EEC FOREST PROJECT

Silvicultural control and non destructive assessment of timber quality in plantation grown Spruces and Douglas fir

CONTRACT N^r MA2B-0024
Final report
TASK 11

"MODELLING YOUNG'S MODULUS ON SMALL CLEAR SPECIMENS IN RELATION TO SILVICULTURAL TREATMENT"

Benoit JOUREZ and **André LECLERCQ**

APRIL 1994

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FOREWORD

The Station de Recherches Forestières of the Ministère de la Région Wallonne (23, avenue Maréchal Juin, B-5030 - Gembloux - Belgium) is bound by an agreement as Associated - Contractor with the Institut National de la Recherche Agronomique (147, rue de l'Université - F75338 Paris cedex 07 - France) within the context of the Project "*SILVICULTURAL CONTROL AND NON DESTRUCTIVE ASSESSMENT OF TIMBER QUALITY IN PLANTATION GROWN SPRUCES AND DOUGLAS FIR*" for which the University of North Wales (School of Agricultural Forest Sciences - Bangor - United Kingdom) and the Institut National de la Recherche Agronomique (Paris - France) have signed a contract [reference Nr MA 2B - CT91 - 0024 (TSTS)] with the European Community Commission on October 28th 1991 for carrying out researches in the following field: "*SILVICULTURAL CONTROL AND NON DESTRUCTIVE ASSESSMENT OF TIMBER QUALITY IN PLANTATION GROWN SPRUCES AND DOUGLAS FIR*".

This Project is lengthening over a period of 30 months, starting on November 1st 1991 and ending on April 31st 1994.

In the framework of this research, the Station de Recherches Forestières of Gembloux is in charge as Task leader, among the 12 Tasks included in the Project, of Task 6 "*Modelling bark thickness in the tree in relation to silvicultural treatment*" and Task 11 "*Modelling Young's modulus on small clear specimens in relation to silvicultural treatment*".

The present report is finalizing the works performed on Young's modulus in relation to silvicultural treatment, and is the fruit of a collaboration with Team 7 (CTBA, Paris, France, Team leader Miss A. EL OUADRANI).

We are very grateful to the ECC authorities which have allowed the realization of such a Project through which strong working collaborations and linkage between laboratories were established.

We are also deeply grateful to Mr Gérard Nepveu for the tremendous work performed as coordinator and to Miss Pat DENNE for the financial organization and coordination taken over.

On the other hand, we thank Dr Robert OGER (Bureau d'Informatique et de Statistique appliquée - Centre de Recherches Agronomiques - Ministère de l'Agriculture- Gembloux) for his valuable help received for the statistical analysis.

Silvicultural control and non destructive assessment of timber quality in plantation grown Spruces and Douglas fir

SUMMARY

The aim of this research work performed in Task 11 "*Modelling Young's modulus on small clear specimens in relation to silvicultural treatments*" was the modelling of Young's modulus (MOE) on small clear specimens of 24 Belgian Norway spruces in relation with the silvicultural treatment. The aim of the research was also to compare Young's modulus on small clear specimens with Young's modulus on commercial size specimens with a view to defining the rate of prediction of wood quality of specimens including the natural timber defects.

This work is corresponding to one task among the twelve of a large ECC Project entitled "Silvicultural control and non destructive assessment of timber quality in plantation grown Spruces and Douglas fir" for which 210 trees have been sampled through 6 different European countries.

The experimental raw material comes from the southern and eastern parts of Belgium and concerns four different kinds of stands characterized by the site productivity class and the thinning intensity.

Within each stand, the trees have been sampled in three different social positions classes.

The small clear specimens have been marked off with reference to the radial and axial positions inside the 24 trees.

On the whole 350 clear wood specimens have been selected and tested by two different laboratories in order to get young's modulus by a non destructive four points flexural method described by the French Standard NF B 51-016.

Young's modulus appears to be positively related with specific gravity and negatively related with growth ring width. Stands growing on high productive sites or those submitted to low thinnings and also suppressed trees give rise to a stiffer wood. Among all these factors, only the social position of the tree within the stand influences significantly the Young's modulus values.

Nevertheless, a slow growth producing a heavier timber is not always linked with a stiffer wood.

Young's modulus differences between juvenile and adult wood vary in connection with the specific gravity class considered. In other words, juvenile wood is stiffer than adult wood when referring to low density classes, but adult wood becomes stiffer than juvenile wood when referring to high density classes. That means that the stiffness of adult wood is more sensitive to changes in specific gravity than the stiffness of juvenile wood.

The distribution of Young's modulus in relation with specific gravity shows a higher variability when specific gravity increases. In searching the reasons for a higher Young's modulus variability when specific gravity increases by looking back to the population of clear specimens, we point out a very low slope of grain on some specimens and above all the presence of compression wood on other specimens.

When rejecting these defects, then it appears that Young's modulus is more strongly related to specific gravity, thus giving rise to more accurate models.

Among all these models, the best one is corresponding to a combination of variables such as specific gravity and growth ring width per sampling level within the tree.

The variance analysis of residues of each model has revealed a tree effect always very highly significant. On the opposite, the other factors, as site productivity, thinning intensity and social position of the tree within the stand, have no significant effect on Young's modulus values.

That means that inter trees variability is far higher than the other sources of variation (intra tree variability, site productivity variability, thinning intensity variability and social position variability).

This also means that the general model established is valid whatever the silvicultural treatment could be.

CHAPTER I : INTRODUCTION

1. Research context
2. Objectives
3. Partners
4. Progress Task meetings

1. Research context

Task 11, object of this report, is a part of a larger programme initiated by ECC and entitled *"Silvicultural control and non destructive assessment of timber quality in plantation grown Spruces and Douglas fir"*.

The overall objective of the Project is *"to estimate the wood quality of any board sawn in a given place in a tree for which the (only) following descriptors are known: dbh, total height, age and optionally, crown ratio"* [third Progress Report of May 10, 1993].

The programme is divided into three main parts, i.e.:

1°. The establishment of models giving the relationships between silviculture and internal and external tree structure;

2°. The improvement and the validation of a software called *"SIMQUA"* based on models established according to the procedure here above;

3°. The investigation of technological characteristics of products resulting from trees sampled according to a known silviculture.

The sampling concerns three main softwood species of great interest for European silviculture: Norway spruce, Sitka spruce and Douglas fir.

For each of the three species, different morphological and structural parameters (branchiness, bark thickness, wood density, ring width and spiral grain) have to be modelized in connection with site and silvicultural characteristics.

The proposed models to be integrated in the software *"SIMQUA"* have to present the best predicting but realistic value in order to allow the best estimation of the quality of products sawn from trees for which an intensive description is available: for instance, branches distribution, bark thickness distribution, ring width distribution, age, height, girth and so on.

Task 11 concerns the third part of the Project: the investigation of technological characteristics of products, more especially, the modelling of Young's modulus on small clear specimens, and the comparison with MOE on commercial size specimens in view to defining the rate of prediction of wood quality of specimens including the natural timber defects.

2. Objectives

Task 11 "*Modelling Young's modulus on clear specimens in relation to silvicultural treatment*" aims to measure MOE on clear wood specimens of Norway spruce with a view to modelling the effect of silvicultural treatment on this last parameter. The experimental procedure involves investigations on the correlations between MOE and ring width, specific gravity, age from the pith and height level in the tree.

3. Partners

Table 1 gives detailed informations on the two research Teams involved in Task 11 with their relevant responsibilities.

Table 1. - *Teams involved in Task 11.*

Species	**Teams**	**Countries**	**Responsibilities**
Norway spruce	A. LECLERCQ (Team 6)	Belgium	Task leader & working Team
	A. EL OUADRANI (Team 7)	France	working Team

The Belgian Team was in charge of collecting all the informations concerning stands and trees parameters, clear wood specimens manufacturing and MOE measurements. The French Team has realized a MOE measurement control on the same specimens.

4. Progress Task meetings

Four main different meetings have taken place during the period of time allotted for Task 11, for a good orchestration of the work to be performed by both Teams involved in the research programme on MOE of small clear specimens (Nepveu [1992 a & b, 1993 a & b]).

1. - *Gembloux* - Belgium (26-27 September 1990)

- establishment of a sampling procedure for stand and tree collection;
- establishment of the general methodology for the sawing process and for the preparation of experimental samples;
- adoption of French Standard (NF B 51-016) for measuring MOE on clear wood specimens.

2. - *Bangor* - Great Britain (20-23 March 1992)

- general agreement on the measurement of needed parameters;
- presentation of the progress in manufacturing clear wood specimens.

3. - *Florence* - Italy (24-26 March 1993)

- adoption of a MOE measurement method;
- agreement on the accuracy of the measurements;
- establishment of a data sheet presentation on floppy disk;
- timetable and deadline for collecting and mailing the data of MOE.

4. - *Göttingen* - Germany (2-5 November 1993)

- first presentatation by graphic treatment of the French data collected by Team 7;
- presentation of MOE results from a small sample in view to realize the calibration of the test equipment between both Teams concerned by Task 11;
- agreement on the main content and timetable for the Task final report .

CHAPTER II : MATERIAL AND METHOD

1. Experimental material

2. Methodology

1. Experimental material

1.1. Choice of species

The Project is focused on three softwood species particularly well represented in the European forests, i.e. Norway spruce [*Picea abies* (L.) Karst], Sitka spruce [*Picea sitchensis* (Bong.) Carr.] and Douglas fir [*Pseudotsuga menziesii* (Mirb.) Franco]. However, in the framework of Task 11, only Belgian Norway spruce has been investigated, considering the linkage between tasks 10 and 11, and the importance of measurements to perform within an exploratory work on a short period of time.

1.2. Choice of stands and trees

The sampling of stands and trees inside each of them has been organized in each country in accordance with the criteria defined during the first meeting in Gembloux in 1990, by the Team in charge of Task 2. These criteria are shortly summarized in table 2.

For more details about the procedure adopted, see the final report on Task 2.

Table 2. - *Stands and trees selecting criteria.*

Criteria for stands sampling	**Criteria for trees sampling**
-Site productivity - [2 levels: high and low]	*-Social position in the stand -* [3 levels: Dominant tree (D) Co-dominant tree (Dd) Suppressed tree (d)]
-Silvicultural treatment - [2 levels: high and low thinning intensity]	*-Trees -* [2 well formed]

1.2.1. Choice of stands

As the objective of this Project is to investigate the impact of growing conditions on timber technological characteristics, two selecting criteria were considered: the *"Site productivity"* and the *"Silvicultural treatment"*.

For the site productivity, mainly responsible of the timber output, two extreme site index classes, as different as possible, have been considered and qualified high and low.

For the silvicultural treatment which directly influences the ring width, two thinning intensity classes were taken into account and qualified "high" an "low". These classes had to reflect the dynamics of the silviculture applied to stands under given environmental conditions.

So, four stands have been sampled in order to give a good picture of extreme growing conditions (site quality, human effect) in Belgium.

1.2.2. Trees selection

The main selecting criteria adopted for tree sampling is the *"Social position"* occupied in the stand, through three main categories i.e.: dominant, co-dominant and suppressed trees. These Social position categories are in fact a good index of the living crown development. Each category is represented by 2 well formed *"Trees"*, so that 6 trees have been sampled per stand.

On the whole, the Project concerns the analysis of **210 trees** composed of 90 Douglas fir trees (24 in France; 24 in Italy; 42 in Germany), 72 Norway spruce trees (24 in Belgium; 24 in Denmark; 24 in France) and 48 Sitka spruce trees (24 in Denmark; 24 in Great Britain). But Task 11 is only paying attention to the 24 Belgian Norway spruces.

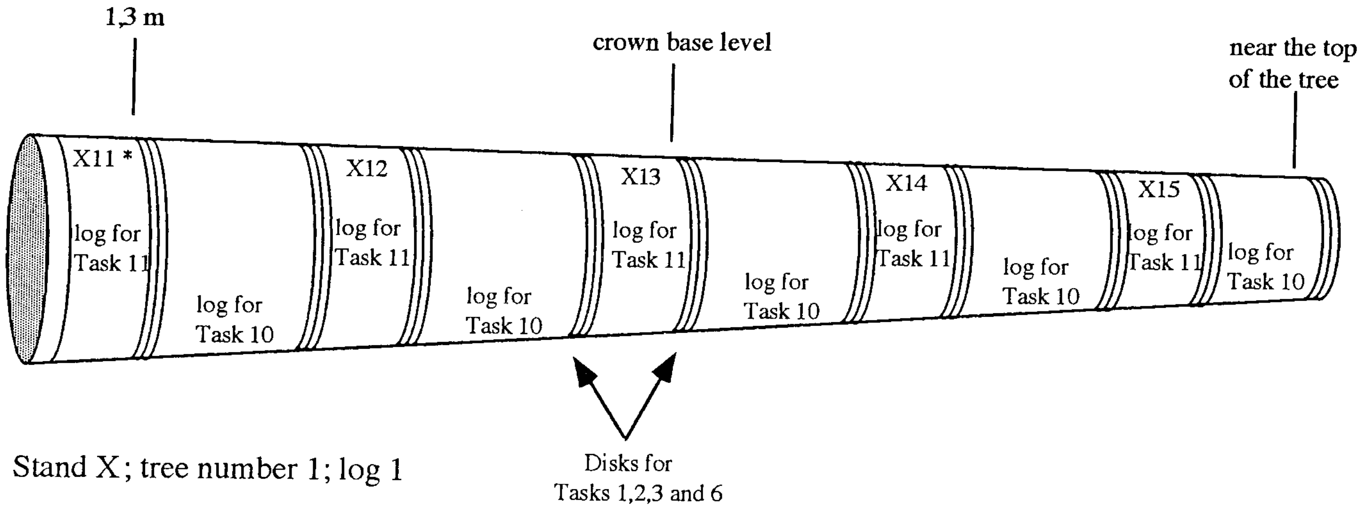
As the third part of the Project (Nepveu [1991], Technical Annex of the Contract - p. 3) is dealing with industrial wood processing, the sampling was organized with a view to collecting trees having about 30-35 cm diameter at breast height (dbh).

The raw material needed by Tasks 1, 2, 3, 5, 6, 9, 10 and 11 has been cut off from the same trees.

2. Methodology

2.1. Tree cutting scheme and samples manufacturing

The raw material needed for modelling MOE consists in logs cut off along the tree heigth at different levels.



* Stand X; tree number 1; log 1

Figure 1. - *Tree cutting scheme for Belgian Norway spruces.*

At least 3 logs (1,10 meter long for Task 11 [X11, X13, X15] and 2,50 meters long for Task 10) were cut off along the height of the tree. The first one is corresponding to the bottom of the tree, the second one is located near the living crown base level and the third one was cut off from the top of the crown. When it was possible, a fourth log [X14] was taken inside the living crown and a fifth one [X15] from the part of the stem between 1,3 m and the crown base level as presented in figure 1.

In following this cutting scheme, we have obtained 90 logs for Task 11. From each log, a central quartely cut plank of 7 centimeters thick and oriented North-South was taken and stored in a well ventilated room insuring a natural seasoning.

During the same time, on the lowest cross face of the plank, the successive 10 years growing periods have been materialized by a color code, starting from the pith.

Later these planks have been cut again in small beams (70 x 30 x 1100 millimeters) starting from the North to the South side. The experimental material has been then stored in a conditioning room, at 20° centigrade and 65% relative humidity (RH), so as to progressively obtain 12% moisture content.

After seasoning, these small beams were cut again into smaller pieces (30 x 30 x 1100 millimeters), so as to theoritically obtain two repetitions for each clear specimens.

The last step consisted in setting up the final dimensions of the experimental material by planing (20 x 20 x 1100 millimeters) and in selecting small quartely cut clear specimens (20 x 20 x 360 millimeters). (Figure 2)

Finally, from 90 logs, **1266** small clear specimens were achieved. After a final selection, a first set of 350 remaining well-formed specimens according to the standard NF B 51-016 was obtained. Annex 2 records the position of each clear specimen within the 24 trees sampled. Other smaller sets were also selected as incomplete replicates:

set A ----- 350 specimens;
set B ----- 245 specimens;
set C ----- 138 specimens;
set D ----- 67 specimens;
set E ----- 16 specimens.

As a whole, 816 specimens were shaped, representing 65% of the total number of sawn specimens.

2.2. Tree characteristics measurement

The sampling methods used on the field (measurement of selected trees, site characteristics) will be detailed in the final report on Task 2. For Task 11, we need the following informations with a view to modelling MOE on clear specimens (see Annex):

- site class;
- thinning intensity;
- for each tree:
    - girth (or diameter) at breast height;
    - total height of the tree;
    - crown base level;
    - age of the tree;
    - cardinal orientation.

