Crop Structure Studies in Ireland

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ABSTRACT

Information requirements on management techniques for fast growing exotic conifers planted in the State afforestation programme emphasised the need for crop structure research. Sample plot thinning series had been used for yield studies in Europe since the last century. More recently, statistically designed experiments have been established in many countries. Research in this field commenced at the end of the 1950's in the State Service. There are now over forty spacing and thinning experiments, the majority in Sitka spruce and coastal lodgepole pine. Some of the spacing experiments have now reached first thinning, and some thinning experiments are approaching rotation age. A data storage retrieval system has been developed to facilitate summary, analysis and comparison of plot measurement. In general results are consistent with research in countries within and outside of Europe. Cumulative volume production differences due to changes in growing space have less practical significance than those for diameter size, diameter and volume distribution. Volumes in the larger tree size categories increase considerably with increased spacing and thinning. This in turn influences profitability and quality. Economic criteria tend to favour increased growing space due to wider spacing and thinning though with the former, especially, serious consideration must be given to possible quality limitations which must be investigated further. Stand stability may be safeguarded by wider spacing, and put at risk by thinning but data are scanty. There are applications for crop structure research in extending stand management options and building models to judge them by, in terms of production, end-use and profitability. There is room for developing broader stand management strategies related to supply and demand and for constructing new forecasts. From present results a rough guide to decision making might be drawn up and improved as additional information becomes available.

INTRODUCTION

Since its inception, over 60 years ago, State forestry in Ireland has developed distinctive characteristics in terms of sites and species planted, age structure, regional distribution and so on. The

GROWING SPACE IN CONIFEROUS CROPS
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expansion of the planting programme from 7000 ha in the ten year period 1923-32 to 90,000 ha in 1963-72 is an indication of the increased harvests to be expected. Consideration of the processes which shape the produce is opportune.

Though Irish forestry was founded on exotic species and the best imported silvicultural techniques, regional and local conditions soon posed problems which required indigenous solutions. Not least in importance was the need to develop systems of stand management suited to the country, especially in relation to Sitka spruce and lodgepole pine. This required conceiving and testing methods to derive the maximum benefits from the new forests in terms of quantity, quality, consistency of produce and value for money invested, while safeguarding capital and increment.

CROP STRUCTURE

Tree growing space has a far reaching influence on crop development. Within stand competitiveness or the lack of it, shapes the tree from an early stage. Crowns, stems and roots react to differences in growing space with consequent effects on timber production, quality, and crop stability. The time at which stands are shaped or modified also influences development in later years. The distribution of tree size and log size within trees effects financial return.

The term crop structure encompasses stand behaviour in relation to spacing at planting time, re-spacing and thinning. These aspects may be subdivided into amount and configuration of growing space and intensity, type and time of thinning.

YIELD STUDIES

Studies in the field of crop structure have been carried out in Europe since the last century. As permanent sample plot measurement became the method for successive evaluation of forest growth and yield, information on the behaviour of stands and the trees comprising them increased. The great diversity found in forest crops required an approach which would reduce variation and thereby permit the comparison of specific silvicultural treatments, such as thinning. Consequently plot series, comprising a range of treatments were set up within uniform stands. Some of these, which have records going back to the beginning of the century have survived up to this decade. The most famous include the Norway spruce plots in the Thuringer Wald, Prussia. The Bavarian thinning series and the Dalby experiment in South Sweden (Assmann 1970, Carbonnier 1954).

The 1930's saw an expansion of research as the area of man-made forest grew. Spacing and thinning experiments were established in various countries. In Denmark, Bornbusch set up thinning experiments in Sitka and Norway spruce (Braathe 1957, Henrikssen 1961, Bryndum 1974). In Norway, Mork had designed a Norway spruce spacing experiment (Braastad 1970). Thinning and spacing series were laid down in Britain in a variety of species between the wars (Hummel 1959, Hamilton and Christie 1974) and at Bowmont, in Scotland MacDonald established a comprehensive Norway spruce thinning experiment (McDonald 1932, McKenzie 1962). Elsewhere O'Connor (1935) broke new ground with his correlated curve trend (CCT) southern pine and Eucalyptus spacing plots in South Africa.

The Bowmont and South Africa studies represented a significant development in crop structure research. The first involved the introduction of statistical techniques to thinning experiments as these plots were laid out in a latin square. The CCT plots introduced an ingenious concept of evaluating tree competition and greatly extended the scope of experiments. Incidently both studies still yield useful results (Hamilton 1976, Van Laar 1976).

From the 1950's onwards experimental work involving statistically or systematically designed experiments proliferated. Numbers of these have been reported on in recent years. Examples include Sitka spruce trials in Ireland and the U.K. (Gallagher 1969, 1976, Jack 1971, Hamilton 1976), Norway spruce in Scandinavia, (Braastad 1979, Bryndum 1978, Eriksson 1979) and Douglas fir in France (Bartoli 1971, Oswald and Pardé 1973). North American studies have concentrated mainly on their native pines, Douglas fir and White spruce (Bennet 1960, 1969, Evert 1970 and Reukema 1972), while in Australasia and South Africa, extensive studies have involved Monterey pine and the southern pines (Hawkins 1971, Shepherd and Forrest 1973, Cremer and Meredith 1976, Sutton 1976, Van Laar 1976).

RESEARCH IN IRELAND

The development by Hummel and Christie (1957) of sets of yield tables for conifers in the U.K. meant that a ready source of tabular aids was available in Ireland for most species planted. There seemed little need therefore to duplicate the British sample plot programme which had been in operation since the 1920's (Forestry Commission 1928). However, in one significant respect forestry in Ireland took a different turn and this influenced thinking on crop structure. The performance of the coastal strain of lodgepole pine suggested that forestry based on this species could be viable on poor sites such as blanket peat and old red sandstone podsols (O Carroll 1962).

Until comparatively recently, little had been known about the growth and yield of coastal lodgepole pine, let alone its optimum silvicultural management. In its native habitat it had been regarded as a scrub species and its development as a commercial tree has been largely an Irish phenomenon (Forbes 1928, O'Driscoll 1964, 1979).

Crop structure studies began with this species when in the late 1950's the focus of research was on plantation establishment in the west of Ireland and a number of spacing experiments were established at Nephin Beg and Glenamoy in Co. Mayo (O Carroll 1958, Swan 1958). A recent inventory had also highlighted variation in lodgepole pine (O'Muirgheasa 1964) necessitating the construction of volume and yield tables for the coastal provenence (Joyce 1961, Joyce and Gallagher 1966). This was done through the assessment of felled trees and temporary sample plots. Data from individual plots were however, insufficient to determine what effects of crop management had on this variable and difficult to handle species. An experimental approach was therefore adopted in the early 1960's and extended to examine crop development in other conifers, Sitka spruce, Norway spruce, Douglas fir and Scots pine. Later Monterey pine and grand fir plots were added. Concurrently, studies in Sitka spruce were under way in Northern Ireland (Jack 1971).

While the establishment and early development of experiments has been described (Gallagher 1964, 1971) an overall view of progress seems timely to examine present and future options in the context of work done elsewhere.

Research Methods

Development

The objectives of the experimental programme were simple; to apply a range of spacing and thinning treatments, to determine benefits and limitations under given conditions, to quantify effects and to demonstrate to management. The choice of approaches evolved with new information, individuals and ideas rather than through any basic plan. These have included single sample plots, standard statistically designed experiments, the CCT type approach and clinal systematic experiments.

Experimental Details

Over 40 experiments have been established since 1958. While some have been lost, due to wind damage, most are still functional (Table 1) and are the source of growth and yield data.

Both spacing and thinning experiments are located on a variety of sites on western and upland peats, on old red sandstone podsols, on gleys, and on dry mineral soils. Thinning experiments are located

Table 1 FWS Crop Structure Experiments 1958-79.

