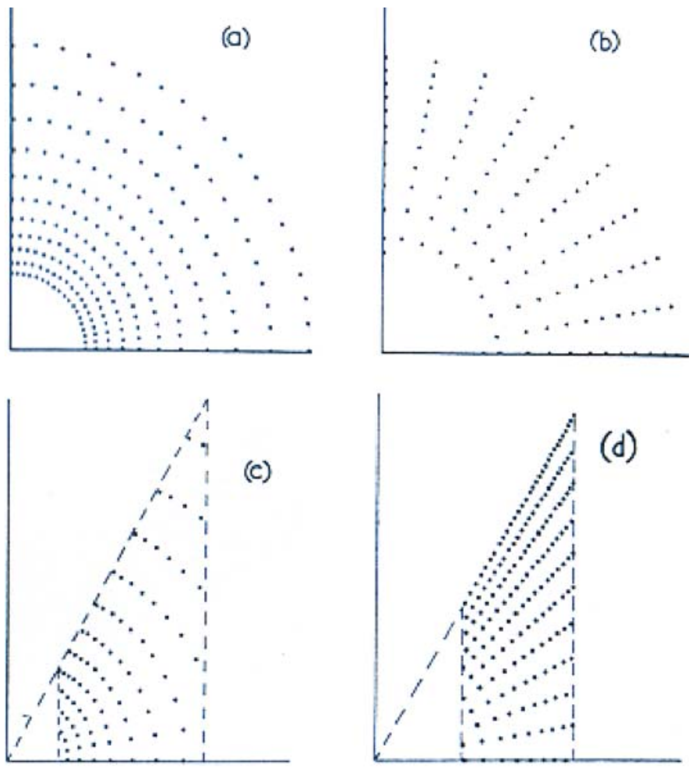

Figure 1. The Nelder systematic designs (Nelder 1962).

Analyzing Systematic Spacing Experiments

As the field layout involves a systematic change in tree growing space the design does not meet the criterion for randomness required for classical statistical analysis. This requires that treatment and site effects are additive and that that experimental errors are independent, i.e. random.

Van Slyke (1963) proposed that the interaction of site effects and treatment effects, i.e. where the spacing of one tree is predetermined by the spacing of the neighbouring tree, can be overcome by careful selection of an homogenous experimental area. This can be confirmed by an assessment of tree characteristics, e.g. root collar or height before competition sets in. Inter arc (i.e. treatment) comparisons of these measurements would show if there were any site differences not shared by the arcs. If at that stage variation was random an analysis of variance could be regarded as acceptable to determine treatment differences. Another constraint is the non-random nature of correlations between neighbouring observations compared with randomized designs where all special arrangements of treatments are equally likely (Affleck 1999). Here, analysis based on spatial correlation could validly replace classical statistical methods. Because of the wide number of treatments (spacings) in these designs, regression analysis, whereby a dependent variable (height or diameter) is related to an independent variable (growing space) are deemed suitable for analyzing Nelder experiments (Hummel 2000, Namkoong 1966). Ultimately these regressions can be expressed graphically or by equations. Linear, curvilinear or non linear (growth function) regression can be used.

The Ballyhoura Experiment

The Nelder designs were introduced into crop structure research in Ireland in 1966 when two trials were established in Sitka spruce and Scots pine by the Forest Service (Gallagher 1980). Around the same time, the Agricultural Institute (now Teagasc) and UCD established a similar trial in Norway spruce. More recently, Teagasc have established a Nelder experiment in poplar at the Kinsealy Research Station (Bulfin pers. comm). Only the Ballyhoura

[1] *Rectangularity is defined as the ratio of the length of the longest to the shortest side of a rectangle; for a square this is 1.*

experiment (14/66, planted in 1966) has survived relatively intact to rotation age.

The experiment is located in Cooldurragha property, Ballyhoura Forest, now under Coillte ownership. The site is a fertile surface water gley; establishment involved single mouldboard ploughing along each spoke of the design. Yield class was estimated at 20 m^3 ha^{-1} yr^{-1} when the stand was measured in 2003 at 40 years of age.

The area comprises four quadrants, two of each design type 1a and 1b. Due to damage just one quadrant from each design was included in the analysis. Details of the designs are given in Table 1.

Quadrant 1a: Tree spacing increases from the centre outwards, from 0.4 m^2 to 25 m^2 per tree (Figure 2). Spokes represent the range of treatments; arcs represent replications of the same treatment. The density of ploughing at the innermost arcs lead to the onset of windthrow, resulting in only the 11 outer arcs being available for analysis. Table 2 shows the range of growing space and stocking examined.