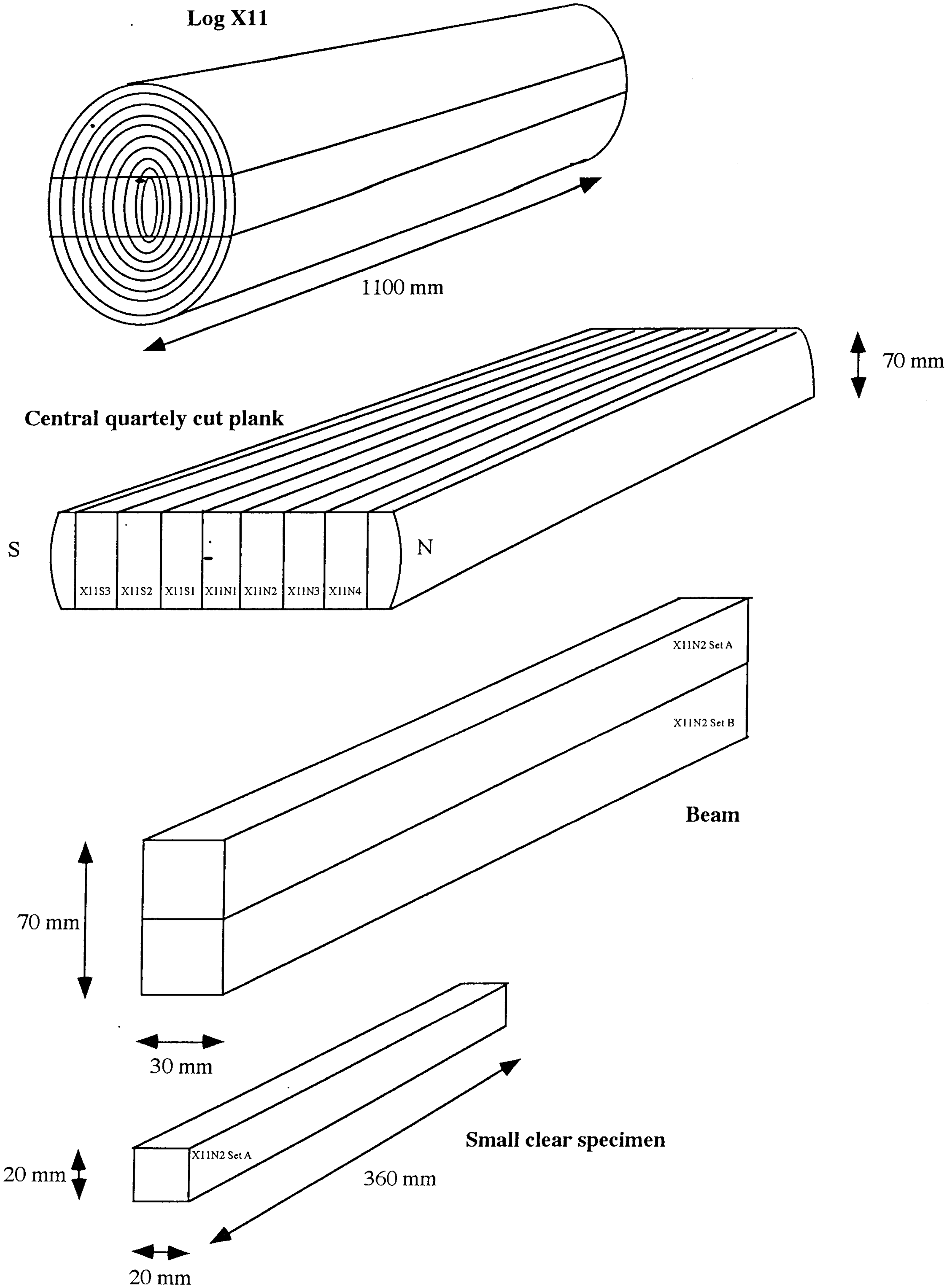


Figure 2. - *Cutting scheme of clear specimens through the log.*

2.3. Young's modulus measuring procedure

2.3.1. Standard NF B 51 - 016

The determination of MOE in static bending using small clear specimens has been made following the French Standard, NF B 51-016 (December 1987). This Standard describes a four points non destructive flexural test in direction parallel to the grain for small specimens.

The principle consists in the determination of MOE of a sample submitted to a progressive increasing load applied across the grain, in pure static bending within the elastic deformation zone .

Figure 3 illustrates the test equipment used in both laboratories.

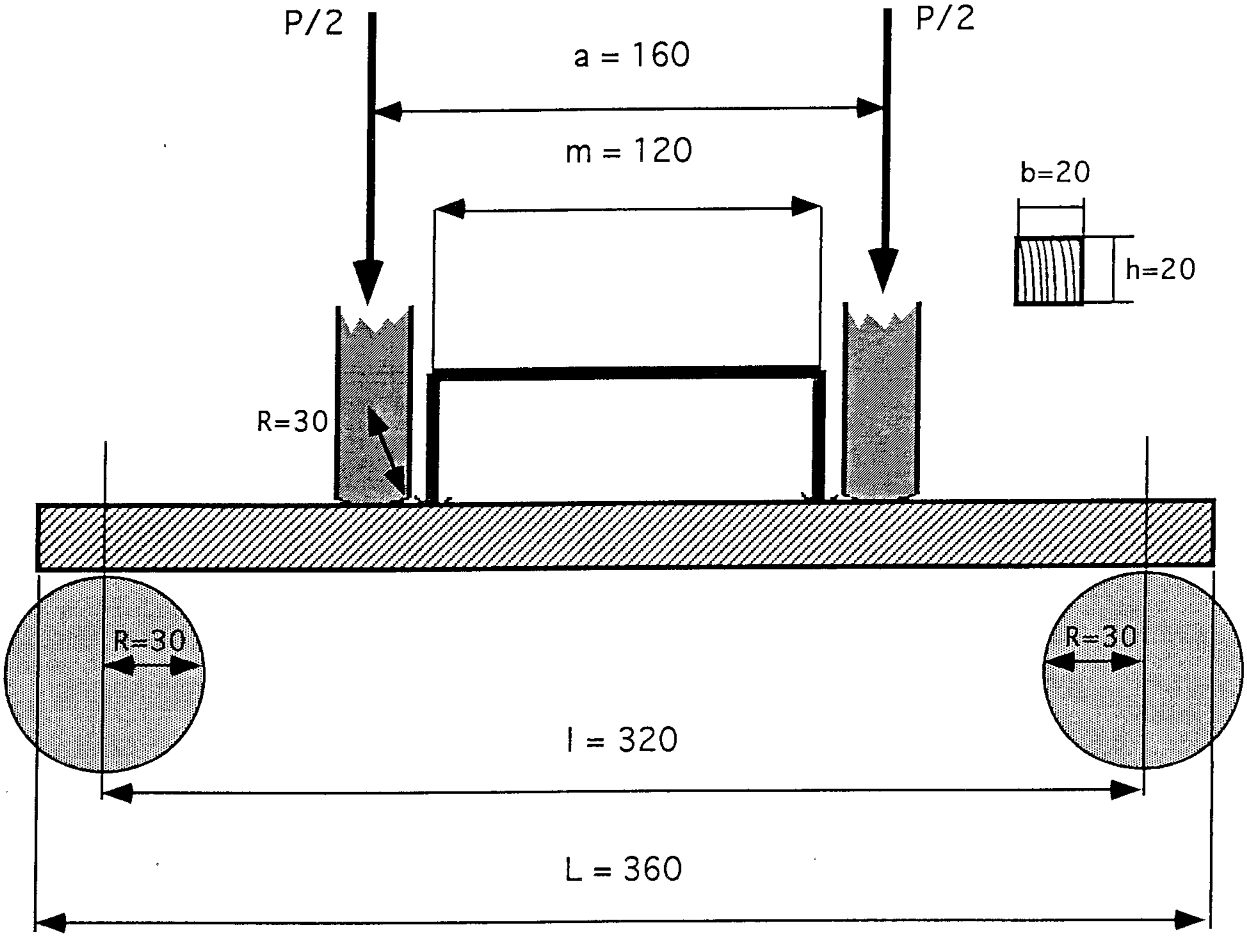


Figure 3. - *Scheme of static bending test equipment.*

The MOE measurements performed by CTBA are realized on a hydraulic test equipment while those made by SRF were achieved on a mechanical test equipment.

The test is realized on quartely cut clear specimens with growing ring oriented tangentially to the loading direction. The deflection measurement is made with a displacement captor located at the upper face of the wood sample between the two loading heads (Figure 4).

The deflection is measured after loading, during the unloading phasis, at a constant speed of 30 ± 10 s between the range of 600 N and 200 N.

The operating procedure is successively repeated 3 times on the same sample, and the deflection used for calculating MOE is the mean value of the 3 measurements.

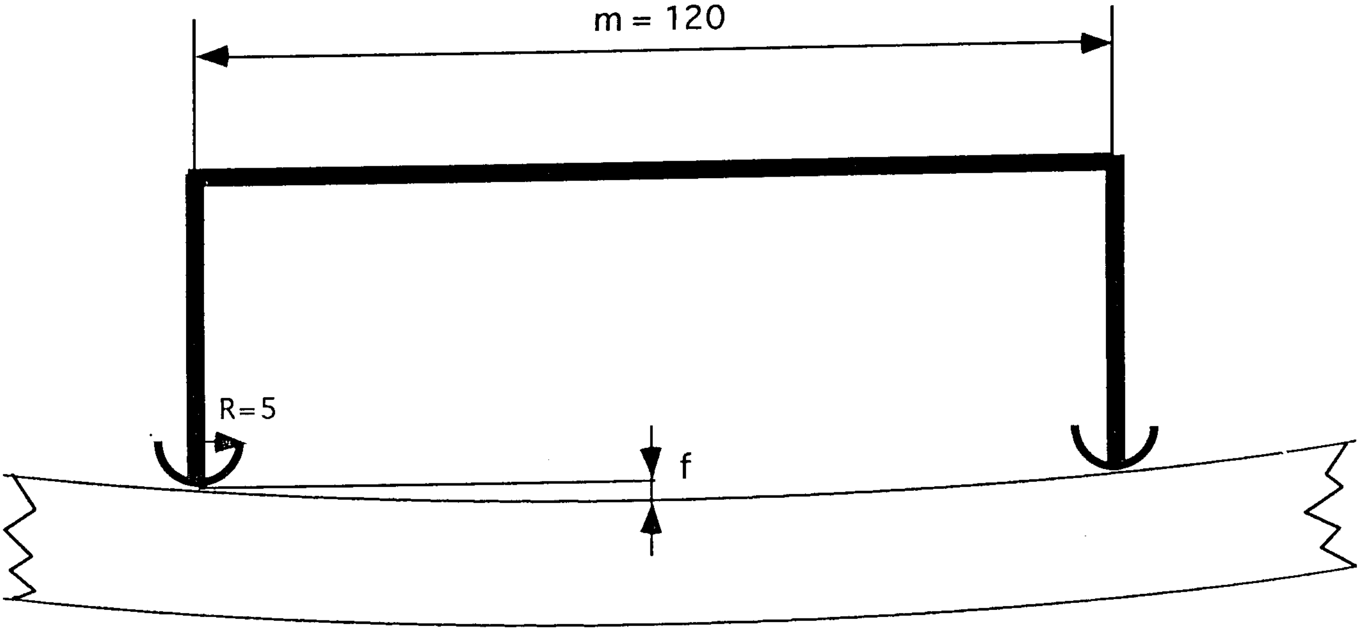


Figure 4. - *Scheme of the deflection equipment.*

The moisture content of the sample under testing must be as close as possible to 12%. If the moisture content moves away from this standard value, while remaining ranging between 10 and 14 %, then it is possible to estimate MOE at 12 % as follows:

$$\mathbf{E_{12} = E_{LH} [1 + C_L (H - 12)]}$$

Where:

C_L: is the variation coefficient of MOE per percent of variation of moisture content, equivalent to 0.02 [DESCH (1956)].

H: real moisture content of the sample under testing.

MOE is calculated by the classical formula:

$$E_{LH} = \frac{3\,P\,(l - a)\,m^2}{8\,b\,h^3\,f}$$

Where:

E_{LH}: Young's modulus on small clear specimens (Mégapascal - MPa);

P : load under flexural test (Newtons - N), equal to the mean value of the differences between the maximum and minimum loads for the three successive tests;

l : distance (millimeter - mm) between the axis of rollers supports;

a : distance (millimeter - mm) between the axis of the two loading heads;

m : distance (millimeter - mm) between the two supports heads of the deflection equipment;

b : sample width (millimeter - mm);

h : sample height (millimeter - mm);

f : deflection (millimeter - mm).

2.3.2. Calibration of test equipments

The 350 samples were tested in two different laboratories: CTBA - Paris and SRF - Gembloux. To insure uniformity in MOE results, a sample of 32 specimens was randomly taken in the sets B, C, D and E, and respectively tested in INRA, "Equipe de Recherches sur la Qualité du Bois" - Nancy, (Team 1), in CTBA (Team 7) and in SRF (Team 6). The results are presented in table 3.

A two-way analysis of variance points out that the nul hypothesis of equality between means [H_0: $m_1 = m_2 = m_3$] must be rejected at the significant level alpha = 5 % ($F_{obs} = 64.98 > F_{0.95} = 3{,}32$). Thus, the results achieved by the three laboratories can not be considered as the same.

Table 3. - *Calibration of test equipments by comparison of MOE measured on a small sample of clear specimens (32 specimens) in INRA, CTBA and SRF laboratories.*

n^r sample	MOE Gx at 12% MPa	MOE CTBA at 12% MPa	MOE INRA at 12% MPa	≠ MOE Gx with CTBA %	≠ MOE Gx with INRA %	≠ MOE CTBA with INRA %
1	7060	6907	6669	2,2	5,5	3,4
2	11718	11545	10737	1,5	8,4	7,0
3	7725	7127	7032	7,7	9,0	1,3
4	10624	10327	9907	2,8	6,7	4,1
5	10671	10681	10210	-0,1	4,3	4,4
6	11253	11664	10766	-3,7	4,3	7,7
7	14039	14439	13165	-2,9	6,2	8,8
8	11855	11784	10828	0,6	8,7	8,1
9	10868	11427	10447	-5,1	3,9	8,6
10	9179	9428	8843	-2,7	3,7	6,2
11	12046	11860	11656	1,5	3,2	1,7
12	12544	12744	11827	-1,6	5,7	7,2
13	12050	11740	11330	2,6	6,0	3,5
14	8684	8522	8218	1,9	5,4	3,6
15	11974	11519	11348	3,8	5,2	1,5
16	9693	10531	9752	-8,6	-0,6	7,4
17	12082	13413	12488	-11,0	-3,4	6,9
18	11960	12153	10640	-1,6	11,0	12,4
19	15767	15712	14836	0,3	5,9	5,6
20	13992	14766	13414	-5,5	4,1	9,2
21	10685	10673	9846	0,1	7,9	7,8
22	12848	13629	12424	-6,1	3,3	8,8
23	9121	9077	8691	0,5	4,7	4,3
24	12249	12941	11622	-5,7	5,1	10,2
25	9631	9930	9354	-3,1	2,9	5,8
26	9405	9041	8831	3,9	6,1	2,3
27	9375	9220	8712	1,7	7,1	5,5
28	11269	11062	10569	1,8	6,2	4,5
29	12440	12512	11685	-0,6	6,1	6,6
30	10676	10656	10037	0,2	6,0	5,8
31	11427	11445	10538	-0,2	7,8	7,9
32	10217	10024	9443	1,9	7,6	5,8
Mean value	**11098**	**11203**	**10496**	**-0,7**	**5,4**	**6,1**

The Newman -Keuls test shows that the measurments performed in CTBA and SRF Laboratories have to be considered as the same. The INRA measurments are significantly different compared to the two other Laboratories.

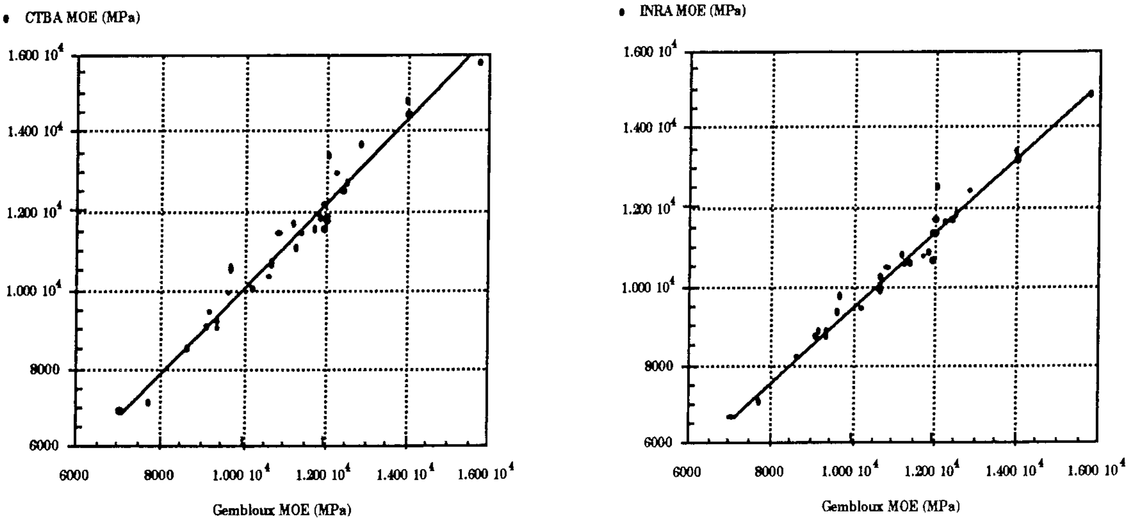
Table 4 gives the results of the variance analysis and the Newman-keuls test, and figure 5 shows the correlations between each couple of laboratories.

Table 4. - *MOE variance analysis and Newman-keuls test realized on a small sample of clear specimens in view to calibrating test equipments.*

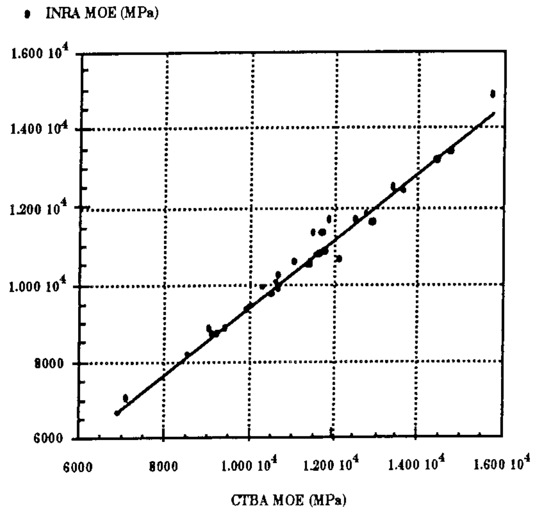
Source of variation	DF	Sum of squares	Mean square	F_{obs}	Pr
Between groups	2	9318046	4659423	65.0	0.0001
Within groups	31	325674412	10505626	146.5	0.0001
Error	62	4445944	71709		

Newman-Keuls test:

CTBA	SRF	INRA
11203	11098	10495



$R^2 = 0.96$ $R^2 = 0.97$



$R^2 = 0.98$

Figure 5. - *Correlations of MOE measurements on control specimens between the different laboratories.*

2.3.3. Young's modulus value at 12 % moisture content

The French Standard NF B 51 -016 specifies that MOE must be measured on samples conditionned at 12 % moisture content.

In practice, it is impossible to get accurately this standard value on the whole sample. Therefore it is necessary, even using a conditioning room, to know the right moisture content of each testing specimen. For this purpose, each testing specimen and their corresponding control specimens (cut off from the prolongation of the testing specimens) were weighted at the same time inside the conditioning room.

Then, all these control specimens were oven dry in order to determine accurately the right moisture content of the testing specimens. All these values were listed for the whole testing sample, as a reference for the other laboratories. The list gives for each specimen its true moisture content with the corresponding weight.

So, by weighing each specimen before testing in each laboratory, it was possible to know directely the corresponding moisture content.

2.3.4. Specific gravity measurements

By specific gravity it must be understood the weight per volume of the clear specimen at 12% moisture content.

The method used for determining specific gravity consists in measuring the length, the width and the heigt of the sample with an accuracy of 0,01mm for calculation of the volume and in weighting the sample on an electronic balance with an accuracy of 0,001g.