Variable	Species	No. of Expts.	Age present or at culmin	Reps.	No. Treat-ments	Range
Spacing at planting	Sitka spruce	5ff	6-19	2-4	5-13	0.2-4.0 m
	Norway spruce	3ff	15	3-4	3-15	1.2-3.6 m
	Lodgepole pine	6	6-20	4	5	1.2-3.6 m
	Scots pine	1	12	2	13	0.2-4.0 m
	Douglas fir	3	11-15	2-4	5	1.2-3.6 m
	Grand fir	1	15	3	5	1.2-3.6 m
Space/ alignment at planting	Sitka spruce	2ff	6-12	2-4	5-13	2.0-0.2x4.0 m
	Lodgepole pine	1f	6	4	5	2.0-2.0x4.0 m
	Scots pine	1f	12	2	13	2.0-0.2x4.0 m
Respacing at 8-10 yrs	Sitka spruce	2	11	2-4	5	700-3000 SPH
	Lodgepole pine		11	4	5	700-3000 SPH
	Douglas fir	1	23	3	5	1.8-3.6 m equivalent
Respacing 8 m top Ht.	Lodgepole pine	3***	14-28	2-3	8	5000-700 SPH in 7 stages
Thinning intensity	Sitka spruce	4	24-38	2-3	3-5	0-80% MAI removed
	Norway spruce	2	36-38	2-3	4-5	0-60% MAI removed
	Lodgepole pine	2*	24-27	2	4	0-70% MAI removed
	Scots pine	2*	-40	2	3-6	0-60% MAI removed
Thinning Type	Sitka spruce	3*	25-31	2-3	2-8	Selection/ systematic
	Norway spruce	2*	21-38	2-3	4-6	Selection/ systematic
Thinning intensity type	Sitka spruce	3	16-18	3	5	Selection/ systematic

Notes: * Experiment written off. f Experiment featuring more than once.
The polar co-ordinate series included are not statistically replicated.

mainly in the more important forest areas in the east, in the south and south-east. There are also trials on the Kilkenny plateau, the Slieve Blooms and northern forests. Sample plots in a widely spaced private plantation in Leitrim have also provided useful data.

The claim by Marsh that O'Connor's CCT plots could answer most questions on stocking, growth and yield for southern pines (1957) was attractive. Two to three replicate, eight plot series were laid down in coastal lodgepole pine on three sites between 1962-65. Though the time of first thinning (or more properly re-spacing) was later than that advocated by the author of this method, i.e. before onset of any competition, useful results were achieved and some plots were maintained for over ten years. Wind damage proved an obstacle to the continuation of these large experiments and by 1974 they had been severely disrupted. However, they did provide material for a revised lodgepole pine yield table (FWS 1976).

Following the first spacing trials established on western peats, a more unified approach was adopted in the 1960's. After examination of information sources a 3 to 4 replicate, randomised complete block series was designed. This compromised between plot size and tree number, allowing bigger (up to .2 ha) plots for wider spacings. Ten experiments were established in five species on a range of sites. Six were devoted to lodgepole pine and Sitka spruce. In the absence of electronic data processing facilities at the time, treatments were spaced orthogonally for easier analysis. Two 'Nelder' systematic designs were added later, one of these in Sitka spruce. 'Spoke' arrangements with systematically changing growing space and plant alignment were used (Van Slyke 1964).

Since then these experiments have been complemented by a replicated Sitka spruce/lodgepole pine (coastal) growing space/alignment experiment and four respacing randomised blocks in the same species. Here plot size and plant number ensure equal numbers of trees for comparison. Again treatments, as defined by proportion of crop removed, were spaced orthogonally.

Thinning experiments are more varied and include a range of intensities, type and times. In general the factors are separated into different experiments where thinning intensities vary at uniform intervals and thinning types are regulated by the same intensity. The range of experiments is not completely satisfactory as conflicts between the number of treatments and number of replicates had not been fully worked out. Space limitation tended to confine replicates to a minimum while allowing a rather wide range of treatments and a consequent risk of these designs was missing plots causing difficulties in analysis. Differences in criteria used to define thinning intensity such as volume removed or remaining, basal area removed or remaining or increment removed combined with inherent stand variations also caused difficulties. Some of these problems are dealt with more satisfactorily in recent trials where larger uniform stands and a number of similarly designed experiments should allow clearer analysis.

Two thinning/fertilising factorial series were laid down in the early 1970's. A large number of thinning replications allowed a fairly sensitive analysis of this factor. A three experiment series has just been established to suppliment information on time, type and intensity of thinning.

Data Collection

A standard type of data collection system has been developed which includes most pole stage experiments (Gallagher 1976, FWS 1978). This is a refinement of the code of sample plot procedure described by Hummel (1959). Sample plot records allow storage of experimental plot, single plot and individual tree data on computer tape in terms of tree numbers, diameter at breast height and tree location by co-ordinate, if required; for plot mapping. Measurement has been simplified in that lengths and diameters measured at arbitrary heights from ground level give a tree volume function.

$$V = 1/12\,L\,(d_1^2 + d_1 d_2 + d_2^2)$$

with d_1 and d_2 frustrum diameters and L its length. tree volume to required top diameters build up plot volumes through the volume basal area line

$$V_d = a + gX$$

all trees being measured for DBH. A sample printout is shown in Fig. 1.

Treatments Applied

Spacing

Distance between plants in square spacing from 1.2 to 3.6m has been the basis of 7 experiments in five species. Distance has been extended to 4.0m in a spacing/alignment experiment and to over 4.0m in almost square arrangement in 'Nelder' grids. Plant alignment varies from almost square spacing at 2.0m to less than 1.0m by 4.0m in these experiments (Table 1).

Respacing

There are five experiments, one established in the early 1960's in Douglas fir and two each in Sitka spruce and lodgepole pine (coastal). These latter have been laid down within the last 5 years.

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FOREST EXPNO BLOCK PLOT  YR   TREAT  STATUS AREA

AVO   6401      1       2  1976  T3  2      MC       0.0405
AGE   NO OF    TOP    MEAN   TOP      MEAN    B.A.    B.A.      VOL       VOL       VOL      VOL        CROWN   CROWN    TOP HT  MEAN HT
      TREES    HT     HT     DIAM     DIAM    TOT     <7        TOTAL     TO 7      TO 18    TO 24      DIAM    %        NUMBER  NUMBER
34    988      0.0    19.5   0.0      24.8    47.56   0.0       473.13    469.10    351.53   99.74      3.57    35.30    0       19
                                                 REGRESSION EQUATIONS
                                                 **********************

                                            Y(TOT)= -0.01624 +  10.28633 * X
                                            Y(7)  = -0.02152 +  10.31126 * X
                                            Y(18) = -0.22191 +  12.00059 * X
                                            Y(24) = -0.56313 +  13.79270 * X

                     ANALYSIS OF VOLUME TO 7 CMS REGRESSION EQUATION
                     VARIANCE=                                  0.00215
                     VARIANCE OF INTERCEPT=                     0.00230
                     VARIANCE OF COEFFICIENT =                  0.84100
                     COEFFICIENT OF DETERMINATION =             0.94049
                     SUM(X-XBAR)**2 =                           0.00256
                     NUMBER OF OBS. =                           10

TREE      DIAM B.H      BASAL AREA      VOL TO 7      VOL TO 18      VOL TO 24      VOL TOTAL

 4          21.9        0.03766856      0.34195437    0.17048999     0.0            0.34635611

10          24.1        0.04561681      0.44434869    0.32908734     0.0            0.44944528

15          22.0        0.03801336      0.45481505    0.33514342     0.0            0.45755349

v23         33.6        0.08866851      0.94366628    0.88700404     0.74090767     0.94636458

31          22.8        0.04082823      0.41595734    0.30222357     0.0            0.42147345

39          29.6        0.06881360      0.61075823    0.51542399     0.31218251     0.61456073

44          20.9        0.03430705      0.31541747    0.15410299     0.0            0.31925705

50          23.3        0.04263858      0.41117948    0.27165029     0.0            0.41592031

58          25.9        0.05268541      0.51622733    0.42633544     0.18349234     0.52051924

63          24.9        0.04869558      0.46481389    0.36500078     0.0            0.46810224
                                              MEAN HEIGHT TREE NUMBERS
                                              ************************
 4   8  10  12  15  17  23  27  31  36  39  41  44  48  50  54  58  61  63   0   0   0   0   0   0   0   0   0   0   0
 0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0


                                              VOLUME TREE NUMBERS
                                              *******************
 4  10  15  23  31  39  44  50  58  63   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0
 0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0


                     B.A. OF DEAD TREES =       0.0      PER PLOT


                                              DBH TREE NUMBERS
                                              ****************

 4   5   8   9  10  11  12  14  15  16  17  19  23  26  27  29  31  34  36  38  39  40  41  42  44

46  48  49  50  52  54  56  58  59  61  62  63  65  66  67   0   0   0   0   0   0   0   0   0   0

END OF PLOT END OF PLOT END OF PLOT END OF PLOT END OF PLOT END OF PLOT END OF PLOT END OF PLOT END OF PLOT
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Fig. 1 Sample Plot Printout.