Quadrant 1b: Here shape changes from almost square at the center of the trial to pronounced rectangularity at the perimeter (Figure 3). Growing space is constant at 9.29 m^2 (c 1,000 stems ha^{-1}). All arcs were assessed. Details are in Table 3.

Table 1. The Nelder design and layout in the two designs at Ballyhoura.

	Nelder Design	
	1a	**1b**
Maximum area per tree (m^2)	24.5	9.3
Minimum area per tree (m^2)	0.4	
Rectangularity ratio (length/breadth)	1.0	1.0 – 3.9
Total number of arcs	19	14
Angle between spokes (degrees)	7.51	7.55
Total number of spokes	13	12
Distance (m) from origin to first arc	4.07	19.84
Distance (m) from origin to outer arc	43.04	47.19
Area of quadrant (ha)	0.15	0.16
Yield class (m^3 ha^{-1} yr^{-1})	14 – 20	20

Table 2. Growing space and equivalent stocking in the Ballyhoura experiment of design 1a.

Arc number	1	2	3	4	5	6	7	8	9	10	11
Growing space (m^2)	24.5	18.9	14.5	11.2	8.6	6.6	5.1	3.9	3	2.3	1.8
Stocking (stems ha^{-1})	405	526	684	888	1153	1500	1953	2534	3296	4286	5560

Table 3. Plant spacing and rectangularity in the Ballyhoura experiment of design 1b.

Arc number	1	2	3	4	5	6	7	8	9	10	11	12
Distance between arcs (m)	1.52	1.57	1.63	1.69	1.77	1.85	1.95	2.06	2.20	2.37	2.56	2.87
Rectangularity ratio (breadth/length)	3.9	3.6	3.4	3.1	2.8	2.6	2.3	2.1	1.8	1.5	1.3	1.0

Figure 2. Nelder design 1a, photographed facing the centre, showing increased growing space from centre outwards and windthrow at centre.

Figure 3. Nelder design 1b, photographed facing the centre, showing that at the high rectangularity individual trees are becoming dominant.

Analysis of the Nelder Design

To determine the relationship between growing space and crop characteristics, non-linear analysis was adopted and the result expressed graphically. Taking on board the arguments on randomization and the uniformity of the site (although free growing data were not available to test its homogeneity), analysis was done as if the data were random to facilitate regression analysis. The regression analysis is summaried in the Analysis of Variance table (Table 4). The example used here illustrates the analysis of design 1a data and application of results (Table 4, Figure 4).

The relationship between seven crop characteristics - basal area, diameter at breast height, height, volume, branch diameter, form factor and spacing - was assessed. Stem analysis was done to provide growth and yield data to examine how height and basal area were related to age.

The main variables influenced by growing space are shown in Table 5. Mean values for each variable are derived from each arc with the same spacing.

Table 4. ANOVA for the negative exponential height-growing space model, Tree Ht=22.5429(1-e$^{(-0.5952*\text{growing space})}$)

	DF	SS	MS	F-Value	%SSTOT
Model	2	46442.23	23221.11	6750.32	99.3
Residual	101	347.98	3.44		0.7
Total	103	46790.22			100.0
$F_{0.05(1),2,101}$ =19.5					

Mean dbh ranged from 11.5 cm at closest spacing (1.8 m^2 or c 1.3 m between trees) to 49.0 cm at the widest, 24.5 m^2 or c 5.0 m between trees. The equivalent figures for the other variables are 15.8 m to 23.2 m for height, 0.104 m^3 to 1.129 m^3 for volume and 13.9 mm to 42.1 mm for branch (lowest live whorl), all of these differences were highly significant on the basis of assumptions made.

The assessment of both 1a and 1b designs showed that growing space had a significant effect on all characteristics. All, with the exception of form factor, increased with growing space. Close spacing reduced diameter and height growth. Varying rectangularity for the same growing space had no effect on tree growth.

Table 5. Values of stem and branch growth parameters in 40-year-old Sitka spruce (Ballyhoura Nelder design 1a).