All these measurements have been performed just before applying mechanical tests on specimens conditioned at 12% moisture content.

2.3.5. Ring width measurements

The mean ring width for each clear specimen has been calculated in recording on transverse sections 2 times the width of the specimen divided by the number of growth ring width appearing on the transversal sides of the sample.

2.3.6. Age measurements

The mean age of each clear specimen is corresponding to the arevage between the maximum and minimum ages noted on the transverse sections of the sample (Cf.§ 2.1).

2.4. Data file organization

All the informations collected were recorded with an EXCEL® software on floppy disks. The French data were sent by Team 7 to the Task leader for being adapted to the analysis procedure by a SAS® software on a VAX computing system in the Centre de Calcul et d'Informatique de la Faculté des Sciences agronomiques de Gembloux.

CHAPTER 3 : RESULTS

1. Introduction
2. Comparison of wood moisture content between laboratories
3. Comparison of results got in SRF and in CTBA
4. Study of Young's modulus in connection with small clear specimens characteristics, silvicultural parameters and position within the tree
5. Influence of compression wood on Young's modulus variability

1. Introduction

Before presenting the MOE values, it is very important to pay attention to the fact that the initial sampling, whilst being systematically realized through all the trees, is finally biased.

As previously already mentionned, a large number of specimens was indeed eliminated from the sampling for not being really clear specimens as defined by the Standard (knots, cracks, grain angle and others defects).

Then, some trees, some height levels, some radial positions are more or less well represented than others within the sampling.

In the same context, it must be observed and kept in mind that trees growing on good sites are better represented than trees coming from poor sites.

2. Comparison of wood moisture content between laboratories

The mean wood moisture content of the 350 testing specimens calculated by the two laboratories are slightly different under testing conditions: 13.17 % for CTBA and 12.04 % for SRF.

Table 5 shows the main statistical values of the two series.

Table 5. *Comparison of wood moisture content between SRF and CTBA (statistical data).*

	SRF	CTBA
Nr of observation	350	350
Minimum value	11,10	11,96
Maximum value	13,05	15.84
Mean value	12,04	13,17
Variance (S^2)	0,102	0,135
Standard deviation (S)	0,32	0.37
Coef. of variation (V)	0,027	0,028

Figure 6 shows the differences in wood moisture content between the two laboratories. The moisture content is systematically higher for CTBA, indicating the need for MOE data conversion.

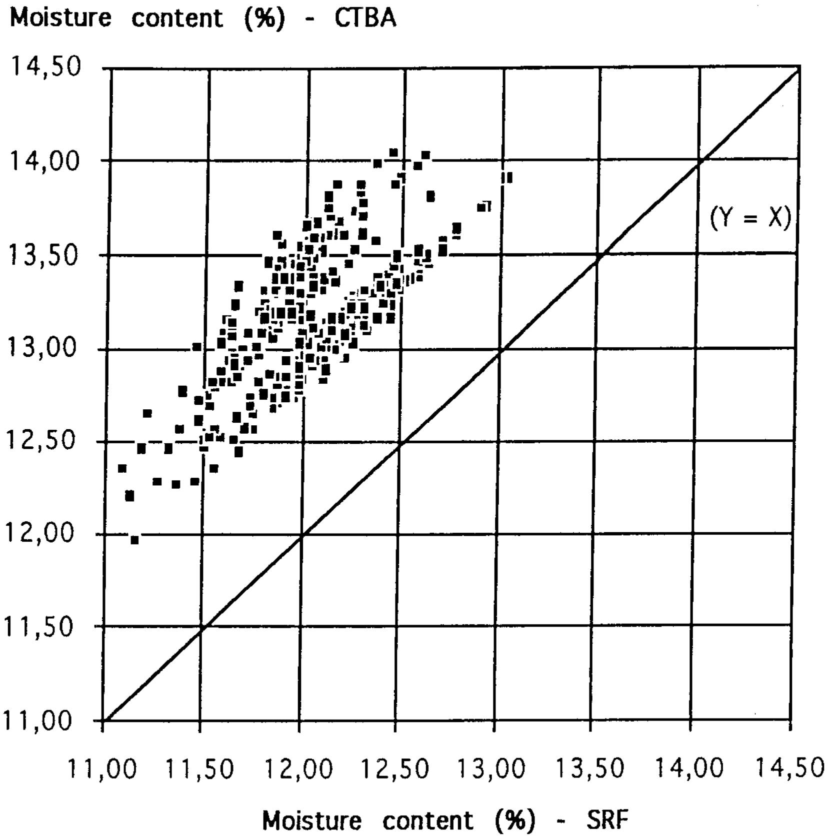


Figure 6. - *Comparison of wood moisture content for the two series of MOE measurements.*

3. Comparison of results achieved in CTBA and SRF

The accuracy needed for determining MOE, as well with regard to the specimen positioning, to the measurement of the deflection, as with regard to the samples sizes measurements or the calibration of the load applied, justifies to replicate the measurements in two different laboratories. Moreover, this duplication allows the control of possible disturbance of testing equipments.

Figure 7 shows the strong correlations between MOE measurements performed by each laboratory. The Paired samples T-Test comparing the mean values of both laboratory series does not reveal significant differences (t_{obs}: 0,656 < $t_{0,95}$: 1,972).

Therefore, in the running work we have considered the MOE mean value calculated with MOE value adjusted at 12% in each Laboratories.

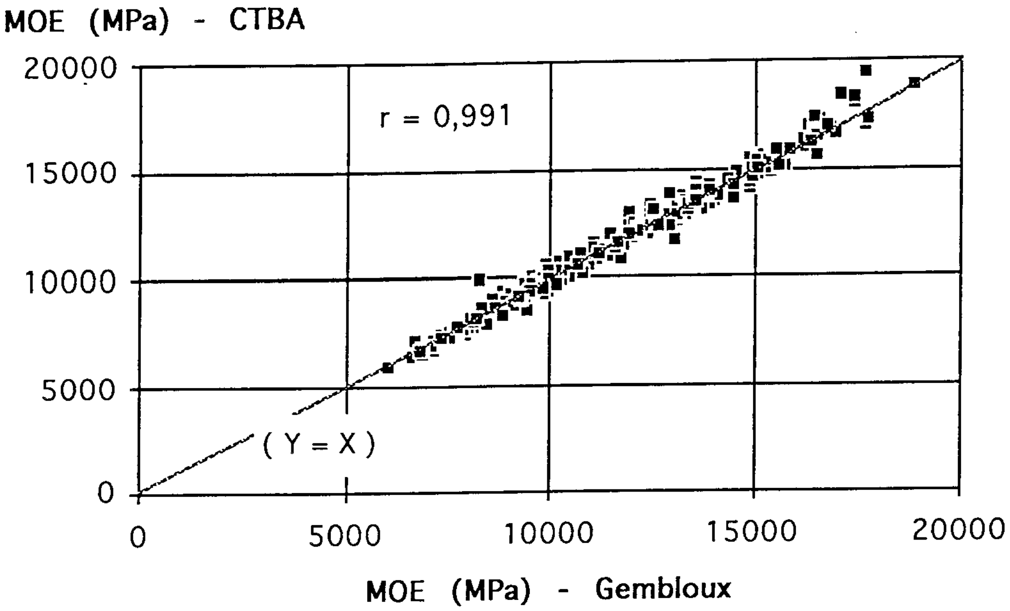


Figure 7. - *Correlation between MOE measurements at 12 % performed in CTBA and SRF.*

4. Study of Young's modulus in connection with small clear specimens characteristics, silvicultural parameters and position within the tree

4.1. Global results

Table 6 presents the basic statistical value of MOE, Specific gravity (sp. gravity) and growth ring width. As already observed previously on other species, growth ring width and MOE are parameters much more variable than specific gravity.

Figures 8, 9, 10 show the distribution of these last parameters together. MOE becomes more and more variable when specific gravity is increasing (Figure 8). It is also obvious that MOE is much more variable when growth ring width is decreasing (Figure 9) because growth ring width is negatively connected with specific gravity (Figure 10).

The question is which factor could induce such a variability for MOE when specific gravity increases or when growth ring width decreases. Soil quality, silvicultural treatment or social position of the tree in the stand could have a major effect on this observed variability.

The position of the sample along the tree height or along the tree diameter could also explain this variability.

Moreover, anatomical features, wood texture, wood defects, compression wood, ultra structure and chemical composition are also able to influence MOE at a same level of specific gravity and growth ring width.

These possible effects will be examined in details hereafter.

Table 6. - *Basic statistical values of MOE, specific gravity and growth ring width.*

Variable	units	Nr	Mean	Minimum	Maximum	V (%)
MOE	(MPa)	350	11663	5992	18904	22.6
Sp. gravity	(Kg/m^3)	350	419	316	544	10.6
Ring width	(mm)	350	3.5	1.14	8.12	35.6

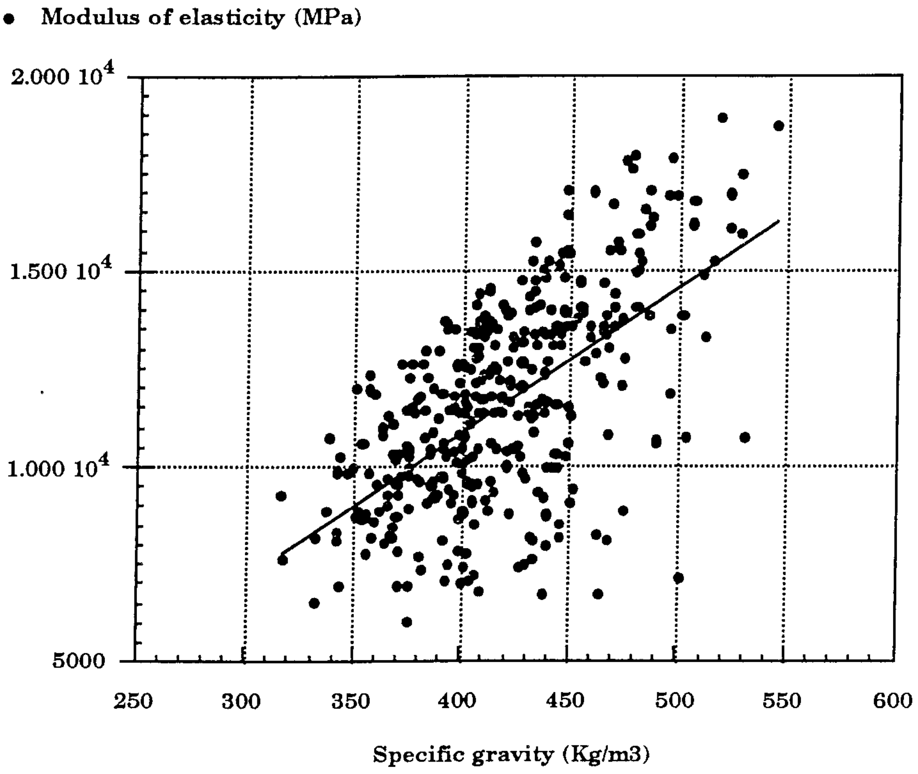


Figure 8. - *MOE versus specific gravity .*

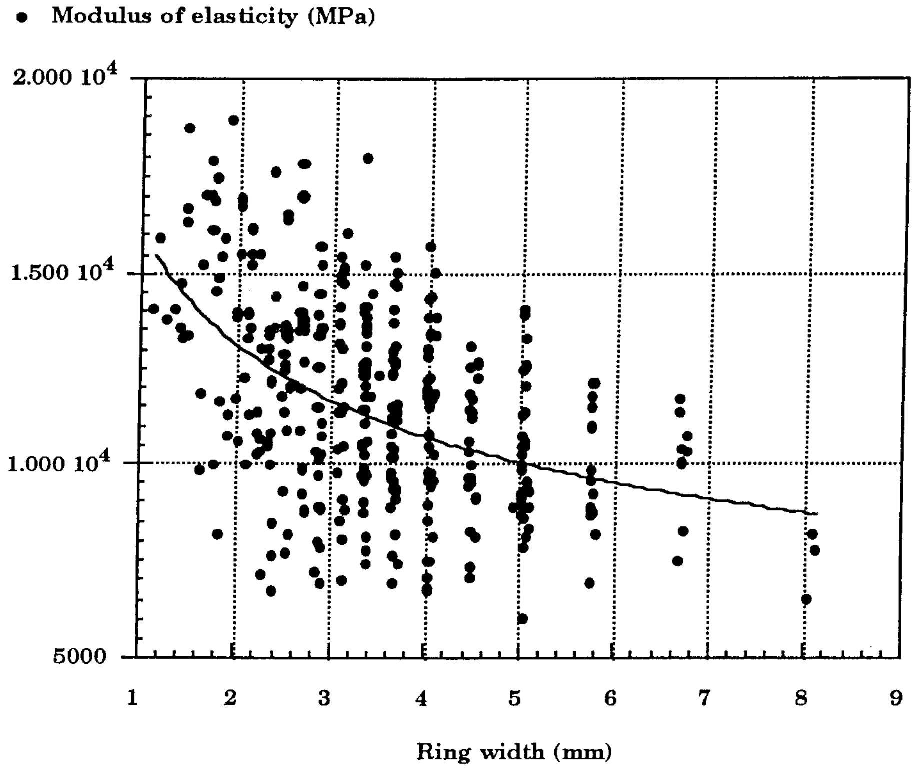


Figure 9. - *MOE versus growth ring width.*

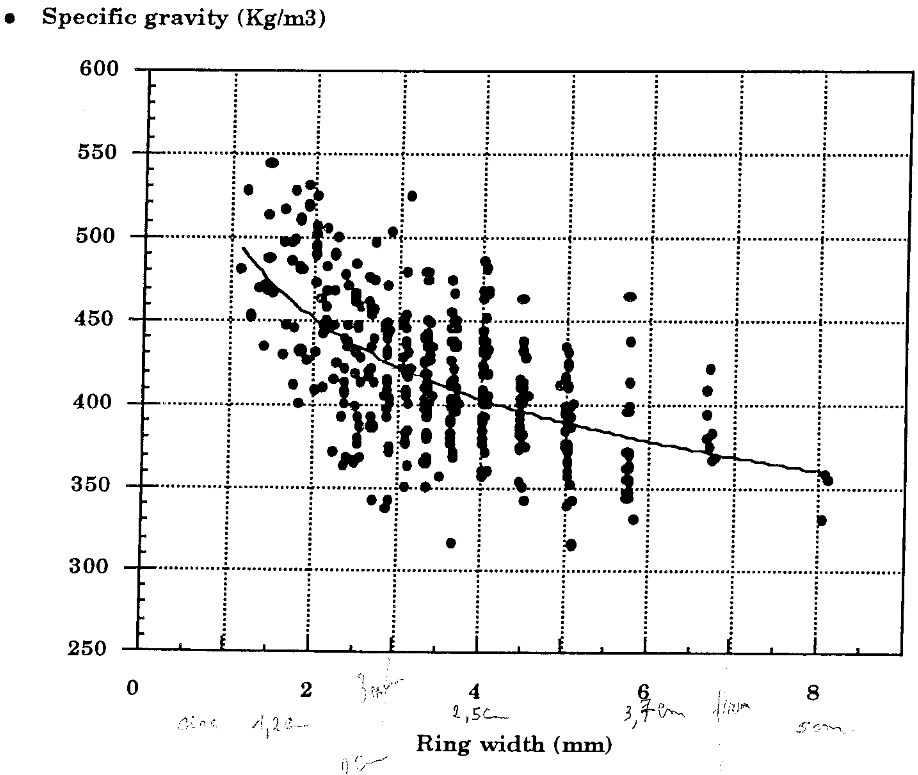


Figure 10. - *Specific gravity versus growth ring width.*

4.2. Evolution of Young's modulus in connection with specific gravity class and growth ring width class

When grouping MOE data per specific gravity class (Table 7, Figure 11) or per growth ring width (Table 8, Figure 12), it clearly appears for both factors a linear connection with MOE within the range of data examined, and a higher MOE variability when specific gravity increases and when growth ring width decreases.

Table 7. - *Basic statistic of MOE versus specific gravity class.*

Sp. gravity class (Kg/m^3)	300	350	400	450	500
mean MOE (MPa)	8698	10159	11769	13797	14836
N^r	12	103	161	59	15
S	1322	1672	2255	2596	3244

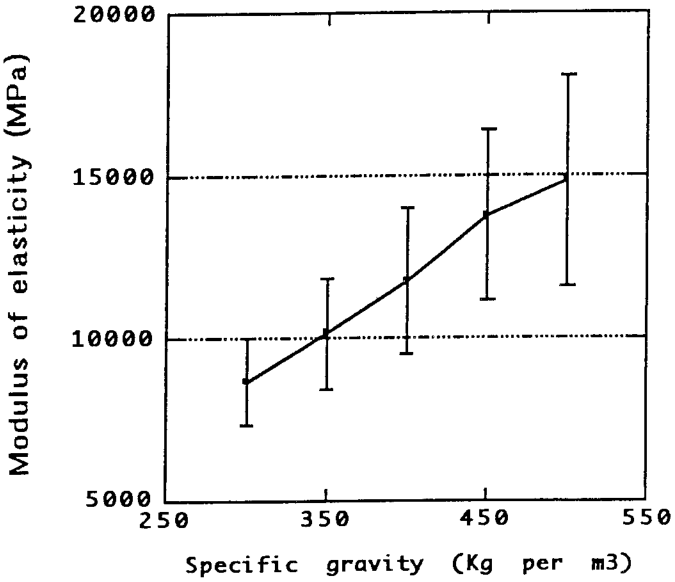


Figure 11. - *MOE versus Specific gravity class.*

Table 8. - *Basic statistic of MOE versus growth ring width class.*

Growth ring width class (mm)	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5
mean MOE (MPa)	14504	12313	11610	10968	10010	10013	/	7483
Nr	30	98	104	62	45	8	/	3
S	2749	2636	2365	2152	1763	1456	/	855

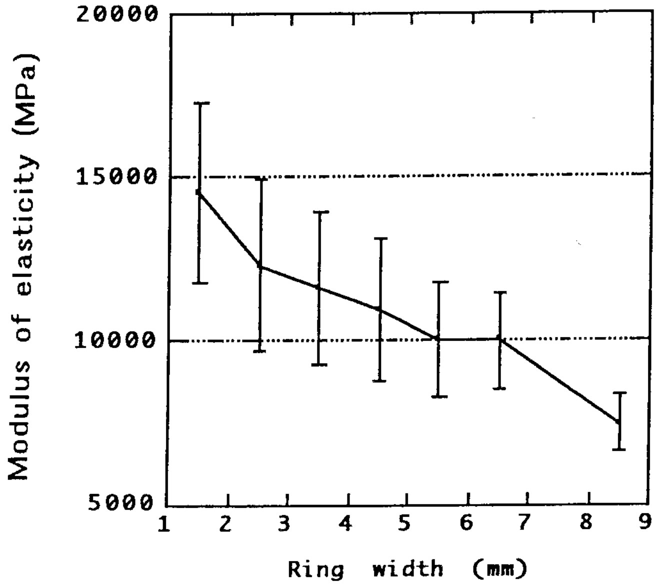


Figure 12. - *MOE versus growth ring width class.*

4.3. Behaviour of Young's modulus in connection with stands and trees selecting criteria

Table 9 summarizes the statistical data for MOE, specific gravity and growth ring width discriminated by site productivity class. It must be noted that there is no significant effect of the site productivity on the MOE value. As seen through figures 8, 9, 11 and 12, MOE should normally have to increase when specific gravity increases and when growth ring width decreases.