Stocking differences of between 700 to 3000 SPH have been achieved by cutting out rows, rows and trees and trees 8 to 10 years after planting. A variant of these treatments has been included in the recent experiments to test the hypothesis that a crop of dominants (1000 SPH) and a ground cover of 'topped' trees would enhance production and quality (Moore 1976).

Thinning

CCT type respacing is included under this treatment as material removed was recorded for inclusion in cumulative volume production. the study was confined to lodgepole pine (coastal) and was to involve reducing a series of plots from $>$ 5000 to 700 SPH in seven stages, commencing at 5-8m top height. One plot was left unthinned at each stage and after first reduction, thinning was determined by diameter differences between plots due thinning and an equivalent number of 'main crop' trees in unthinned plots. While these series are now written off because of wind damage one did survive untill fourth thinning comprising plots with a minimum stem number of 900 SPH.

The thinning intensities applied to Sitka spruce, Norway spruce, lodgepole pine and Scots pine plots have varied from no reduction to $>$ 45% volume removed at first thinning and up to 80% periodic annual volume increment removed subsequently. One of the older trials in Sitka spruce at Avoca forest has now reached fourth thinning stage. A variety of thinning types have included single and multiple row thinnings, selection thinnings from above and below and combinations of these, mainly in Sitka spruce. Two IUFRO trials were established in the early '70's in Norway and Sitka spruce. The Norway spruce experiment is replicated in more than 10 European countries and incorporates different rack widths, systematic removal and varying times of first thinning (Abetz 1976). Combined three level thinning and fertiliser trials were also established in Sitka spruce and a recent series in this species examines time and intensity in more detail.

ANALYSIS

Most experiments are designed for analysis of variance or co-variance, with regression to determine trends from varying treatment intensity. Systematic designs rely on regression only.

The nature of spacing and thinning experiments gives rise to differing problems. With spacing experiments set out, at, or not long after planting time, the apparent uniformity of site, plant selection and control of planting means that a wide range of treatments can be confined to apparently uniform areas. However there may be hidden variation as instanced in Table 2, where treatment results were significantly different but an unexpected factor caused a persistent anomaly. As similar experiments have been repeated in the same species on different sites, amalgamation of results will probably give more consistency.

Problems with thinning experiments have arisen, perhaps, from a desire to answer too many questions at once. Wide treatment ranges were ofter included at the expence of replication. In 11 out of 15 experiments replicates were confined to two. Difficulties arose here because of high within treatment variation and loss of plots through wind damage. Table 3 shows an improvement in significance of thinning intensity effects with increased replication.

Table 2. Analysis of Sitka Spruce Spacing at 11 Years (Doneraile).

Treatments	Diameter at breast height (cm)			
	'63	'65	'71	'74
1.2 m square	.24	0.81	4.38	7.1
1.8 m square	.30	1.06	6.43	10.1
2.4 m square	.25	0.76	5.40	9.3
3.0 m square	.27	0.83	6.32	10.5
3.6 m square	.27	0.87	6.83	11.5
L.S.D.	.06**	.29**	2.05**	2.49**

RESULTS

Detailed results are not given but some discussion on the findings from examples of Forest and Wildlife Service (FWS) experiments, especially in Sitka spruce and lodgepole pine (coastal) in relation to work done elsewhere allow general comment on trends and inferences.

Survival and Mortality

All FWS experiments suggest that there is little effect of respacing on survival and these conform with the findings elsewhere (Sjolte Jorgensen 1967, Low 1974, Low and Van Tol 1975).

Later on smaller trees are killed off through competition as stocking increases. Though most experiments are too young for meaningful results on total loss through mortality a survey of unthinned Sitka spruce (Gallagher 1972) indicates a potential loss at close spacings of up to 50% by stems and over 15% by basal area by 14m top height. This compares with 18% loss in 18 year Douglas fir, 60% stem loss in 44 year Scots pine and 25% loss in mature Norway spruce at close spacings (Anderson 1963, Wardle 1967, Oswald and Pardé 1973). American studies have recorded up to 40-50% stem losses in close spaced unthinned lodgepole pine, slash pine and ponderosa pine (Alexander 1960, Evert 1972, Keister, et al 1968). In Finland 25% volume loss occurred in unthinned Scots pine by rotation age (Mielikäinen 1979).

Table 3. Experimental results from 4 Sitka spruce Thinning Series.

Experiment	Coolgreaney 1/63	Avoca 1/64	Kinnitty 3/68	Muskerry 1/73
Treatments	2	3	5	3
Replications	2	2	3	6
Diameter increment at breast height years 1-4 after first thinning (cm).				
No thinning			1.36	1.20
Very light		1.60	1.45	
Light			2.27	
Mod. heavy (Ecl)				
Mod. heavy (Sel.)	2.39	2.17	2.39	
Mod. heavy (line)	2.71			2.02
Very heavy (line)				2.31
Very heavy (Sel.)		2.67	2.72	
Level of Significance %	22.7	5.7	0.9	<0.1

Diameter and Volume Growth

Spacing

Figs. 2 and 3 compare FWS patterns in Sitka spruce and lodgepole pine experiments with numbers of other trials, some taken from the reviews of Sjolte Jorgensen (1967) and Evert (1972), and others more recent (Stiel and Berry 1973, Braastad 1970, 9, Kilpatrick et al 1980, Hamilton and Christie 1974). In general, similar trends are apparent. Crop stem diameters at breast height increase with increased spacing and differences are maintained over time, differentiation occurring from about 7 years depending on crop vigour. Diameters at wide spacing may increase to twice those closer grown, by canopy closure, in all treatments. Diameter distributions also change.

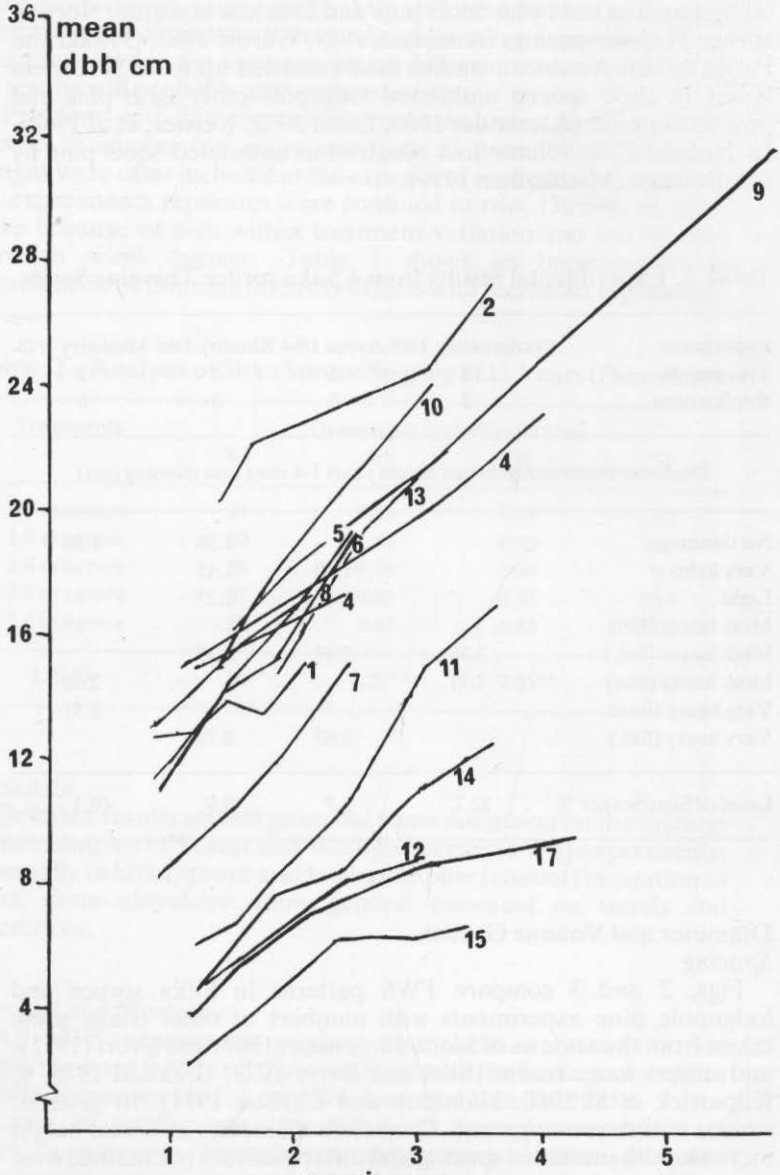

Fig. 2 Diameter growth in spacing experiments.
(For sources see Table 4)