	GROWING SPACE (m^2)										
	1.8	2.3	3.0	3.9	5.1	6.6	8.6	11.2	14.5	18.9	24.5
dbh (cm)	13.4	18.2	22.0	20.2	23.1	26.7	25.7	34.4	35.5	39.3	37.8
Height (m)	15.8	17.6	19.7	19.9	21.6	21.4	21.2	22.8	22.9	23.4	23.2
Tree Volume (m^3)	0.104	0.230	0.355	0.300	0.447	0.562	0.516	0.944	0.935	1.214	1.129
Branch diameter (mm)	13.9	18.6	20.3	19.5	23.1	25.1	25.2	34.5	33.8	36.4	42.1

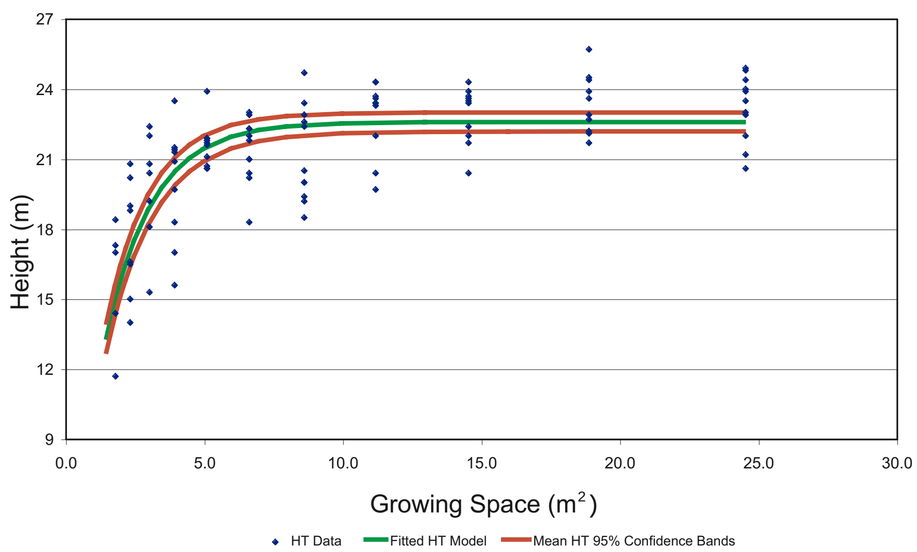

Figure 4. Negative exponential model for height (HT) as a function of growing space.

The results also suggest that variable stand density yield models can be constructed from the relationships of height, basal area, volume and time. The difference between models for a densely and widely stocked stand is quite distinct.

Discussion

A number of considerations arise from the plot design. At Ballyhoura some windthrow occurred, limiting the measurements to two quadrants. For further application a number of replications of the experiment would provide more precise statistical inference. Such replication would be relatively inexpensive compared with the more traditional approaches referred to above.

Sites should be chosen with care to ensure the greatest possible uniformity. Also, establishment techniques should be chosen to avoid creating site differences, (which would lead to non-random effects), thereby conforming to the requirements for analysis of variance techniques. For example, the Ballyhoura site was ploughed with a single mouldboard between spokes, which meant that site treatment changed with spacing. Ground preparation also caused windthrow at the closest spacing. Carefully chosen farmland sites, with uniform soil and drainage characteristics, not requiring site preparation, are more suitable for Nelder sites. It is also advisable to record the crop variation by measuring height and root collar before competition at the closest spacing sets in.

To get most out of these designs the location of a spacing rectangularity plot (design 1b) along with growing space plots (design 1a) is advisable to confirm the Sitka spruce result that growth characteristics are relatively unaffected by rectangularity.

The results should help the forest manager in establishing objectives for the final crop in terms of the dbh, height, volume and quality to be achieved. The absence of rectangularity effects should allow considerable flexibility for access and stand management.

Although the trial described here has limitations, the results can be plainly seen on the ground and as such it constitutes a useful demonstration area. Only one species has been analysed under Irish conditions. Farmers are now planting a wide variety of species including a greater range of broadleaves than was the case when this trial was established. In order to get the best value in terms of yield and quality from plantations Nelder trials would help to optimise plantation establishment and management, especially in the case of broadleaves, where spacing at establishment is often discussed. The establishment of trials on newly planted sites should not strain resources unduly, especially if done as a co-operative venture between forest owners or with timber or woodland management companies.

While the Nelder design is statistically less rigorous than randomized experiments it is still a very effective tool for understanding the impact of growing space in plantations where correlations are very strong. Measurements are easily done and results can be tabulated and graphed. Non-linear regression analysis techniques can be used to model data from the experiment. The analysis needs an interactive framework, allowing the internal goodness of fit of the model to be tested, and, if the fit is poor, other approaches can be investigated.

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