These linkages seem to change when we observed the connection between these parameters and the site quality. Wood produced on high site productivity is indeed characterized by a higher stiffness although being lighter with a faster growth.

This seems to point out that with a same specific gravity and a same growth ring width, wood produced on high site productivity proves to be higher in quality and more homogenous.

Table 9. - *Basic statistical value of MOE, specific gravity and growth ring width in connection with the site productivity class.*

Variable	units	N^r	Mean	Minimum	Maximum	S
MOE	(MPa)	191*	11912	5992	18904	2350
		*159***	*11364*	*6521*	*18663*	*2913*
Sp. gravity	(Kg/m^3)	191	411	339	519	36.7
		159	*428*	*316*	*544*	*47.3*
Ring width	(mm)	191	3.94	1.83	8.12	1.18
		159	*2.97*	*1.14*	*8.04*	*1.11*

* High site productivity class ** *Low site productivity class*

The thinning intensity has normally to influence strongly growth ring width and, then, specific gravity and MOE. Table 10 shows indeed that a higher thinning produces larger growth rings and a lower stiffness, but specific gravity seems to be stable whatever the thinning intensity could be. On a statistical point of view, there is no significant influence of the thinning intensity on MOE values.

Table 10. - *Basic statistical value of MOE, specific gravity and growth ring width in connection with the thinning intensity class.*

Variable	units	N^r	Mean	Minimum	Maximum	S
MOE	(MPa)	158*	11490	6521	18904	2653
		*192***	*11806*	*5992*	*18663*	*2611*
Sp. gravity	(Kg/m^3)	158	417	316	519	40.0
		192	*420*	*339*	*544*	*44.8*
Ring width	(mm)	158	3.76	1.14	8.12	1.33
		192	*3.29*	*1.20*	*6.77*	*1.13*

* High thinning intensity ** *Low thinning intensity*

Considering the fact that the effect of the social position of the tree in the stand is very highly significant on MOE, specific gravity and growth ring width, dominant trees are characterized by the fastest growth, the lowest specific gravity and the smallest stiffness compared to co-dominant trees and above all with suppressed trees (Table11).

This discrimination between dominant trees, co-dominant trees and suppressed trees remains obvious when we considered MOE values on samples having the same mean growth ring width (Table 12).

Thus, within the same range of ring width, suppressed trees have a better wood quality than dominant trees.

Table 11. - *Basic statistical value of MOE, specific gravity and growth ring width in connection with the social position of the tree in the stand.*

Variables	units	N^r	Mean	Minimum	Maximum	S
MOE	(MPa)	**165***	**10659**	**5992**	**19999**	**2157**
		114**	12188	6891	17832	2548
		*71****	*13156*	*7117*	*18904*	*2837*
Sp. gravity	(Kg/m^3)	**165**	**404**	**317**	**531**	**32.9**
		114	423	316	511	41.9
		71	*449*	*351*	*544*	*47.1*
Ring width	(mm)	**165**	**3.97**	**1.43**	**8.12**	**1.28**
		114	3.37	1.73	6.69	1.07
		71	*2.63*	*1.14*	*5.07*	*0.87*

* **Dominant trees** ** Co-dominant trees *** *Suppressed trees*

Table 12. - *MOE, specific gravity and growth ring width mean values of samples having the same growing characteristics in relation with the social position of the tree in the stand.*

Variables	units	Dominant (47 specimens)	Co-dominant (35 specimens)	Suppressed (22 specimens)
MOE	(MPa)	10734	12062	12760
Sp. gravity	(Kg/m^3)	404	422	427
Ring width	(mm)	3.5	3.4	3.3

4.4. Evolution of Young's modulus in connection with the radial and axial positions of the samples in the tree

4.4.1. Effect of radial position in the tree

The evolution of MOE (measured through the 24 sampled trees) along the radius of the tree for all levels or only for level 1 is given in table 13 and illustrated in figures 13 and 14.

These results have to be interpreted with caution because some radial positions (1, 5, 6 and7) in the tree are indeed numerously underrepresented or only deal with dominant trees.

In taking into account this remark and considering only the radial positions 2, 3 and 4, MOE seems to remains stable along the radius within the context of this sampling.

This result appears to be not totally consistent with the litterature on this subject wich generally states that MOE is increasing from the pith up to the bark (Kliger & al. [1992]).

Table 13. - *MOE, specific gravity and growth ring width mean values related to the radial position in the tree.*

Radial position		1	2	3	4	5	6	7
All levels	MOE	11907	11948	12069	11557	10339	8813	8558
	N^{r}	15	117	119	62	28	7	2
	S	2164	2415	2713	2719	2576	1369	451
	Sp. gravity	415	421	422	422	408	388	360
	Ring width	4.6	3.6	3.2	3.2	3.8	5.5	5.9
Level 1 (all ring width)	MOE	8357	11396	11509	11475	9884	8813	8558
	N^{r}	3	28	46	40	24	7	2
	S	344	2248	2657	2743	2425	1369	451
	Sp. gravity	426	433	432	424	404	388	360
	Ring width	3.3	3.1	3.0	2.9	3.8	5.5	5.9

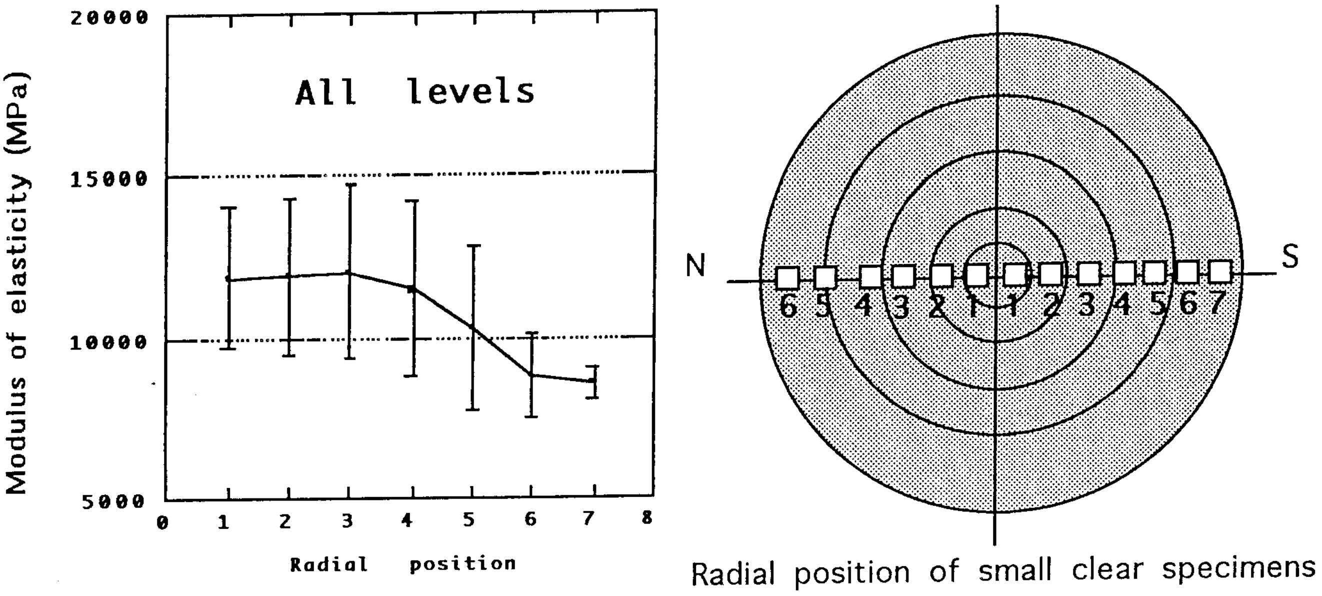


Figure 13. - *MOE versus radial position in the tree for all height levels.*

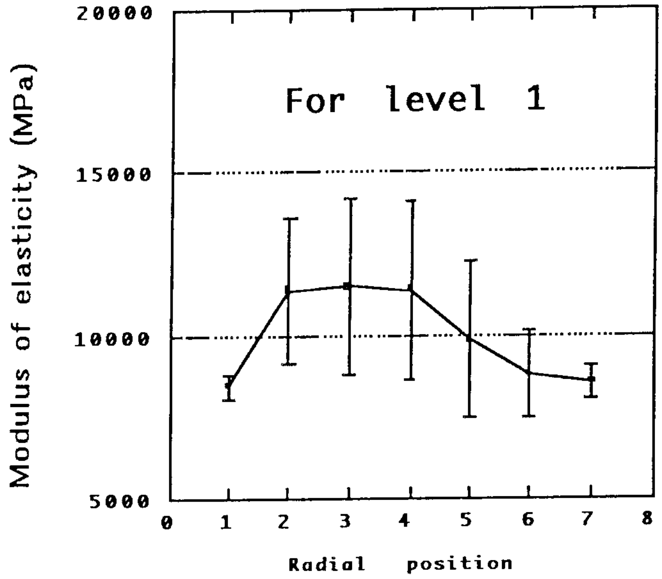


Figure 14. - *MOE versus radial position in the tree for height level 1.*

4.4.2. Effect of axial position in the tree

Firstly, if we consider the samples only belonging to a position close to the bark at each height level, i.e. wood produced during a same growing period for the 24 trees sampled, MOE is increasing from breast height up to the living crown level, with a maximum at an intermediate position inside the clean stem, and then, is decreasing inside the living crown, being relatively constant for levels 4 and 5 which are corresponding to juvenile wood (Table 14, Figure 15).

Secondly, if we consider the samples only belonging to a position close to the pith, MOE is evolving in the same way as previously along the tree height with always a maximum inside the clean stem between breast height and the living crown (Table 15, Figure 16).

In the two cases, MOE behaves in a same way without any visible effect of growth ring width and specific gravity. The statistical analysis on the whole data collected shows an very highly significant effect of the height level in the tree on MOE, which has to be taken in mind for modelling (Table 16).

Table 14. - *MOE, specific gravity and growth ring width mean values of samples close to the bark in connection with the axial position in the tree.*

Level	1	2	3	4	5
MOE (MPa)	11302	14004	13209	11303	11265
N^r	48	22	48	12	31
S	3043	2682	2701	2704	2242
Sp. gravity (Kg/m^3)	427	434	428	411	418
Ring width (mm)	3.1	3.0	2.9	3.4	3.9

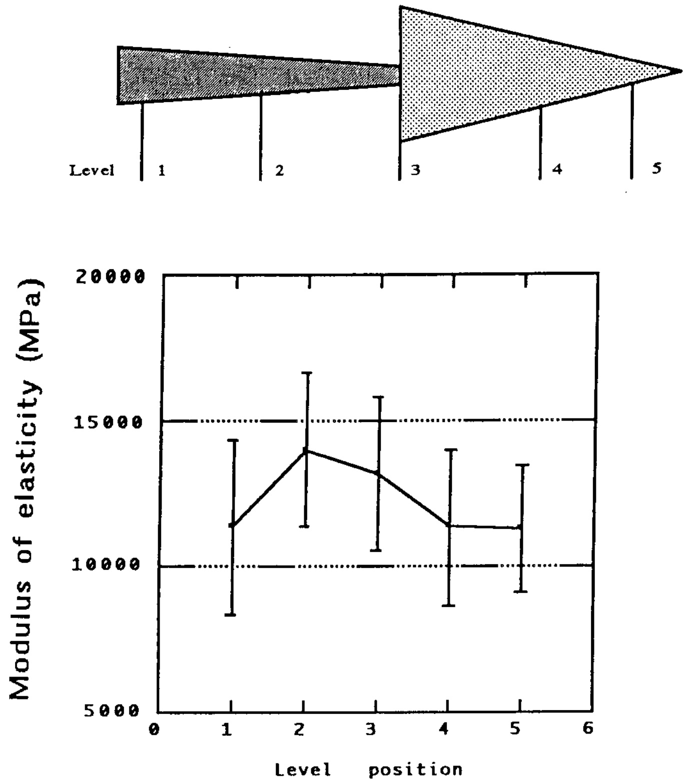


Figure 15. - *MOE versus height level in the tree (samples close to the bark).*

Table 15. - *MOE, specific gravity and growth ring width mean values of samples close to the pith, in connection with the axial position in the tree.*

Level	1	2	3	4	5
MOE (MPa)	11396	13042	12767	11055	11127
N^{r}	28	14	38	8	29
S	2248	2263	2510	1703	2263
Sp. gravity (Kg/m^3)	433	423	425	396	409
Ring width (mm)	3.1	4.0	3.4	4.0	4.0

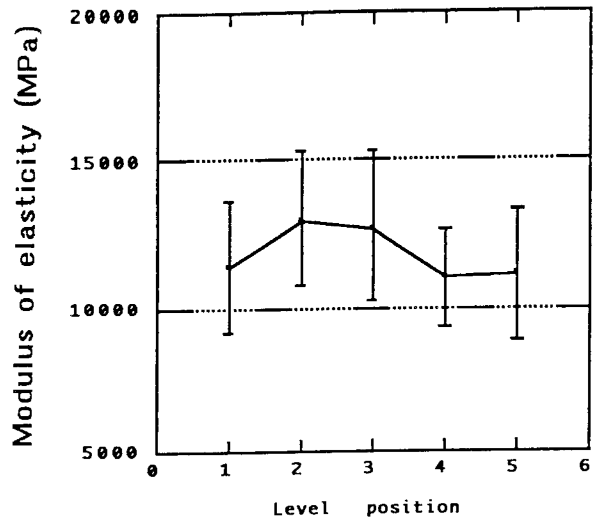


Figure 16. - *MOE versus height level in the tree (samples close to the pith).*

Table 16. - *Variance analysis of MOE as a function of height level in the tree, on the whole sampling (350 samples).*

Source	Sum of squares	DF	Mean square	F_{obs}
Between groups	244473 10^3	4	61118 10^3	9.7***
Within groups	2171620 10^3	345	6294547	

4.5. Influence of juvenile wood on Young's modulus

It is well known that juvenile wood presents worst qualities than adult wood. Normally, juvenile wood is characterized by larger growth ring width, a lower specific gravity (excepted when compression is very abundant), a lower stiffness and a higher shrinkage (Krahmer,1985; Senft and al.,1985; Smith and Briggs, 1985).

Arbitrarily, juvenile wood has been considered as corresponding to samples belonging to the central part of the tree up to 20 years old. Beyond this critical age, samples are supposed to be adult wood. The segregation between the experimental data, based on this criteria, is presented in terms of means values in table 17.

While having a faster growth and a slightly lower specific gravity, juvenile wood in our sampling has a MOE pretty close to MOE of adult wood. The difference between both MOE is not significant.

When ranging MOE of juvenile and adult wood according to specific gravity class (Table 18, Figure 17), it clearly appears not only that growth ring width decreases for both kind of wood when specific gravity becomes higher, but also that MOE of adult wood is more sensitive to variations of specific gravity than juvenile wood (Figure 17).

Table 17. - *MOE, specific gravity and growth ring width mean values in relation with juvenile wood.*

Variable	unitées	N^r	Mean	Minimum	Maximum	Std. dev.
MOE	(MPa)	219*	11719	5992	18904	2764
		131**	*11571*	*6908*	*18663*	*2391*
Sp. gravity	(Kg/m^3)	219	425	317	528	43.7
		131	*409*	*316*	*544*	*39.0*
Ring width	(mm)	219	3.15	1.14	8.12	1.18
		131	*4.08*	*1.47*	*6.77*	*1.13*

* Adult wood

** *Juvenile wood*

For each specific gravity class, compared to adult wood, juvenile wood is characterized by a faster growth which does not induce the same expected trend on MOE. A faster growth for juvenile wood produces indeed a higher MOE mean value for specific gravity classes lower than 500. For the specific gravity class 500 and upper, a faster growth for juvenile wood induces a lower MOE than that of adult wood.

Table 18. - *MOE, specific gravity and growth ring width mean values per specific gravity class in relation with juvenile and adult wood.*

Variable	Specific gravity class					
	300	350	400	450	500	550
MOE	7621	9090	10997	12142	15039	16675
(MPa)	*9293*	*10090*	*11104*	*13150*	*13438*	*14692*
Sp. gravity	317	357	403	446	494	528
(Kg/m^3)	*316*	*362*	*398*	*445*	*495*	*538*
Ring width	3.7	4.3	3.4	2.9	2.2	1.5
(mm)	*5.1*	*4.7*	*4.3*	*3.5*	*3.0*	*1.7*

* Adult wood   ** *Juvenile wood*

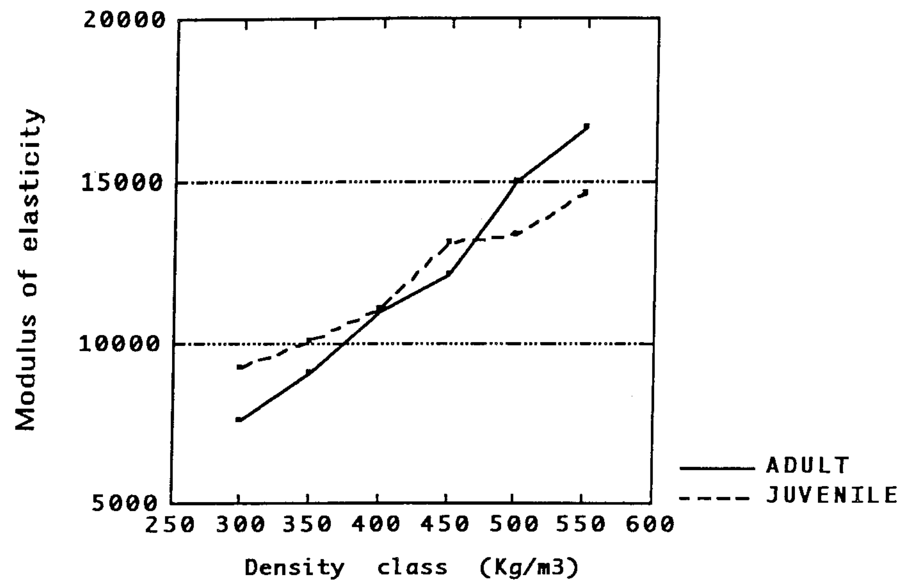


Figure 17. - *Connection between MOE and specific gravity class for juvenile and adult wood.*

5. Influence of compression wood on Young's modulus variability

As pointed out previously, a larger MOE variability mainly exists for the upper specific gravity classes or for the lowest ring width classes, which affects the modelling accuracy.