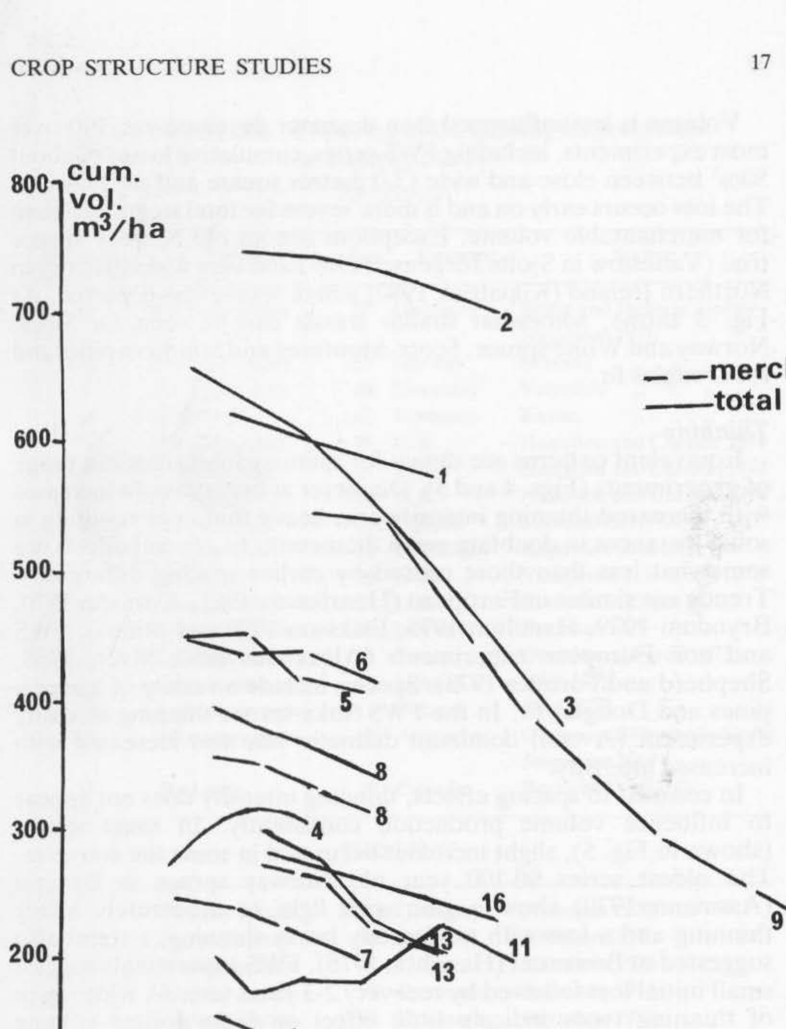

Fig. 3 Volume production in spacing experiments.
(For sources see Table 4)

Volume is less influenced then diameter development, but over most experiments, including FWS series, cumulative losses of about $50m^3$ between close and wide (3.0 metres square and over) occur. The loss occurs early on and is more severe for total stemwood than for merchantable volume. Exceptions are an old Norway spruce trial (Vaneslow in Sjolte Jorgensen 1967) and very wide spacings in Northern Ireland (Kilpatrick 1980) where severe loss occurred. As Fig. 3 shows, somewhat similar trends can be seen for Sitka, Norway and White spruce, Scots, Monterey and Southern pines and for Douglas fir.

Thinning

Equivalent patterns are shown for thinning intensities in a range of experiments (Figs. 4 and 5). Diameter at breast height increases with increased thinning intensity are; heavy thinnings resulting in some instances in doubling mean diameters. In general effects are somewhat less than those caused by earlier spacing differences. Trends are similar in European (Henriksson 1961, Assmann 1970, Bryndum 1979, Hamilton 1975, Eriksson 1979 and others), FWS and non European experiments (Alexander 1960, Myers 1958, Shepherd and Forester 1973). Species include a variety of spruces, pines and Douglas fir. In the FWS Sitka spruce thinning intensity experiment (Avoca) dominant diameter has also increased with increased intensity.

In contrast to spacing effects, thinning intensity does not appear to influence volume production consistently. In some series, (shown in Fig. 5), slight increases occur and in some the converse. The oldest series 90-100 year old Norway spruce in Bavaria (Assmann 1970) show a gain with light to moderately heavy thinning and a loss with moderately heavy thinning, a trend also suggested at Bowmont (Hamilton 1976). FWS experiments suggest small initial loss followed by recovery 2-3 years later. A wide range of thinning types indicate little effect on Sitka spruce volume production (Gallagher 1976). This was in contrast to results from Hamilton (1976) who found volume loss through low thinning.

Volume and Diameter Distributions

Changes in diameter and by inferences volume distribution because of varying crop structure treatments are important effects. Diameter distributions in FWS Sitka spruce and lodgepole experiments as between widest and narrowest spacings have become distinct by 11 years. A comparison is made with an 18 year Douglas fir trial (Oswald and Pardé) Fig. 6. Considerable early differentiation, at 10 years has also been shown for Monterey pine (Van Laar 1976). Jack (1971) used frequency distributions in 21 year Sitka spruce to confirm that both tree size and frequency of

Table 4. Details of Spacing and Thinning Experiments in Figures 2 to 5.

SPACING

Graph No.	Species	Age	Country	Source
1	Norway spruce	62	Germany	Busse and Jachn in Sjolte Jorgensen 1976
2	Norway spruce	55	Norway	Branseg ,, ,, ,, ,,
3	Norway spruce	48	Germany	Vaneslow ,, ,, ,, ,,
4	Scots pine	48	Germany	Kunze ,, ,, ,, ,,
5*	Norway spruce	37	U.K.	Hamilton and Christie 1974
6*	Sitka spruce	35	U.K.	Hamilton and Christie 1974
7	Scots pine	35	U.K.	Hamilton and Christie 1974
8	White spruce	35	Canada	Stiel and Berry 1973
9*	Sitka spruce	31	N. Ireland	Kilpatrick et al 1980
10	White pine	30	U.S.	Vimmerstedt in Evert 1972
11	Douglas fir	27	U.S.	Eversole in Evert 1972
12	Norway spruce	28	Norway	Braastad 1979
13*	Douglas fir	18	France	Oswald and Pardé 1973
14*	Sitka spruce	15	Ireland	FWS 1978
15*	Lodgepole pine	11	Ireland	FWS 1978
16	Monterey pine	15	Australia	Cromer and Pawsey in Sjolte Jorgensen 1967
17	Red pine	9	Canada	Beery in Evert 1972

THINNING

Graph No.	Species	Age	Country	Source
1	Norway spruce	102-85	Germany	Assmann 1970
2	Norway spruce	90	Sweden	Eriksson 1979
3*	Norway spruce	64	U.K.	Hamilton 1976
4	Norway spruce	55	Denmark	Bryndum 1974
5	Norway spruce	53	Denmark	Bryndum 1979
6	Norway spruce	43	Sweden	Eriksson 1979
7	Norway spruce	42	Denmark	Bryndum 1979
8*	Ponderosa pine	52	U.S.	Myers 1958
9	Lodgepole pine	87	U.S.	Dahms 1971
10	Lodgepole pine	33-44	U.S.	Alexander 1960
11	Sitka spruce	40	Denmark	Henriksson 1961
12*	Sitka spruce	29	Ireland	FWS 1978
13*	Lodgepole pine	26	Ireland	FWS 1978
14	Monterey pine	23	Australia	Shepherd and Forrest 1973
15	Norway spruce	40	Finland	Vuokila 1975

* Volumes given as merchantable volume production (to 7-9cm top dm), others, total volume prod. Thinnings are allocated to 6 intensities in Figs. 4 & 5 from 'A' (no thinning) to 'F' (heaviest intensity) from source description.