In order to get a better understanding of the reasons for such a variability, we compared two series of samples belonging to high MOE (set A) and low MOE (set B) within the specific gravity class 450 (Figure 18).

The macroscopical and microscopical observations made on these two sets revealed that set B was always consisting of samples not totally in accordance with the definition of clear specimen due to the presence of very slight slope of grain, and mostly, to the presence of compression wood. On the other hand, set A was completely in accordance with the definition of clear specimen.

When selecting the clear specimens for mechanical tests according to the specifications of the French standard NF B 51 002, inside both laboratories, a particular attention to compression wood has not really been paid.

The microscopical observations made on the two sets of samples have pointed out that all the samples belonging to set B were characterized by a presence of compression wood, which macroscopically appears darker within the growth ring.

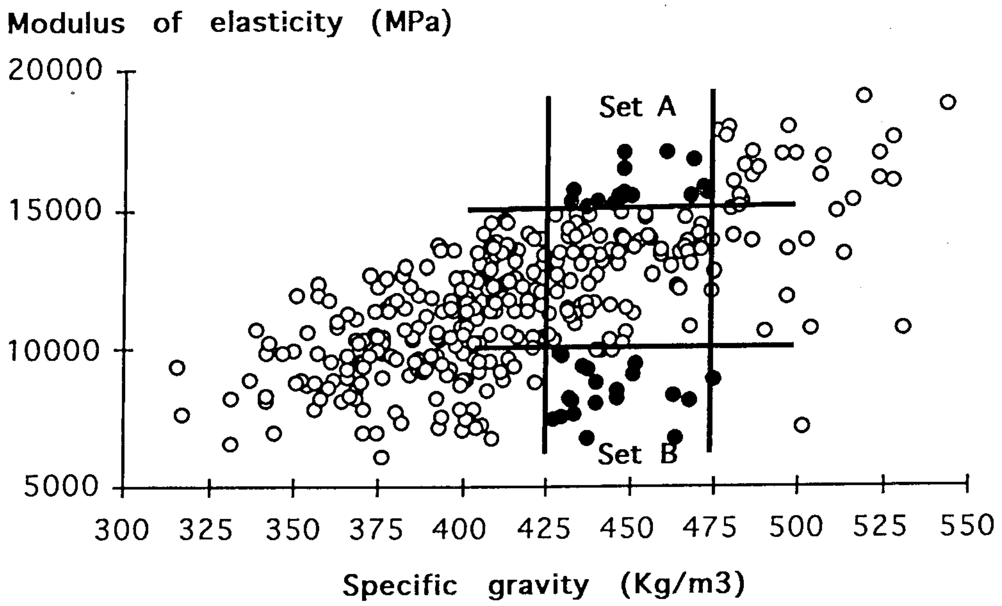


Figure 18. - *Comparison inside a same specific gravity class of two sets of samples characterized by extreme MOE values.*

As already observed on Norway spruce by TIMELL (1973), or on Douglas fire by Krahmer (1985), Senft & al. (1985), samples including compression wood have always a lower MOE than normal wood of the same density.

For instance, table 17 gives the MOE values for two samples of same specific gravity and growth ring width, the first one belonging to set A and the second one belonging to set B (Photo 1 and 2).

Table 19. - *Effect of compression wood on MOE value.*

Sample N^r	Specific gravity (Kg/m^3)	Growth ring width (mm)	MOE (MPa)	Observation
W45-S3	430	2.9	15049	set A - normal wood
T61-N3	440	2.9	8071	set B - compression wood

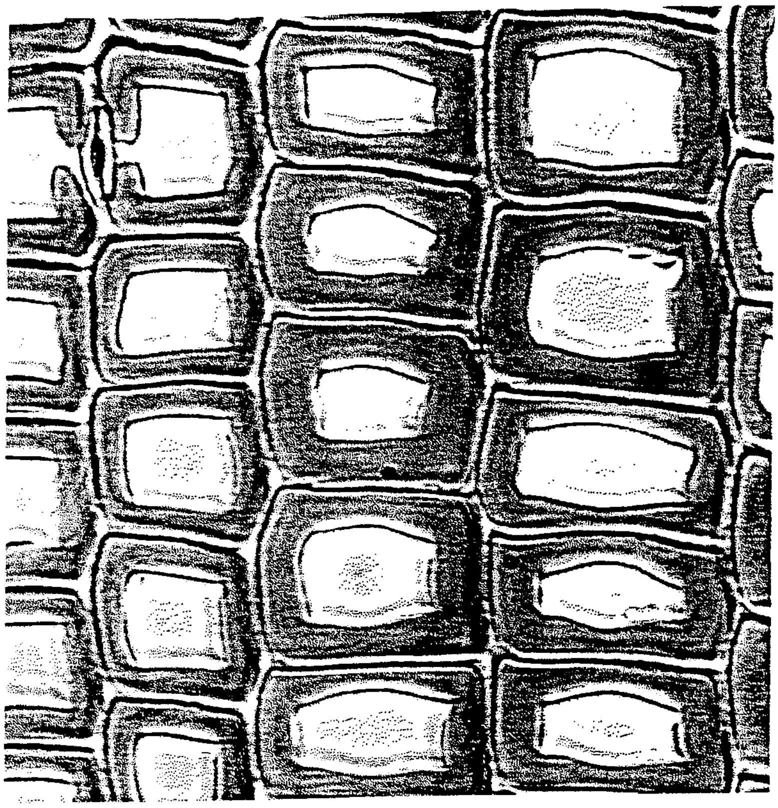


Photo 1. - *Anatomical features of normal wood (sample W45S3).* [2 cm = 20 microns]

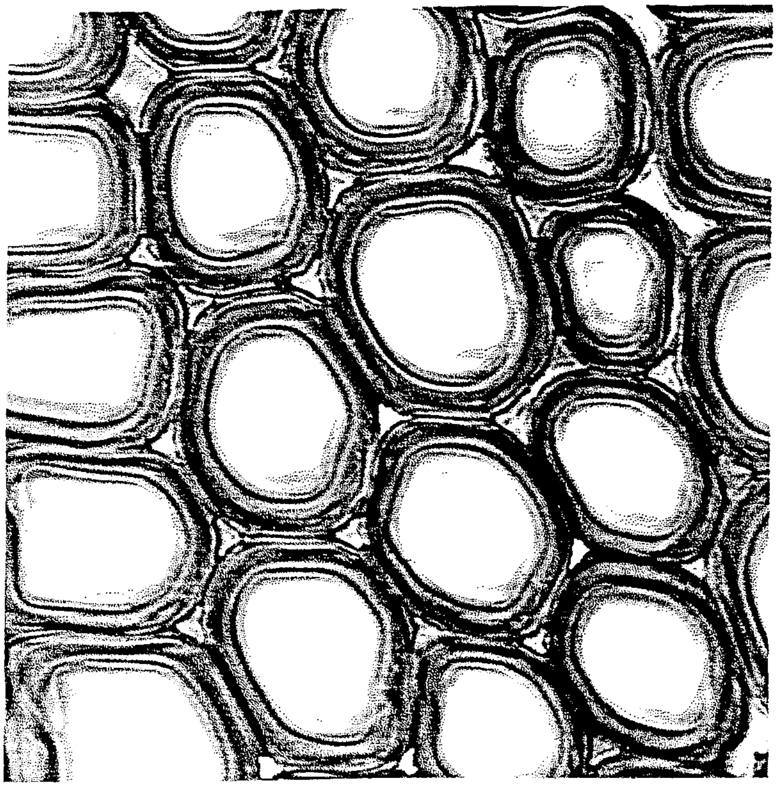


Photo 2. - *Anatomical features of compression wood (T61N3).* [2 cm = 20 microns]

This means for the future that the selection of clear specimens for mechanical testing has also to take care of the possible presence of compression wood.

That is the reason for why all the samples participating to the mechanical tests have been systematically and strictly controlled by a third party taking into account the following selecting criteria: slope of grain and, above all, compression wood. This selection has involved the disregarding of 126 samples.

Figure 19 illustrates the distribution of MOE in connection with specific gravity without and after selection, and shows a more homogeneous MOE distribution when strictly considering normal wood.

Consequently, the selected data are much more promising for modelling.

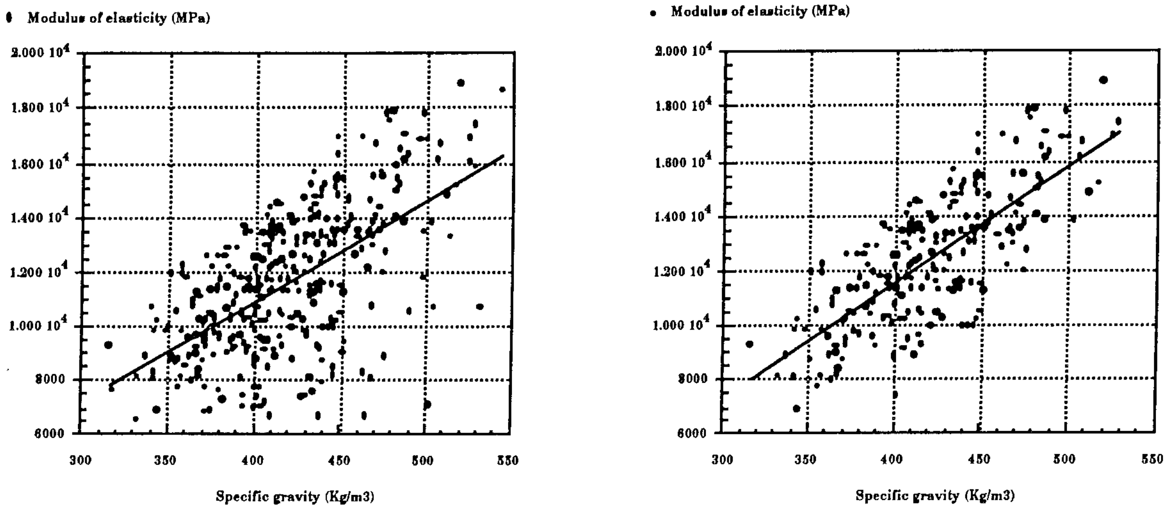


Figure 19. - *Distribution of MOE versus specific gravity before and after selection of samples includng compression wood.*

CHAPTER 4 : YOUNG'S MODULUS MODELLING

1. Introduction
2. Young's modulus modelling based on simple regression
3. Young's modulus modelling based on multiple regression
4. Models after strict selection of normal wood

1. Introduction

The problem of connections between MOE and specific gravity, growth ring width, age from the pith and height level has been solved by the regression analysis (PROC REG on SAS®) as this method consists in putting into close relationship a dependent variable as MOE with one, two or several independent variables as each explanative characteristic (DAGNELIE, 1969; 1970).

The choice of independent variables is systematically realized by the forward selection method based upon the principle of insuring every time the minimum of the residual sum of squares of deviates (DAGNELIE, 1975).

The choice of models are deliberately limited to those including at the most two independent variables.

Moreover, the relevance of the model chosen is appreciated by an analysis of residues in connection with the site productivity, the thinning intensity and the social position parameters (PROC GLM on SAS®).

In a first step, models involving one or two independent variables have been calculated on the whole data collected (350 samples). In a second step, models strictly limited to normal wood have been established (224 samples).

De Reboul (1988) has found that MOE is highly dependent of specific gravity, ring width and cambial age of small clear specimens. In the following works we have investigated these relations and also with the height level of small clear specimens in the tree.

2. Young's modulus modelling based on simple regression.

2.1. Relationship between Young's modulus and specific gravity

2.1.1. Regression equation

$$\mathbf{MOE = -\ 3864.1 + 37.061\ Specific\ gravity}$$

$R^2 = 0.36$ $S = 2106$ $N^r = 350$

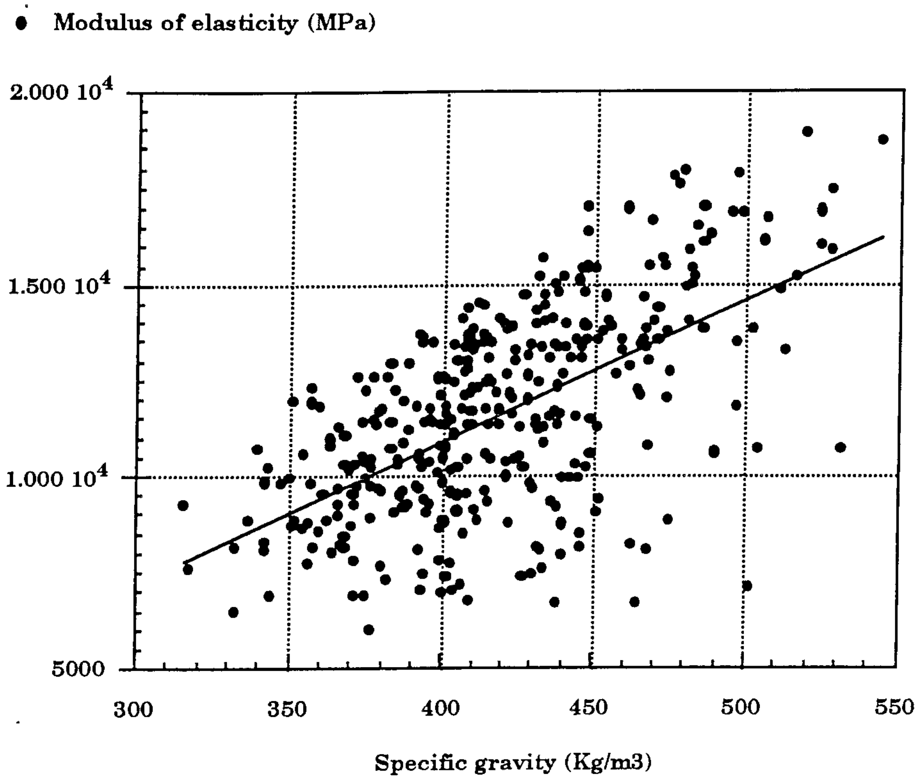


Figure 20. - *Regression of MOE versus specific gravity.*

2.1.2. Analysis of residues

Table 20 gives the results of the variance analysis of residues and figure 21 illustrates the distribution of residues related to the estimated values.

Table 20. - *Variance analysis of residues for the model "MOE versus specific gravity".*

source of variation	DF	sum of squares	mean square	F_{obs}
Productivity	1	87070846	87070846	3.04 ns
Thinning (product)	2	18590719	9295359	0.32 ns
Social position	2	58441957	29220978	1.02 ns
Productivity x social position	2	7258933	3629466	0.13 ns
Thinning x social position (product)	4	28466565	7116641	0.25 ns
Tree (product - thinning - social po.)	12	343694742	28641228	9,88***
Error	326	964543078	2958721	

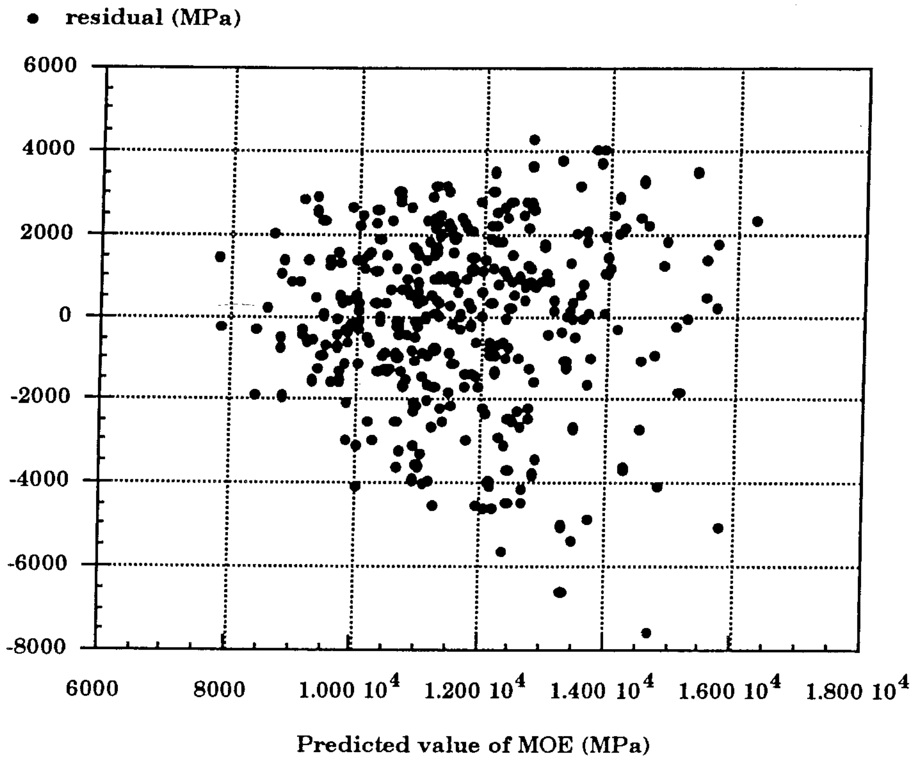


Figure 21. - *Distribution of MOE residues for the model "MOE versus specific gravity".*

2.1.3. Comments

The fact that the site productivity, the thinning intensity and the social position do not influence significantly the MOE variability and that there is a very highly significant tree effect on MOE indicates that the largest part of variation of MOE is due to the inter-tree variability. This is in accord with the observations of De Reboul (1988).

That means that the select model is valid whatever the silvicultural treatment could be (site productivity, thinning intensity and social position).

The model itself gives rise however to a large disturbance of residues for the highest predicted values.

For instance, table 20bis presents the mean MOE residues for each tree sampled. Unfortunately, the differences observed between trees may not be interpreted.