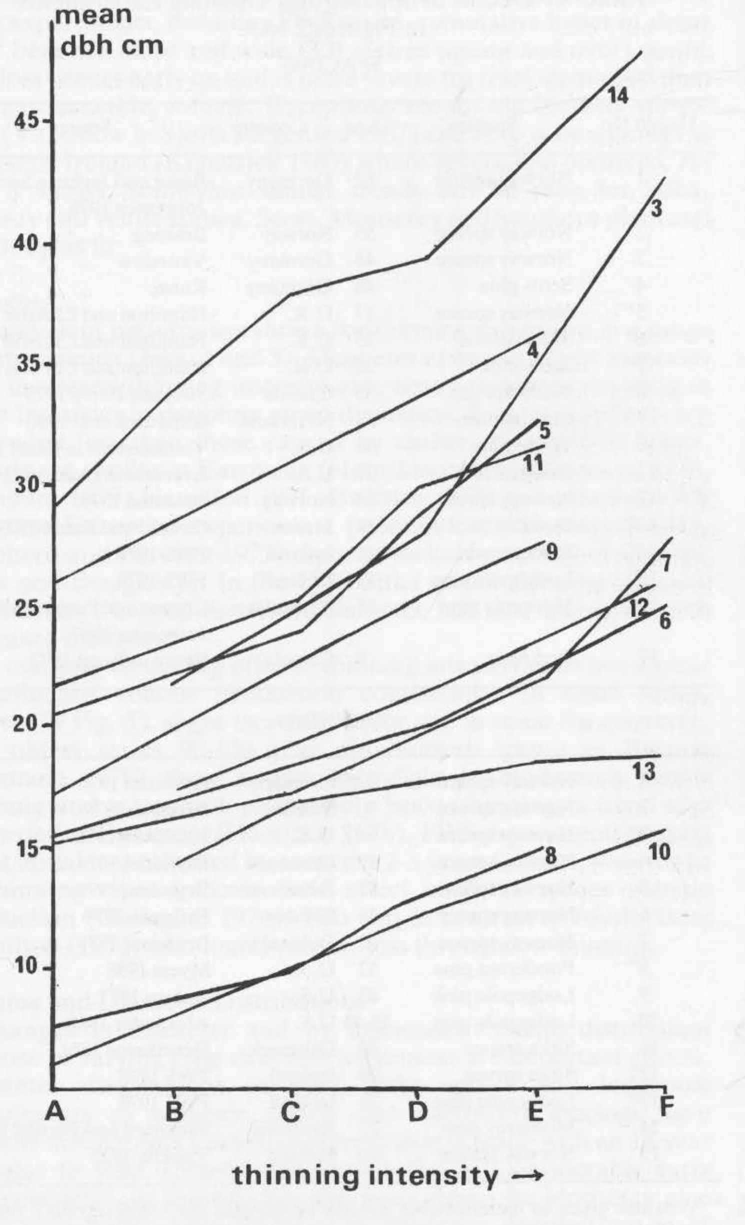

Fig. 4 Diameter growth in thinning experiments.
(For sources see Table 4)

larger trees increase with spacing. Henrikssen (1961) showed distribution peaking in 50 year old Sitka spruce at 30-35cm DBH in thinned plots compared with 20-25cm DBH in unthinned plots. Thinning type also induces changes in diameter distributions as evidenced from a second FWS experiment at Avoca some 6 years after first thinning, (Fig. 6).

Volume categories also change. At the Avoca (FWS) thinning intensity experiment most volume had been transferred on to the >20cm top diameter categories after more than 10 years of heavy thinning. Wardle (1967) showed distinctive volume category patterns occurring over time with spacing, where the slopes of total and merchantable volumes were negative with spacing, slopes became neutral to positive with increased top diameter volume category. Braathe (in Sjolte Jorgensen 1967) showed the transfer of volume from 20cm to 30cm DBH trees in older Norway spruce stands with spacings increasing from 1.2m to 3.0m.

This is also shown in mature pine stands in the U.S. where the volume of densely stocked stands is held in trees half the diameter of thinned stands (Dahms 1971). Thinning/spacing models in a variety of species in the U.K., U.S. and New Zealand show similar trends in diameter/volume development (Hamilton and Christie 1974, Feduccia and Mann 1976, James 1976, de Vries and Hildebrand 1978). This work is now underway in FWS studies (Lynch 1980).

Stability

It is not possible to draw detailed conclusions from FWS experimental data though there are some pointers. No significant blow has as yet occurred in spacing experiments, though some have now exceeded 10m height. Abstracted information from two reports (Gallagher 1974, 76) shows that no thinning is least risky and that damage increases with intensity. Combinations of heavy row and selective thinning appear to have made stands susceptible in stands of over 12m top height (Table 5).

Though many other factors such as stand top height, soil, topography and climate must also be considered there is general confirmation of risk immediately following heavy thinning (Bradley 1969, Persson 1969, Hütte 1969).

Wood Quality

Wood quality is not discussed in detail in this paper but some brief comments are given to complement discussion on the results already considered. The measurements taken in FWS experiments show that diameter growth and branch size increased significantly with increased spacing. Wider ring width and increased knot size must

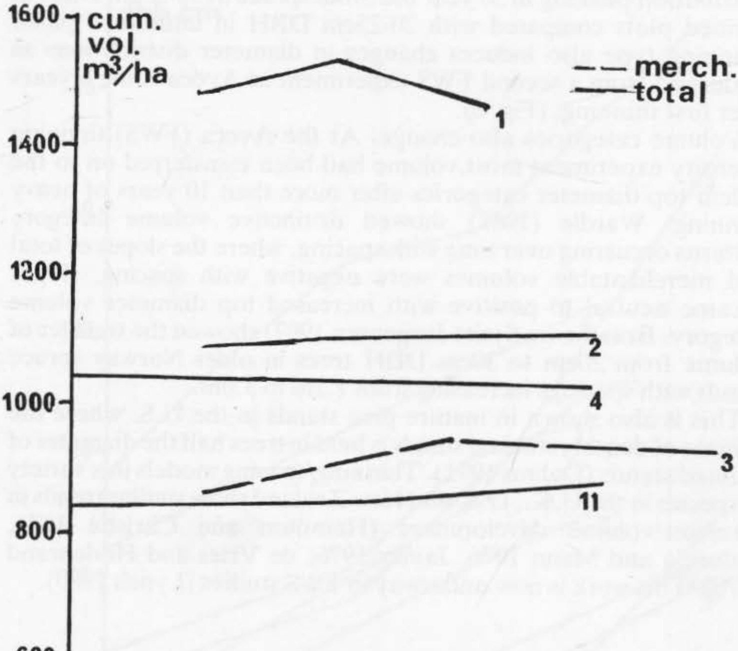

Fig. 5 Volume production in thinning experiments.
(For sources see Table 4)

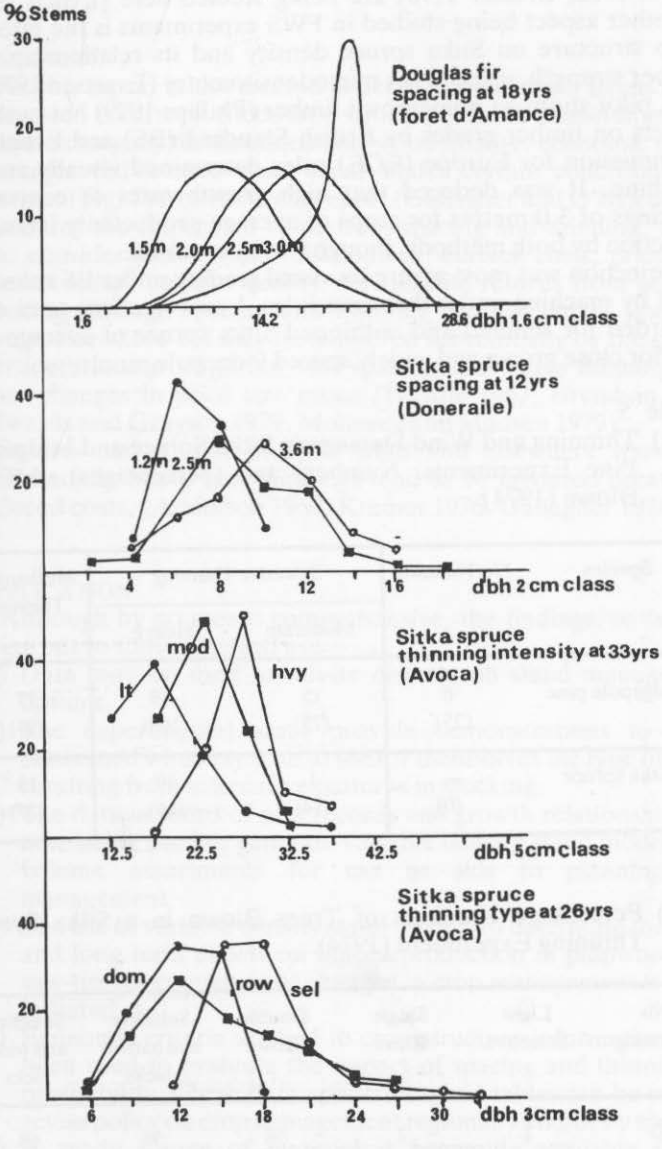

Fig. 6 Diameter distributions in crop structure experiments.

therefore have some effect on quality. These trends are universally evident, and together with other effects such as taper, branch/stem ratios, location of branches along the stem (Sjolte Jorgensen 1967, Evert 1972, Brazier 1976) are being studied here (Lynch 1980). Another aspect being studied in FWS experiments is the effect of crop structure on Sitka spruce density and its relationship with timber strength, using X ray microdensitometry (Evertsen 1979).

A pilot study on homegrown timber (Phillips 1979) has outlined effects on timber grades by British Standard (BS) and Economic Commission for Europe (ECE) rules determined visually and by machine. It was deduced that high growth rates or equivalent spacings of 3.0 metres for crops of average productivity increased rejection by both methods, though less by machine.

Rejection was most severe by visual grading under BS rules and least by machine under the same rules. Low rejections rates were recorded for thinned and unthinned Sitka spruce of average rate and for close grown and widely spaced lodgepole pine.

Table 5

(a) Thinning and Wind Damage in Sitka Spruce and Lodgepole Pine Experiments. Numbers and (percentages) of Trees Blown (1974).

Species	No Thinning	Selective Thinning		Mechanical Thinning
		Moderate	Heavy	
Lodgepole pine	6 (75)	15 (75)	18 (100)	17 (94)
Sitka spruce	— (0)	1 (4)	10 (66)	15 (27)

(b) Percentage Numbers of Trees Blown in a Sitka Spruce Thinning Experiment (1974).

No Thinning	Light Selective	Single Rows	Double Rows	Selective and narrow racks	Selective and wide racks
0	1	2	58	98	68

Somewhat similar results for Norway spruce have been recorded recently in Denmark (Moltesen and Madsen 1979) where the impact of very heavy thinning may be limiting.

Economics

As this aspect is also treated in detail elsewhere (O'Brien 1980), discussion is cursory. Since crop structure affects diameter growth, volume category distributions and wood quality, economic effects of major importance must occur under certain conditions. An abstract (Fig. 7) from a recent report (Gallagher and O'Brien 1979) illustrates the impact on value from spacing and thinning, taking into consideration volume distribution, current costs, prices and interest rates, but not quality. Favourable returns from reduced stocking through spacing and thinning are not out of line with results elsewhere but may be tempered substantially by the quality considerations arising from wide spacings and heavy thinnings and from changes in price size ratios (Wardle 1967, Bryndum 1976, Edwards and Grayson 1979, Moltesen and Madsen 1979).

Studies carried out in FWS trials and elsewhere show that moderatedly heavy row thinnings tend to be favoured because of reduced costs, (Anderson 1969, Kramer 1976, Gallagher 1976).

APPLICATION

Although by no means comprehensive, the findings, so far, are being put to some practical use.

(1) Data may be used to advise directly on stand management options.

(2) The experimental areas provide demonstrations to those concerned who may wish to see for themselves the type of crops resulting from alternative patterns in stocking.

(3) The data in terms of plot records and growth relationships are now being used to generate variable density stand models and volume assortments for use as sids to planning and management.

(4) The use of variable density stand models to determine the short and long term effects on timber production in pulpwood and saw-timber categories of changes in crop management is being initiated.

(5) Economic criteria applied to crop structure information have been used to evaluate the impact of spacing and thinning on profitability. These data applied to yield tables can be used to revise policy on crop management regionally and/or by species.

(6) A ready source of material is becoming available for an extended assessment of timber quality.

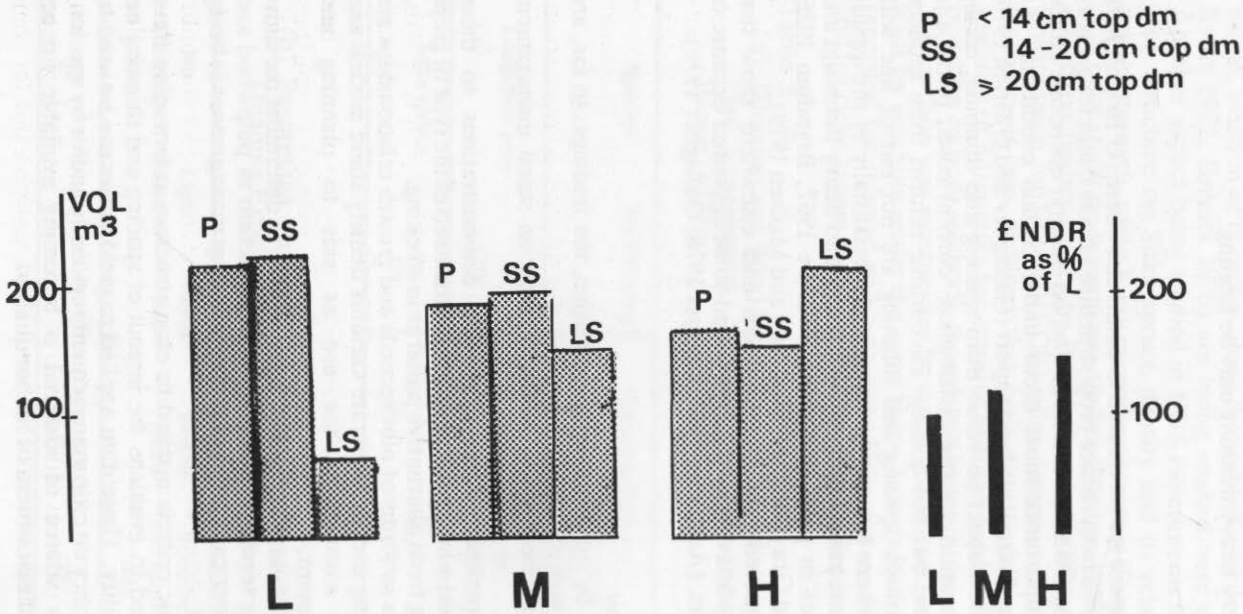

Fig. 7 Volume Assortments and Returns from Sitka spruce Thinning Intensities (29 yrs).

DISCUSSION

Up to now the crop structure research programme has provided a body of information where there was none before. Although this is still rather crude to apply, the experiments do give easy to use data for a wide range of crop conditions. While the evidence from our own experiments and work done abroad relates to most conifers, research here applies particularly to Sitka spruce and lodgepole pine.

The operation of an efficient data collection system means that additional information can be included each year and analysed without undue difficulty. The data collected since the mid 1970's will increase this base very considerably. As the quantitative effects of spacing and thinning become more established trends will be easier to determine and predict.

Results are in general, consistent with those from crop studies done elsewhere. The greatest effects are on diameter and diameter distribution, changes occurring soon after spacing, respacing or thinning. Volume is lost at spacings over 2.5m and probably immediately after thinning. Cumulative volume loss with wide spacings is permanent but decreases in relative importance with age, as this loss is in small sized assortments. With thinning the effect is less and there is probably recovery a few years after treatment. Total volume loss in merchantable timber may be in the order of 10% with wide spacings, and less due to heavy thinning regimes. The converse happens with larger size timber assortments and up to very low stocking densities, large proportions of the crop achieve sawlog sizes. These trends offer the possibility of greater flexibility in times, types and intensity of thinning while providing an easier way to handle log size.