Table 20bis. - *Mean MOE residues for the model "MOE versus specific gravity" and dendrometrical characteristics of each trees.*

Tree numbers	N^r of samples	Mean residues	Social position	Girth13 (cm)	Total height (m)	Relative height of CBL (%)
Stand: **Dohan**		(high site productivity - high thinning intensity)				
1	10	+294	d	85	22.93	59
2	11	+1436	Dd	96	24.21	52
3	18	-177	D	116	26.60	52
4	13	+886	Dd	94	24.56	54
5	21	-1.4	D	117	26.52	47
6	11	+2077	d	80	24.91	61
Stand: **Solwaster**		(low site productivity - low thinning intensity)				
7	22	-3486	D	124	22.62	40
8	9	+806	d	82	22.19	66
9	14	+420	Dd	105	23.40	48
10	12	+1094	Dd	98	20.00	52
11	19	+1439	D	116	21.09	43
12	10	-1234	d	84	19.01	48
Stand: **Ternell**		(low site productivity - high thinning intensity)				
13	15	-702	Dd	105	23.42	53
14	20	-500	D	115	23.37	43
15	6	+543	d	79	20.74	61
16	4	-1857	d	79	18.74	69
17	11	-509	Dd	104	21.45	52
18	18	-2038	D	138	25.15	48
Stand: **Wellin**		(high site productivity - low thinning intensity)				
19	19	-42	Dd	110	26.33	54
20	18	-104	D	130	28.15	58
21	11	+392	d	88	25.55	69
22	18	+773	Dd	101	26.52	56
23	11	+647	d	84	22.82	60
24	30	+995	D	123	26.95	51

2.2. Relationship between Young's modulus and growth ring width

2.2.1. Regression equation

$$\mathbf{MOE = 61816 \ Ring\ width^{(-0.292)}}$$

$R^2 = 0.23$ S = 2340 $N^r = 350$

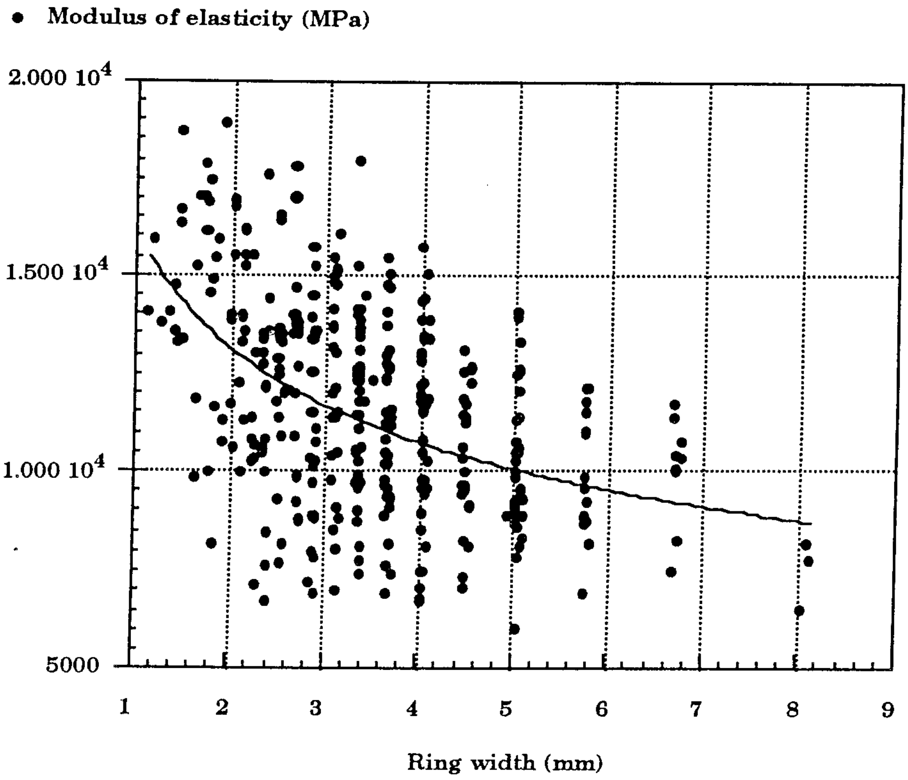


Figure 22. - *MOE versus growth ring width.*

2.2.2. Comments

This model is less accurate than the previous one and does not require an analysis of residues.

2.3. Relationship between Young's modulus and mean age from the pith of samples

2.3.1. Regression equation

$$MOE = 12166 - 19.165\ Age$$

$R^2 = 0.01$ $S = 2625$ $N^r = 350$

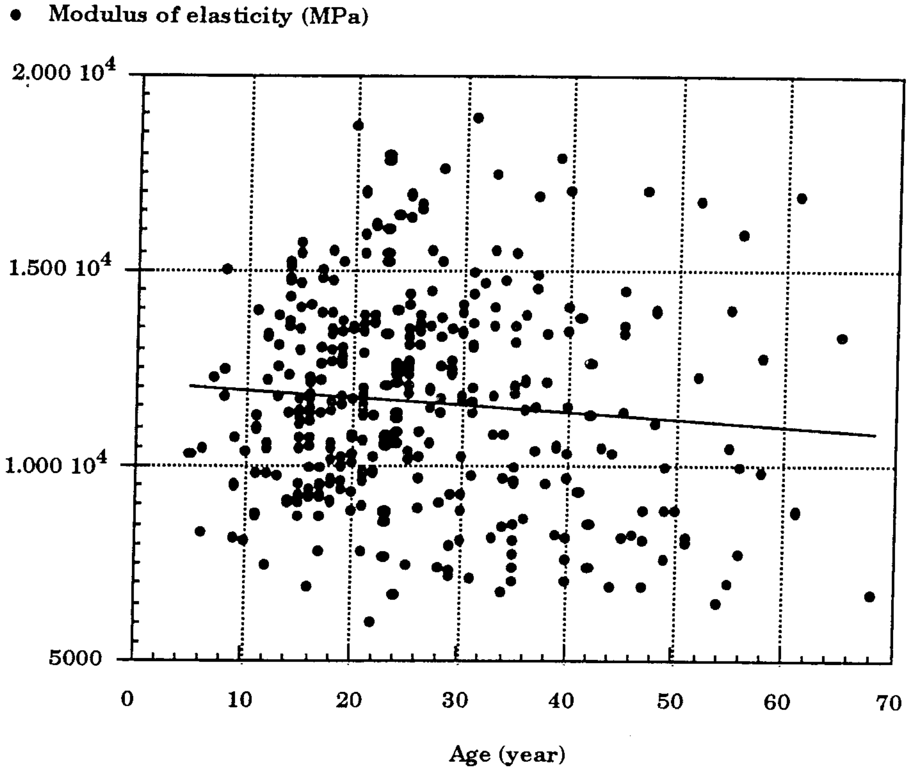


Figure 23. - *MOE versus mean age from the pith of samples.*

2.3.2. Comments

The variable "Age" is unconvenient for estimating MOE. MOE seems to be a characteristic unlinked with age from the pith.

2.4. Relationship between Young's modulus and height level in the tree

2.4.1. Regression equation

$$MOE = 11389 + 12.396\ Height$$

$R^2 = 0.01$ $S = 2621$ $N^r = 350$

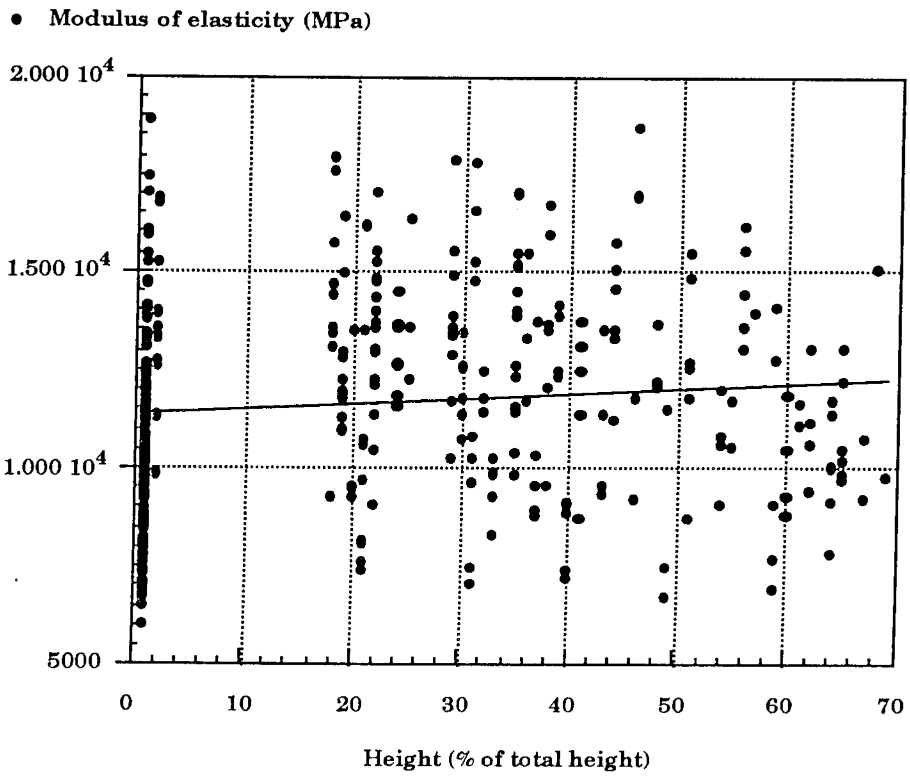


Figure 24. - *MOE versus Height level in the tree.*

2.4.2. Comments

MOE is not related to the height level in the tree. Whatever the tree height level could be, MOE presents the same variability.

3. Young's modulus modelling based on multiple regression

3.1. Relationship between Young's modulus, specific gravity and height level in the tree

All the general statistical works performed on our sampling have shown that the best explanative variables for MOE are specific gravity combined with height level in the tree.

3.1.1. Regression equation

$$\mathbf{MOE = -\ 3510.2 + 37.85\ Specific\ gravity\ -\ 1608.58\ /\ Height}$$

$R^2 = 0.44$ $S = 1970$ $N^r = 350$

3.1.2. Analysis of residues

Table 21 gives the results of the variance analysis of residues and figure 25 shows the distribution of residues related to the estimated values.

Table 21. - *Variance analysis of residues for the model "MOE versus specific gravity and height level in the tree".*

source of variation	DF	sum of squares	mean square	F_{obs}
Productivity	1	80717047	80717046	3.13 ns
Thinning (product)	2	9264887	4632443	0.18 ns
Social position	2	75899799	37949899	1.47 ns
Productivity x social position	2	7755280	3877639	0.15 ns
Thinning x social position (product)	4	27216373	6804093	0.26 ns
Tree (product - thinning - social po.)	12	309879095	258232257	10.57 ***
Error	326	796476918	2443181	

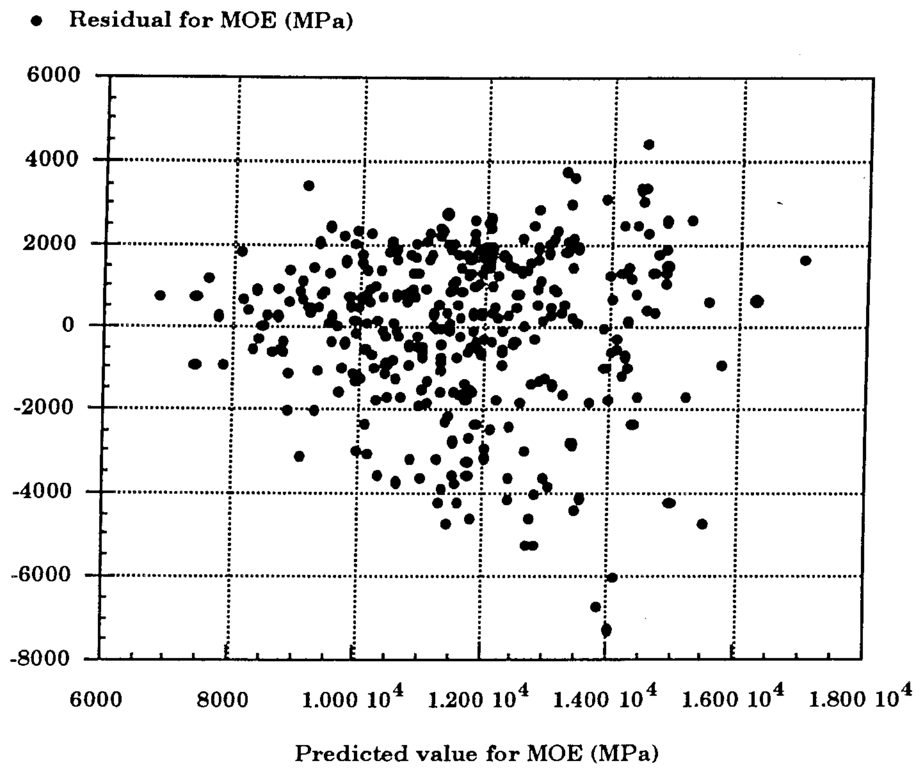


Figure 25. - *Distribution of MOE residues for the model "MOE versus specific gravity and height level in the tree".*

3.1.3. Comments

The fact to introduce a second independant variable "height" (which represents the relative height position of clear specimen in the tree), increase slightly the accuracy of the model.

One more time a very highly significant the tree effect is point out.

On an other hand the site productivity, the thinning intensity and the social position of the tree in the stand have no significant effect on MOE.

3.2. Relationship between Young's modulus, specific gravity, growth ring width per log level

As noted previously (Chapter 3, § 4.4.), MOE of small clear specimens is largely affected by the log level in the tree. So, distinct models have been calculated per log level. Only three log levels have been taken into account for modelling. Level 1 is corresponding to the log cut under breast height, level 3 is characterized by the log cut at the crown base level and level 5 is corresponding to the log taken at the top of the tree

3.2.1. Regression equation

$$\mathbf{MOE = a + b\ Specific\ gravity - c\ /\ Ring\ width}$$

Table 22. - *Regression equations for MOE versus specific gravity and growth ring in relation with log level.*

Level 1 (breast hight)

$$\mathbf{MOE = -\ 3290.3 + 30.4\ Specific\ gravity + 4094.7\ /\ Ring\ width}$$

$R^2 = 0.49$ S = 1883 $N^r = 150$

Level 3 (crown base level)

$$\mathbf{MOE = 8.5 + 25.4\ Specific\ gravity + 5323.9\ /\ Ring\ width}$$

$R^2 = 0.39$ S = 1974 $N^r = 92$

Level 5 (top of the tree)

$$\mathbf{MOE = -\ 4937.7 + 36.2\ Specific\ gravity + 4009.5\ /\ Ring\ width}$$

$R^2 = 0.48$ S = 1644 $N^r = 39$

3.2.2. Comments

Only for the log levels 1 and 2, MOE is slightly better explained in using specific gravity and growth ring width.

4. Young's modulus modelling after elimination of compression wood

The following analysis has been realized on a sampling of 224 clear specimens selected in order to avoid very slight slope of grain and, above all, compression wood. Only the best previous models have been retested with the present sampling.

4.1. Relationship between Young's modulus and specific gravity

4.1.1. Regression equation

$$\mathbf{MOE = -\ 5521.5 + 42.9\ Specific\ gravity}$$

$R^2 = 0.56$ $S = 1569$ $N^r = 224$

4.1.2. Analysis of residues

The results of variance analysis of residues are given in table 23 and illustrated in figure 26.

Table 23. - *Variance analysis of residues for the model "MOE versus specific gravity", strictly considering normal wood.*

source of variation	DF	sum of squares	mean square	F obs
Productivity	1	35230773	35230774	4.03 ns
Thinning (product)	2	1398253	699127	0.08 ns
Social position	2	5974800	2987400	0.34 ns
Productivity x social position	2	2398038	1199019	0.14 ns
Thinning x social position (product)	4	9831914	2457979	0.28 ns
Tree (product - thinning - social po.)	12	104959110	8746609	4.55 ***
Error	200	384612188	1923061	

4.1.3. Comments

The new model provides a better prediction for MOE related to specific gravity. (R^2 without selection of compression wood: 0.36; R^2 after elimination of compression wood: 0.56) The variance analysis of residues points out again a tree effect .

The distribution of the residues as a function of predicted values is this time better balanced whatever the predicted value could be.

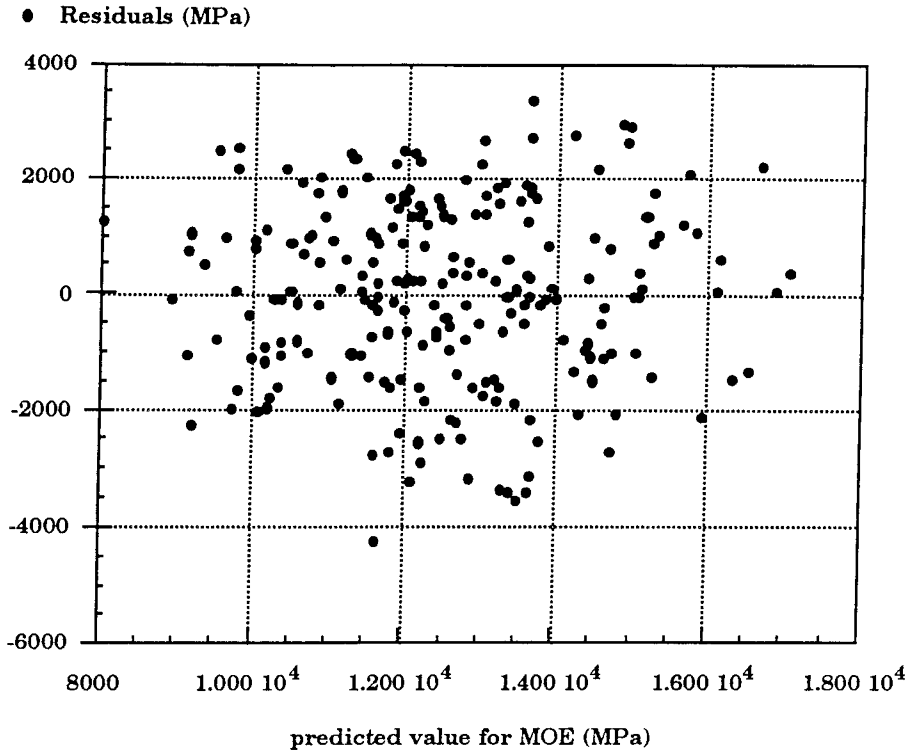


Figure 26. - *Distribution of MOE residues for the model "MOE versus specific gravity", strictly considering normal wood.*

In connection with other parameters as growth ring width, age from the pith and height level, there is no improvement of the level of MOE prediction.