Effects on quality, because of open growth, may be limiting, at least in the short term. While knottiness can be countered by green pruning wider ring width also results from less competition and this manifests itself in the timber grade. However, the effects on species are different and the precise nature of strength pattern within rings and between young rings and older rings has not yet been quantified. Also, the feasibility of extending structural specifications to a wider range of management practices may give more definitive information on the value of such crops.

Economic arguments for reduction in stocking, especially by thinning, are strong at present, with prices prevailing for saw timber sizes and difficulties in the pulp trade. Also, an emerging trend towards shorter rotations to capitalise earlier on past plantings provides added incentive to increase diameter growth by silvicultural means. However conditions do change and the long term timber patterns should be kept under review. Energy needs may also change the value of small sized material, but for some time to come we will need forests capable of efficient saw timber production and this is best achieved by thinning.

Our geographical position in a windy environment calls on ways to reduce risk, especially on wet sites and in relation to lodgepole pine. Late canopy openings must be avoided. This can only be achieved by wider initial spacing, respacing or early thinning. Here, the production of lower quality, larger sized material must be set against a high pulpwood content in the crop.

The results of crop structure research are to be seen against a background of practice in many countries, especially outside Europe, developing towards more open plantations than those grown under traditional methods, (Low and Van Tol 1973).

The question as to what should be the direction of future research is now posed. The short term goals include up-to-date analysis of crop structure experiments to develop a range of spacing/thinning options to suit by rotation length and end product requirements. Also it will be important to maintain experiments to as near rotation age as can be achieved to allow the calculation of relationships involving stand parameters which cover the life of the crop. Greater study on the behaviour of individual trees of various species for more detailed quantitative evaluation, such as biomass components and the effect of growing conditions on quality will also be required.

Longer term aims should include the construction of stand models for major species extended to the edges of the thinning/spacing/time spectrum. These could be incorporated into inventory forecasts to reflect the impact of a wide range of management strategies on production. Forecast information might be expressed in timber end use category, money or even biomass given appropriate conversion factors. Also a range of economic tests could be developed to compare options in terms of investment. An integrated programme of crop structure research should help to regulate future wood supplies in an orderly way.

Finally the results from crop structure research, so far obtained might be considered now in relation to planning the future management of plantations. Should such concepts, as those applied in New Zealand (Sutton 1976) be adopted here? Will future end use requirements push management in a particular direction? What are the likely consequences of change?

All the results, with the important exception of those relating to timber quality suggest material and financial benefits from increased tree growing space. There is also added management flexibility (Vuokila 1976, Gillespie 1979) in that the time for making and altering decisions is increased and risk taking may be reduced. Reservations not withstanding, the information received so far may help decision making in that answers can be given to some of the important questions that must be asked when chosing a management option. These relate to end use requirements, the importance of quality in relation to log size and price, site risks relating to thinning, growth rate (yield class) as a factor, and the likely assortments arising from a particular choice of management. Armed at least with some answers the likelihood of the best choice is improved.

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REFERENCES

ABETZ, P. 1976. Der Europäische Stammzahlversuch in Fichte (*P. abies* Karst) Mitteilungen der Forstliche Versuchs und Forschungsanstalt, Bad. Wurtt. Heft 80. 7-13.

ALEXANDER, R. R. 1960. Thinning lodgepole pine in the Central Rocky Mts., Inc. For. 58. (2). 99-104.

ANDERSSON, S. O. 1963. Produktionstabeller fir norrländska tallplanteringer Svenska Skogsv Forën Tidskr. 51. (in Sjolte Jorgensen 1967).

——— 1969. Row and strip thinning. Symp. Thinning and Mechanisation. IUFRO Stockholm 98-105.

ASSMANN, E. 1970. The principles of Forest Yield Study. Pergammon Press.

BARTOLI, M. 1971. Premiers resultats d'une experience de densité sur le Douglas. Technique et Forêt.

BENNET, F. A. 1960a. Spacing and Early growth of Slash pine. Jour. For. 58 (12). 966-967.

——— 1969 Spacing and Slash pine. Quality timber production. USDA For. Serv. S.E. For. Exp. Stn., Res. Pap. 53.

BRAATHE, P. 1957. Thinning in even aged stands. Summary of European literature. Fac. of Forestry, Univ. New Brunswick.

BRAASTED, H. 1970. A spacing experiment with *Picea abies*. Report Norwegian. For. Res. Inst. nr. 105 bd. 28 h. 5.

——— 1979. Growth and stability in a spacing experiment with *Picea abies*. Report Norwegian. For. Res. Inst. 34. 7 Ås.

BRADLEY, R. T. 1969. Damage to trees, ground and roots. Symp. Thinning and mechanisation. IUFRO Stockholm 130.

BRAZIER, T. D. 1976. The effect of forest practices on quality of the harvested crop. Proc. Div. 6. XVI IUFRO Congress Oslo.

BRYNDUM, H. 1974. A thinning experiment in Norway spruce at Ravnholt Forest Estate. Forstl. Forsøgsv. Danm. nr. 273 bd. 34 h.1.

——— 1976. Preliminary results from new Danish thinning experiments with Norway spruce on fertile soils, "Aspects of thinning". Proc. IUFRO Div. 4 meeting Edinburgh. Bull. 55. For. Comm. Lond. 22-36.

BRYNDUM, H. 1978. Hugstforsøg i ung Rodgran leret maenejard. Saertryk af Forst. Forsøgsv. Danm. 295 bd. 41 h.1.
——— 1979. Personal communication.
CARBONNIER, Ch. 1954. Yield studies in planted spruce stands in Southern Sweden. Reports of the Forest research Institute of Sweden. Vol. 44. No. 5.
CREMER, K. W. and MEREDITH, E. M. 1976. Growth of Radiata pine after row thinning compared with selective thinning. Aust. For. 39 (3): 193-200.
DAHMS, W. G. 1971. Fifty five year old lodgepole pine responds to thinning. USDA For. Serv. Pac. Nw. For. and Range Exp. Sta. Res. Note 268.
DE VRIES, P. G. and HILDEBRAND, J. W. 1978. Analysis of 11 years growth of Carribbean pine in a replicated Graeco-latin square spacing thinning experiment in Surnam. Mededelingen Landbouwhogeschool. Wageningen 78-17.
EDWARDS, P. M. and GRAYSON, A. J. 1978. Respacing of Sitka spruce. Quart. J. For. 73; 205-218.
ERIKSSON, H. 1979. Personal communication.
EVERT, F. 1971. Spacing studies, a review. Inform. Report For. Mgt. Inst. Ottowa. FMRI 37.
EVERTSEN, J. 1979. Unpublished report, I.I.R.S.
FEDUCCIA, D. P. and MANN, W. E. 1976. Growth following initial thinning of loblolly pine, planted on a cutover site at 5 spacings. USDA For. Res. Pap. So. 120 5. For. Exp. Stn.
FORBES, A. C. 1928. Pinus contorta or P. murrayana. Gardiners chronicle. March 31st 1928. 232-283.
FOREST AND WILDLIFE SERVICE, 1976. Unpublished research communication.
——— 1978. Unpublished Int. Reports.
FORESTRY COMMISSION 1928. Growth and yield of conifers in Great Britain. Bull. 10. For. Comm. Lond.
GALLAGHER, G. J. 1964. Spacing and thinning in For. Res. Rev. 1957-64. Forestry Div. Dept. Lands, Dublin, 66-75.
——— 1971. Spacing and thinning in For. Res. Rev. 1964-70. Forest and Wildlife Service, Dublin, 66-76.
——— 1969. The thinning of Sitka spruce. Two experiments. Irish For. 26 (2): 3-19.
——— 1972. Some patterns in crop structure and productivity for Sitka spruce. Irish For. 32 (2), 33-52.
——— 1974. Windthrow in State Forests in the Republic of Ireland. Irish For. 31, (2), 154-167.
——— 1976. A IUFRO Sitka spruce stem reduction experiment. Mitteilungen der Forstliche versuchs und forschungsanstalt. B Württ. Heft 80 49-54.
——— 1976. Sample plots. Data collection storage and retrieval. Permanent plots in forestry growth and yield research, IUFRO meeting S4.01. Dept. of For. Yield Research Res. Note 43. Stockholm. 57-66.
——— 1976. The development of thinning and harvesting systems in Sitka spruce and Contorta pine crops. Aspects of thinning Proc. IUFRO Div. 4 meeting, Edinburgh 55. For. Comm. Lond. 49-55.
——— and O'BRIEN, D. 1979. Sample plots and experiments in crop development studies. Pap. to Symp. IUFRO Subject Group 4.01. Oxford.
GILLESPIE, J. 1979. Wood markets and silvicultural practice. Unpublished thesis.
HAMILTON, G. J. 1976. The Bownmont Norway spruce sample plots. Forestry 16. XLIV 2. 109-120.
——— 1976. The effects of line thinning on increment "Aspects of Thinning". Proc. IURFO Div. 4 meeting. Edinburgh Bull. 55 For. Comm. Lond. 37-45.
——— and CHRISTIE, J. M. 1974. Influence of spacing on crop characteristics and yield. Bull. 52. For. Comm. Lond.

HAWKINS, D. J. 1971. Pre-merchantable thinning in plantations of Slash pine and Honduran Caribbean pine in Queensland. 15th IUFRO Congress. Gainsville, Florida.

HENRIKSSEN, H. A. 1961. A thinning experiment with Sitka spruce in Nystrup Dune forest. Forstl. Forsøgsv. Danm. 27. 175-232.

HUMMEL, F. G., and CHRISTIE, J. M. 1957. Methods used to construct revised Yield Tables for conifers in Great Britain. Rep. For. Res. 1957. For. Comm. Lond.

HUMMEL, F. C., LOCKE, T. M. L., JEFFERS, G. J. R. and CHRISTIE, T. M. 1959. Code of sample plot procedure Bull. 31. For Comm. Lond.

HÜTTE, P. 1969. Untersuchung über Einfluss des Durchforstung auf die Sturmfestigkeit der Fichte. Symp. Thinning and mechanisation. IUFRO Stockholm. 158-162.

JACK, W. H. 1971. The influence of tree spacing on Sitka spruce growth. Irish For. 28. (2) 23-33.

JAMES, R. N. 1976. Implications for silviculture from the Tarawere Valley regimes trial. N. Z. Inc. For. Sc. 6 (2): 171-181.

JOYCE, P. M. 1961. Volume tables for Pinus contorta. Forestry Div. Dept. Lands, Dublin.

——— and GALLAGHER, G. J. 1966. Provisional yield tables for pinus contorta (Coastal) Res. Record 2. Forestry Div. Dept. Lands, Dublin.

KEISTER, T. D., BIGLER, C. and BURNS, P. Y. 1968. Results of a test of classical thinning methods in a Slash pine plantation. J. For. 66: 409-411.

KILPATRICK, D. J., SANDERSON, J. M., SAVILL, P. S. 1980. The Baronscourt Sitka spruce spacing experiment. Personal communication.

KRAMER, H. 1976. Der Einfluss verschiedener Durchforstunsgarten auf Wachstum und Bestandesschäden. Untersuchungsergebnisse aus Fichtenbeständen in der Bundesrepublic Deutschland. Aspects of Thinning. Proc. IUFRO Div. 4 meeting. Edinburgh. Bull. 55 For. Comm. Lond. 82-94.

LOW, A. J. 1974. Initial spacing in relation to establishment and early growth on conifer plantations. For. comm. Res. and development paper. 110.

——— and VAN TOL, G. 1973. Initial spacing in relation to stand establishment. Proc. IUFRO Div. 1 and 3. Stand Establishment. Wageningen. 301-313.

LYNCH, T. J. 1980. Thinning and spacing research in Sitka spruce and lodgepole pine (coastal). Symp. Growing space in conifer crops. Supplement to Irish Forestry.

MacDONALD, J. A. B. 1932. The value of early thinning in Norway spruce. Scot. For. 46 (2), 112-117.

McKENZIE, A. M. 1962. The Bowmont Norway spruce sample plots 1930-1960. Forestry 129-138.

MARSH, E. K. 1957. Some preliminary results from O'Connor's correlated curve trend (CCT) experiments in thinning and spacing and their practical significance. Comm. For. Conf. Australia and New Zealand. Govt. printer Pretoria.

MIELIKÄINEN, K. 1979. The influence of low thinnings on the wood production and value of a pine stand. Folia Forestalia. 401. Inst. For. Fin. Helsinki.

MOLTESEN, P. and MADSEN, T. L. 1979. Styrkesorteringens inflydefse pa tyndings hugstens økonomi i Rodgran. Saertryk af Dansk Skovforenings Tidschrift 64. 169-196.

MYERS, C. A. 1958. Thinning improves development of young stands of Ponderosa pine in the Blackhills. J. For. 56 (9): 656-659.

MOORE, D. 1976. The Oceanic Forest. Irish For. 33 (I). 4-15.

O'BRIEN, D. 1980. The economics of spacing and thinning. Symp. Growing Space in Conifer Crops. Supplement to Irish For.

O CARROLL, N. 1958. Unpublished material.

O CARROLL, N. 1962. The Progress of Peatland Afforestation in the Republic of Ireland. Irish For. 19 (1): 93-101.

O'CONNOR, A. J. 1935. Forest Research with special reference to planting distances and thinning. British Empire Forestry Conference. S. Africa, Pretoria.

O'DRISCOLL, J. 1964. A tree improvement programme for Pinus contorta. Irish For. 21: (1), 3-11.

——— 1979. The importance of lodgepole pine (Pinus contorta, Loud.) in Irish forestry Pap. Symp. R.I.A. Dublin.

O'MUIRGHEASA, N. 1964. Census of Woodlands 1958/9. For. Res. Rev. 1957-64. For. Div. Dep. Lands, Dublin. 83-113.

OSWALD, H. and PARDÉ, D. 1976. Une expérience d'espacement de plantation de Douglas en forêt domaniale d'Amance. Technique et Forêt.

PERSSON, P. 1969. The influence of various thinning methods on the risk of windfalls, snow breaks and insect attacks. Symp. Thinning and Mechanisation. IUFRO Stockholm 169-174.

PHILLIPS, H. 1979. Wood quality/grading study. Proc. 13th Symp. Wood quality and its silvicultural control. University College, Dublin.

REUKEMA, D. L. 1972. Twenty one year development of Douglas fir stands repeatedly thinned at varying intervals. USDA For. Serv. Res. Pap. NW For. and Range Exp. Stn., No. PNW 141.23.

SHEPHERD, K. R. and FORREST, W. G. 1973. Growth of Radiata pine following thinning. Comm. For. Rev. 55.2. 133-142.

SJOLTE JORGENSEN, D. 1967. The influences of spacing on the growth and development of coniferous plantations. Int. Rev. For. Res. N.Y. 2. 43-94.

STIEL, W. M. 1970. Thinning 35 year old white spruce plantations from below 10 year results. Dep. Fisheries and For. Canadian For. Service. Publ. 1258.

——— and BERRY, A. B. 1973. Development of unthinned white spruce plantations to age 50 at Petawawa Forest Experimental Station. Environment Canada. Forestry Service, Ottawa.

SWAN, M. 1958. Unpublished material.

SUTTON, W. R. J. 1976. New Zealand experience with radiata pine, Aspects of Thinning. Proc. IUFRO Div. 4 meeting, Edinburgh, Bull. 55. For. Comm. Lond.

VAN LAAR, A, 1976. Thinning research in South Africa in "Aspects of Thinning". Proc. IUFRO Div. 4 meeting Edinburgh. Bull. 55. For. Comm. 56-60. Lond. 62-71.

VAN SLYKE, A. L. 1964. A study of spacing and thinning with Nelders new systematic designs. Unpub. Rep. Rep. Faculty of Forestry B. C. Vancouver.

VUOKILA, Y. 1975. Thinning of young spruce plantations as a problem of timber production. Folia Forestalia 247. Inst. For. Fin. Helsinki.

——— 1976. Yield from first thinning. Folia Forestalia, 264. Inst. For. Fin. Helsinki.

WARDLE, P. A. 1967. Spacing in plantations. Forestry 40 (1), 47-69.