4.2. Relationship between Young's modulus, specific gravity and height level in the tree

4.2.1. Regression equation

$$\mathbf{MOE \doteq - 5252.98 + 43.40\ Specific\ gravity - 1445.01\ /\ Height}$$

$R^2 = 0.63$ $S = 1434$ $N^r = 224$

4.2.2. Analysis of residues

The results of the variance analysis of residues are given in table 24 and illustrated in figure 27.

Table 24. - *Variance analysis of residues for the model "MOE versus specific gravity and height level in the tree" strictly considering normal wood.*

source of variation	DF	sum of squares	mean square	F_{obs}
Productivity	1	29478794	29478794	3.47 ns
Thinning (product)	2	4462824	2231412	0.26 ns
Social position	2	15070506	7535253	0.89 ns
Productivity x social position	2	2438223	1219111	0.14 ns
Thinning x social position (product)	4	13500076	3375018	0.40 ns
Tree (product - thinning - social po.)	12	101801181	8483432	5.66 ***
Error	200	299650053	1498250	

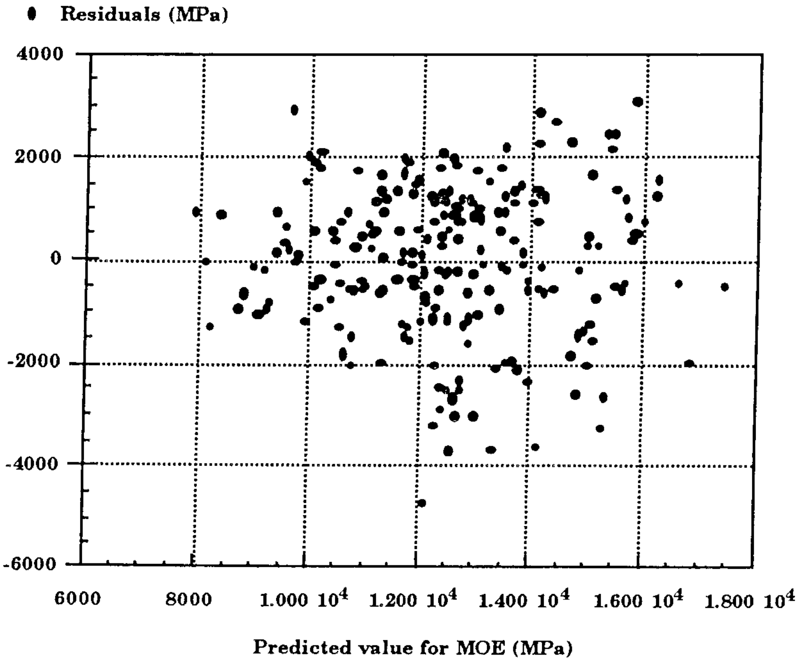


Figure 27. - *Distribution of MOE residues for the model "MOE versus specific gravity and height level in the tree", strictly considering normal wood.*

4.2.3. Comments

One more time, the accuracy of MOE prediction is improved in considering only samples strictly selected.

4.3. Relationship between Young's modulus, specific gravity and growth ring width per log level

4.3.1. Regression equation

$$\text{MOE} = a + b \text{ Specific gravity} - c \,/\, \text{Ring width}$$

4.3.2. Comments

In distinguishing MOE log level by log level, the MOE prediction is only partly improved. The gains are mainly consistent for predicting MOE at breast level and at the top of the tree.

Table 25. - *Regression equations for MOE versus specific gravity and growth ring width in relation with the log level, considering strictly normal wood.*

Level 1 (near breast height)

$$\text{MOE} = -\ 8276.80 + 46.06 \text{ Specific gravity} + 1491.00 \,/\, \text{Ring width}$$

$R^2 = 0.76$ $S = 1266$ $N^r = 79$

Level 3 (near the crown base level)

$$\text{MOE} = -\ 416.98 + 28.01 \text{ Specific gravity} + 4641.50 \,/\, \text{Ring width}$$

$R^2 = 0.53$ $S = 1454$ $N^r = 76$

Level 5 (near the top of the tree)

$$\text{MOE} = -\ 2524.51 + 30.85 \text{ Specific gravity} + 5709.23 \,/\, \text{Ring width}$$

$R^2 = 0.75$ $S = 1045$ $N^r = 18$

CONCLUSIONS

Based upon a sampling of 24 Belgian Norway Spruces coming from 4 stands, different by their site productivity and the thinning intensity, this study concerns the determination of MOE on 350 clear wood specimens according to the French Standard NF B 51 016 (1987) in view to established a model allowing the prediction of MOE.

The distribution of MOE related to growth ring width and to specific gravity shows a higher variability for low growth ring width values and for high specific gravity values.

Within this sampling, the mean clear specimen is characterized by a light wood (mean specific gravity = 419 kg/m^3, S = 43), a high growth (mean growth ring width = 3.5 mm, S = 1,2) and a medium MOE (mean MOE = 11663 MPa, S = 2631).

MOE is positively linked with specific gravity and negatively related to growth ring width.

When considering samples of same specific gravity and same growth ring width, it appears that the timber produced on the best sites is stiffer.

High thinning intensity gives rise to a higher growth and to a weaker stiffness for samples having the same specific gravity.

The social position of the tree in the stand also influences growth ring width, specific gravity and MOE.

The suppressed trees, compared to dominant and co-dominant trees, always proved to have a lower growth ring width, a higher specific gravity and a higher stiffness.

Concerning the axial position of the sample in the tree, MOE is always higher between breast height and the crown base level.

Light juvenile wood is stiffer than light adult wood but heavy juvenile wood is less stiff or more flexible than heavy adult wood.

The fact to disregard clear wood specimen including very slight slope of grain or above all compresssion wood has reinforced the homogeneity of MOE distribution in relation with specific gravity, then indicating the need for a strict selection of small clear specimen mainly with regard to the presence of compression wood.

The prediction of MOE seems to be already acceptable by using models based upon specific gravity and height level in the tree.

However, the fact of being very restrictive in choosing the clear specimens, improves more consistently the prediction of MOE ($R^2 = 0.63$).

In this context, the best one was obtained in differenciating MOE by log level.(level 1: $R^2 = 0.76$, level 3: $R^2 = 0.53$ and level 5: $R^2 = 0.75$).

For each model established, it must be noted that the variance analysis of residues has always pointed out a very highly significant tree effect. The other factors as site productivity, thinning intensity and social position of the tree within the stand have no significant influence on MOE.

Then, this means that the inter-tree variability has a far higher impact on MOE than the other sources of variation (intra-tree variability, site productivity variability, thinning intensity variability and social position variability).

In conclusion, the general model obtained is valid whatever the silvicultural treatment could be.

The comparison of MOE on small clear specimens and on commercial size specimens have not been achieved due to the lost of the major part of commercial size specimens through the fire at the end of 1992 inside the facilities of SRF.

Silvicultural control and non destructive assessment of timber quality in plantation grown Spruces and Douglas fir

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LIST OF ABBREVIATIONS

B	Belgium
CBL	Height of the crown base level
C_L	Coefficient de tenue à l'humidité
CTBA	Centre Technique du Bois et de l'Ameublement
d	Suppressed tree
D	Dominant tree
dbh	Diameter at breast height
Dd	Codominant tree
DF	Degrees of freedom
F_{obs}	Observed variable F of Snedecor
Gx	Gembloux
H	High
HT	Total height of the tree
INRA	Institut National de la Recherche Agronomique
Kg	Kilogramme
L	Low
MOE	Modulus of elasticity or Young's modulus
MPa	Mega pascal
m	Meter
m^3	Cubic meter
min	Minimum
max	Maximum
mm	Millimeter
N	Newton
N^r	Number of observations
n^r	Number
ns	Non significant
Pr	F Snedecor variable probability
PRODUCT	Productivity
R^2	Determination coefficient

RH	Relative humidity
s	Second
S	Standard deviation
S^2	Variance
SAS	Software System for data Analysis
SRF	Station de Recherches Forestières de Gembloux
T_{obs}	Observed variable T of student
V	Coefficient of variation

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ANNEX 1

Stand and tree data

Table 29 - *Stand description of Norway spruce sampled in Belgium.*

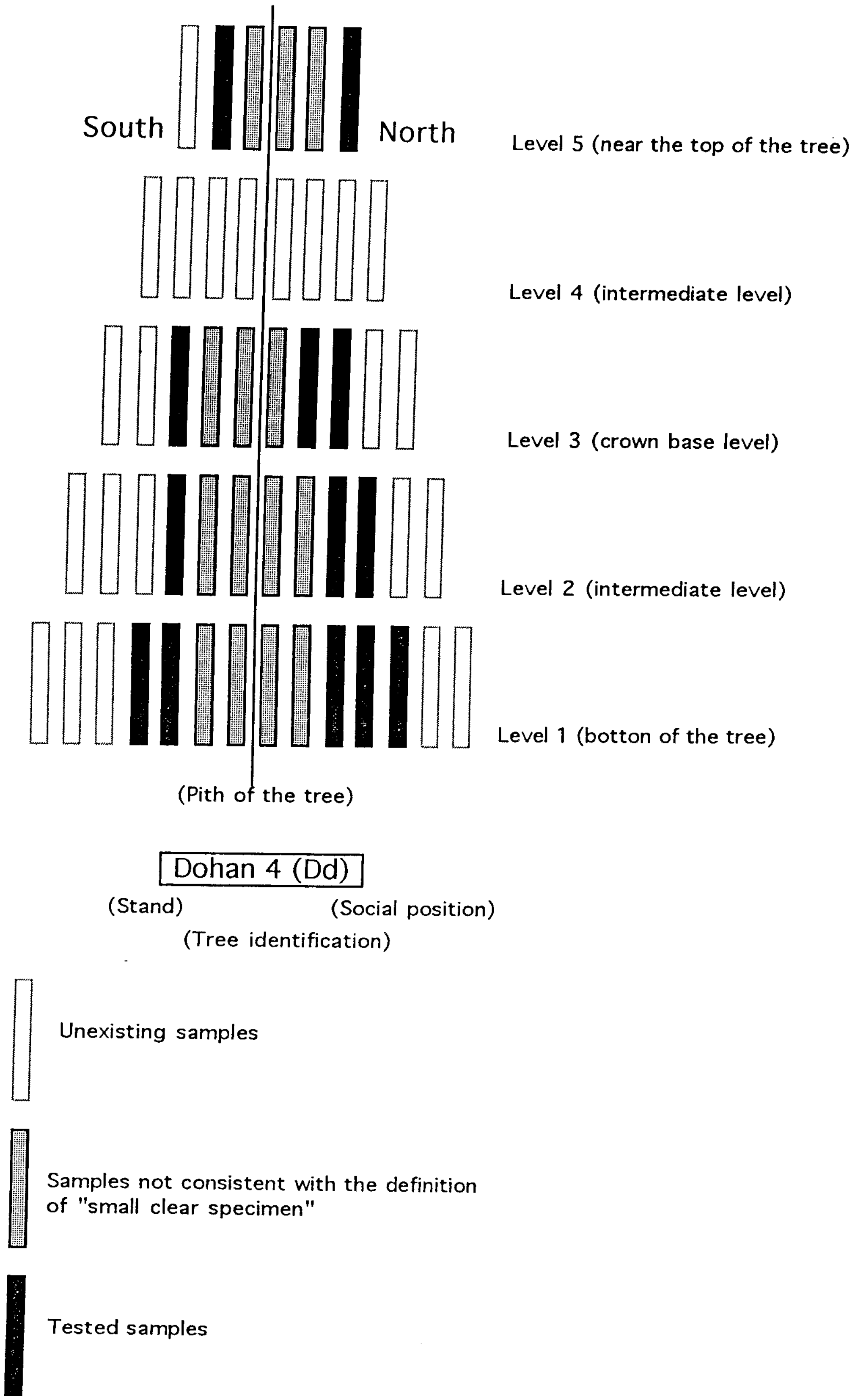
STAND	DOHAN	SOLWASTER	TERNELL	WELLIN
Site index (m)	26.3	18.7	20.8	25.3
Productivity	high	low	low	high
Basal area(m^2/ha)	33.4	32.2	41	44.1
Number of trees (/ha)	543	494	685	838
Thinning	high	low	high	low
Mean dbh of the biggest 300 trees / ha (cm)	30.8	31.4	32	31.4
Age	48	78	61	48

Table 30. - *Tree description of Norway spruce sampled in Belgium.*

STAND	TREE	SOCIAL POSITION	AGE (year)	GIRTH13 (cm)	GIRTHCB (cm)	HT (m)	CBL (m)
DOHAN	1	d	47	85	58	22.93	13.52
	2	Dd	47	96	67	24.21	12.60
	3	D	49	116	81	26.60	13.85
	4	Dd	48	94	68	24.56	13.22
	5	D	47	117	86	26.52	12.58
	6	d	47	80	51	24.91	15.13
SOLWASTER	1	D	79	124	94	22.62	8.98
	2	d	80	82	46	22.19	14.68
	3	Dd	75	105	78	23.40	11.34
	4	Dd	77	98	72	20.00	10.35
	5	D	78	116	90	21.09	9.03
	6	d	80	84	61	19.01	9.15
TERNELL	1	Dd	60	105	75	23.42	12.36
	2	D	62	115	91	23.37	10.07
	3	d	62	79	50	20.74	12.69
	4	d	60	79	43	18.74	13.00
	5	Dd	60	104	66	21.45	11.08
	6	D	66	138	86	25.15	12.04
WELLIN	1	Dd	40	110	70	26.33	14.15
	2	D	47	130	75	28.15	16.39
	3	d	44	88	50	25.55	17.64
	4	Dd	49	101	65	26.52	14.75
	5	d	51	84	52	22.82	13.73
	6	D	50	123	87	26.95	13.77

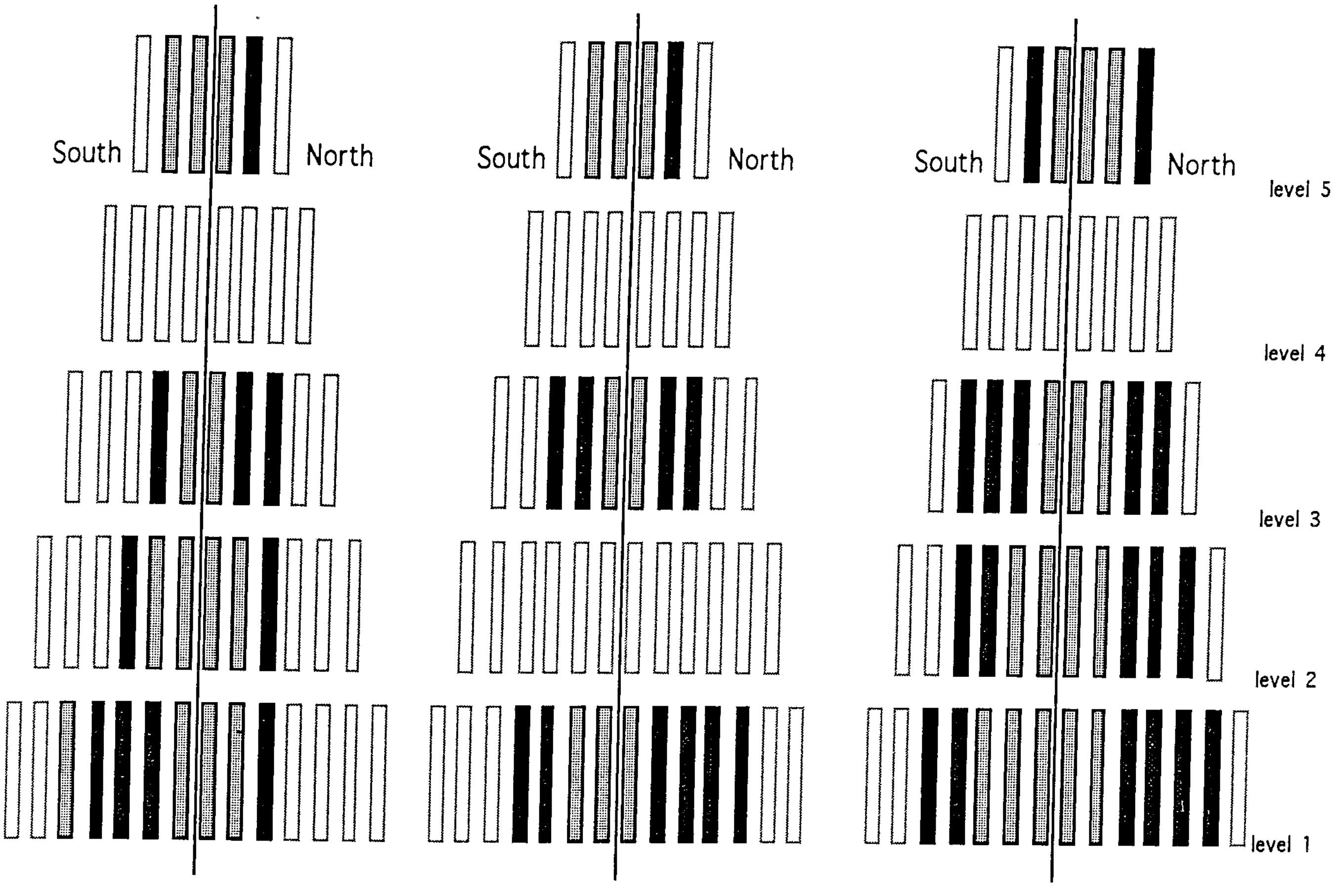
ANNEX 2

Samples position in the tree



Remark: Figures 29, 30, 31and 32 schematize the intratree position of 350 tested samples

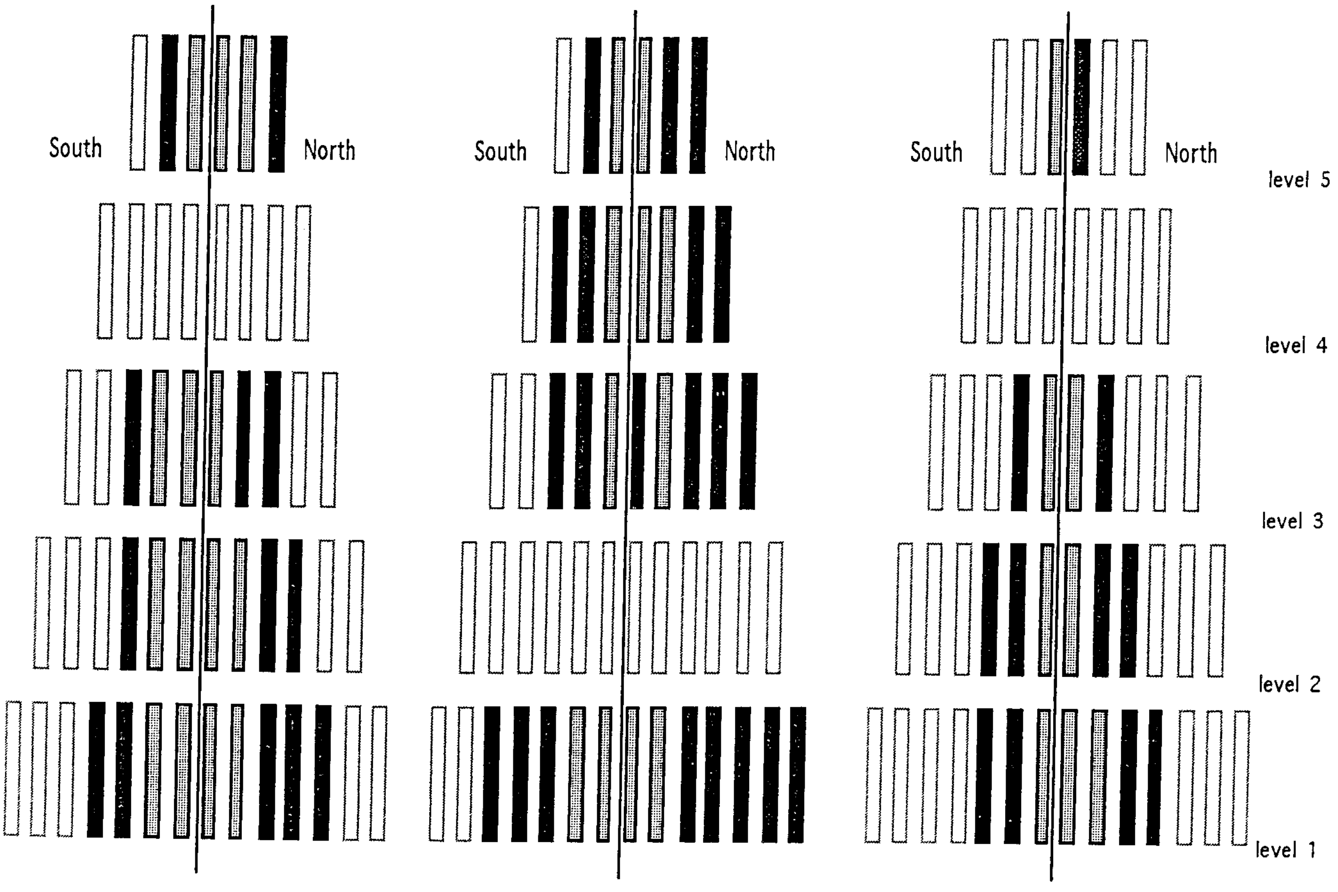
Figure 28 - Legend of figures 29 to 32.



Dohan 1 (d)

Dohan 2 (Dd)

Dohan 3 (D)

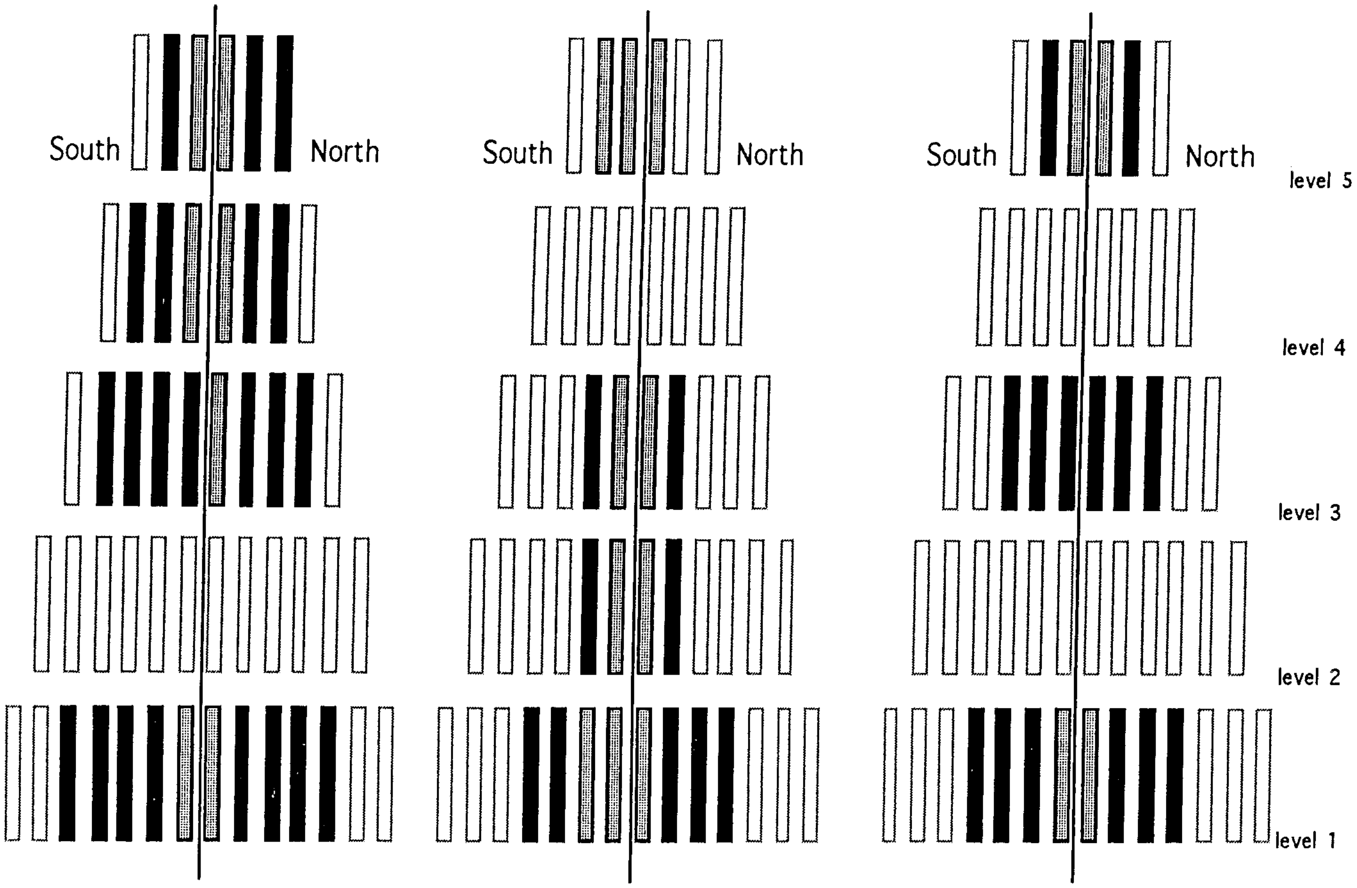


Dohan 4 (Dd)

Dohan 5 (D)

Dohan 6 (d)

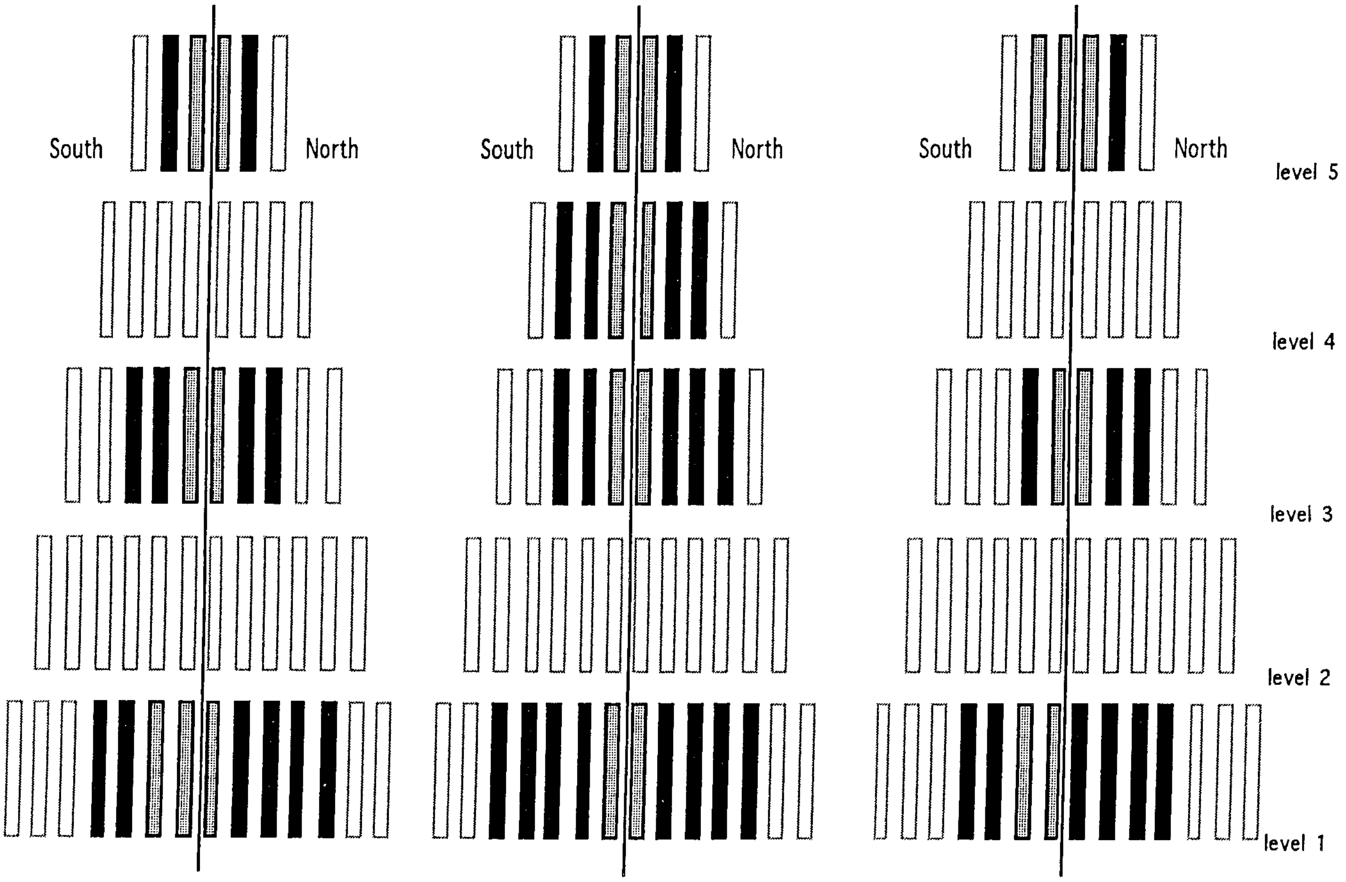
Figure 29. - Samples position in the tree: Dohan stand.



Solwaster 1 (D)

Solwaster 2 (d)

Solwaster 3 (Dd)



Solwaster 4 (Dd)

Solwaster 5 (D)

Solwaster 6 (d)

Figure 30. - Samples position in the tree: Solwaster stand.

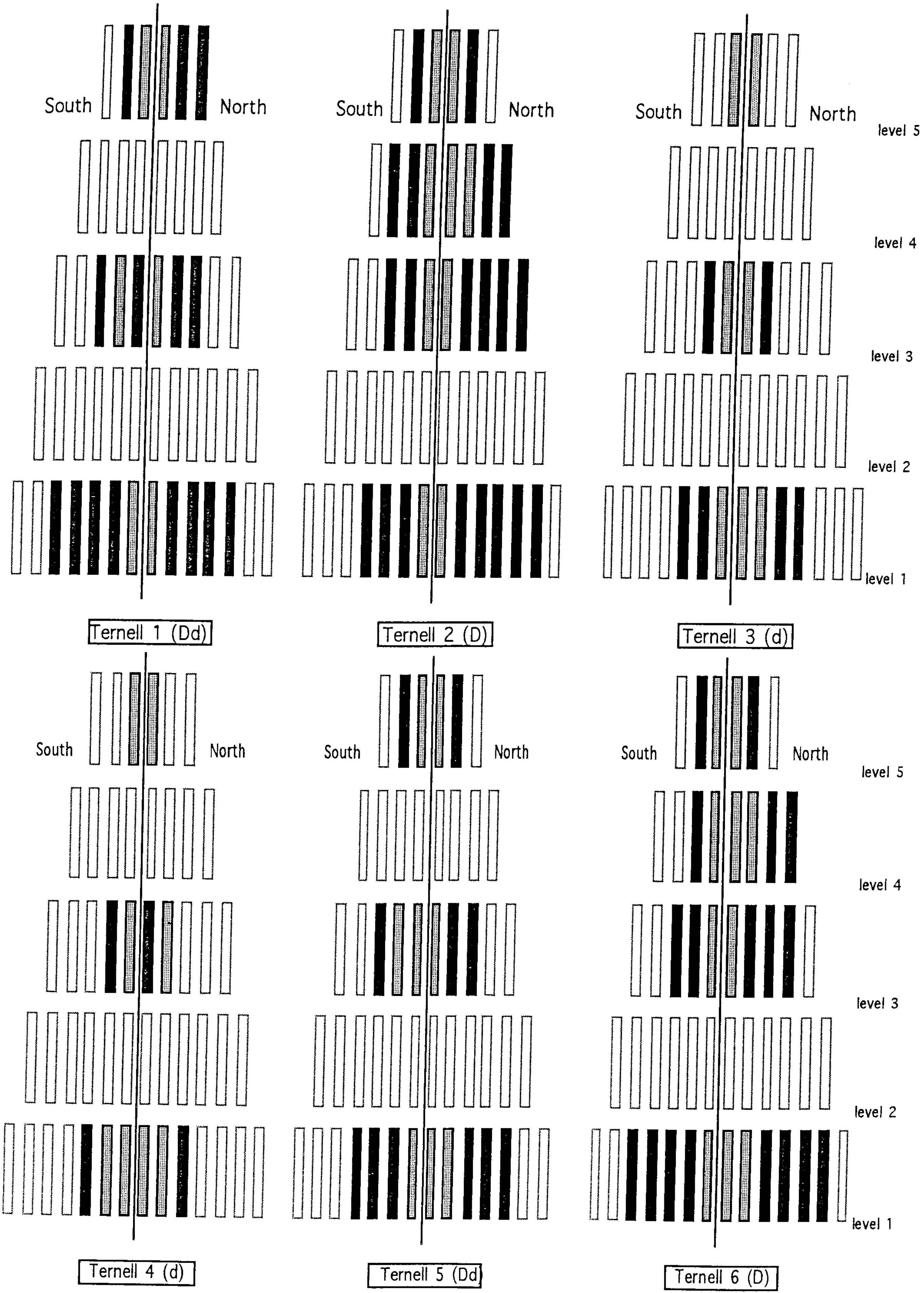


Figure 31. - Samples position in the tree: Ternell stand.

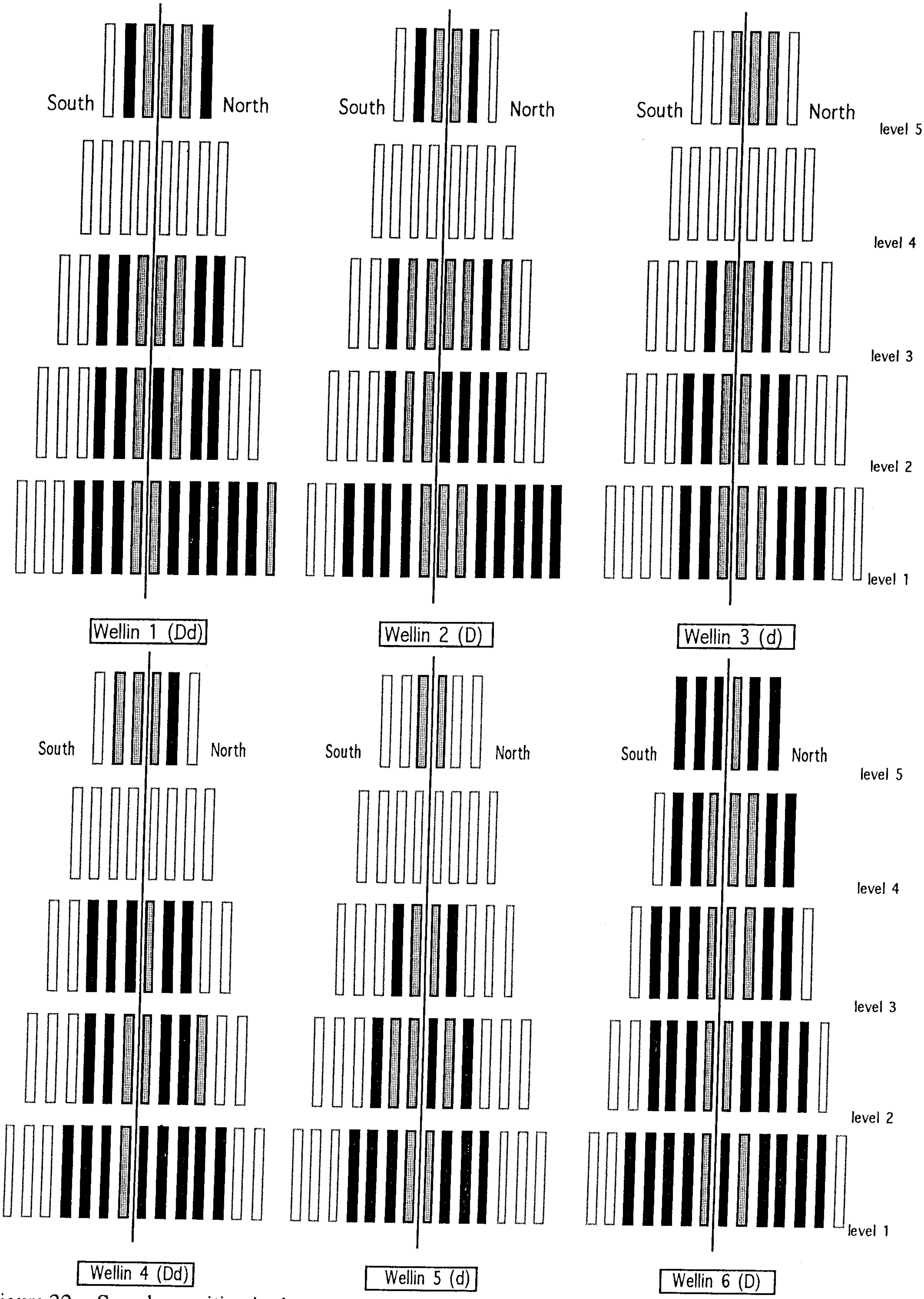


Figure 32. - Samples position in the tree: Wellin stand.