EEC FOREST PROJECT

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

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Final report
TASK 6

"MODELLING BARK THICKNESS IN THE TREE IN RELATION TO SILVICULTURAL TREATMENT"

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August 1993

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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 finalising the works performed on tree bark thickness in relation to silvicultural treatment, and is the fruit of a strong collaboration between scientific Teams of different European countries for data collection, particularly with the Institut für Forstbenützung der Georg - August Universität in Göttingen which has deeply worked on specific models for Douglas fir.

As Task leader, we would like to address our hearty thanks to all the Scientific Teams participating to this Task for the important scientific work performed, i. e.:

British Team: (Team 8)	Dr PAT DENNE Mr MARK MITCHELL
Danish Team: (Team 9)	Prof. Dr PER OLESEN Mr A. BERGSTEDT Mr GEORG JENSEN
French Team: (Team 3)	Prof. Dr FRANCOIS HOULLIER Mr DANIEL RITTIE Mr C. LI
German Team: (Team 4)	Prof. Dr GERÖ BECKER Mr JOHANNES WOBST
Italian Team: (Team 11)	Prof. Dr LUCA UZIELLI Dr MARCO FIORAVANTI

On behalf of all the partners involved in Task 6, 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 for the tremendous work performed by the coordinator, Mr Gérard NEPVEU and for the financial organization and coordination taken over by Miss Pat DENNE.

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

Based upon a sampling of 186 trees of Norway spruce, Sitka spruce and Douglas fir from Belgium (24 Norway spruce), Denmark (24 Norway spruce and 24 Sitka spruce), France (24 Norway spruce), Germany (24 Douglas fir), Great Britain (24 Sitka spruce) and Italy (24 Douglas fir) specially cut for the Project, this study which is a part (Task 6) of a larger ECC Project, has shown the effects of the tree, its Social position in the stand, the thinning intensity and the site productivity on bark thickness and bark volume.

All along the stem, bark thickness has a particular profile characterized by a steep decrease from the bottom up to a given height variable from species to species, due to a bottom effect, then being relatively constant up to the living crown base level and finally decreasing slightly in the living crown part. The most important bottom effect has been observed on Douglas fir .

Referring to a variance components analysis, variability in bark thickness is mainly due to the tree itself and the stand factor which globalized the cumulated effect of thinning intensity and site productivity. However, it appears that the trees selected by couple for each Social position in each stand are similar whatever the species could be, and may be considered, in fact, as true replicates.

For each species, the Social position of the tree in the stand influences bark thickness in the same way. In all cases, dominant trees have indeed the thickest bark, whilst suppressed trees are always characterized by the thinnest bark and co-dominant trees range to this respect in an intermediate position.

The effect of site productivity is not clear through this sampling, due to interferences of different factors, mainly the differences in tree age which let appear a significant effect of the country (differences in growing conditions and between productivity classes). Nevertheless,

when tree age is almost the same in different countries, the general trends are going in the direction of a decrease of bark thickness when the site productivity becomes lower.

The same general trends are observed in connection with the thinning intensity because bark thickness generally decreases when thinnings are less intense.

In fact, bark thickness is far to be constant according to the stand selection criteria (site productivity, thinning intensity) but is noticeably affected by the tree selection criteria (Social position).

Bark thickness, bark volume and amount of bark are mainly depending on the growing conditions with a major effect of the Social position compared to the thinning intensity and the site productivity.

Unfortunately, a general model was unsuitable for an accurate prediction of bark thickness. The best predicted values of bark thickness was obtained in using common models, linear ones for Norway spruce and Sitka spruce but non linear ones for Douglas fir.

CHAPTER I : INTRODUCTION

1. Research context

2. Objectives

3. Partners

4. Progress Task meetings

1. Research context

Task 6, 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 projet is *"to estimate the wood quality of any board sawn in a given place in a tree for which the (only) following descriptor 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.

Concerning bark thickness, the models achieved will be integrated in the software *"SIMQUA"* instead of an arbitrary and constant bark thickness value all the tree long as it is presently the case.

2. Objectives

Task 6 "*Modelling bark thickness in the tree in relation to sivlvicultural treatment*" aims to model the bark thickness evolution all along the tree stem with reference to descriptive parameters of the site (site index), of the silvicultural treatment (thinning intensity), of the trees (age, Social position in the stand) and their relevant dendrometrical characteristics (height, girth, crown ratio, crown base level).

The interest of this Task is extending beyond the framework of this Project because bark thickness and above all bark volume of a given tree are important data for timber marketing and the sawing industry.

To our knowledge few informations are available in the litterature on this subject, showing there the real interest of this research even if the application of results could be restricted on an European point of view according to the sampling representativeness.

3. Partners

Table 1 gives detailed informations on all the research teams involved in Task 6 with their respective responsabilities and peculiar working fields.

Table 1. - *Teams involved in Task 6.*

Subtask	Species	Teams	Countries	Responsabilities
Subtask 6.1 :	Douglas fir	L. Uzielli G. Becker	Italy Germany	(Subtask leader)
Subtask 6.2 :	Norway spruce	F. Houiller A. Leclercq P. Olesen	France Belgium Denmark	(Subtask leader) (Task leader)
Subtask 6.3 :	Sitka spruce	P. Denne P. Olesen	Great Britain Denmark	(Subtask leader)

These partners are in charge of bark thickness measurements on each tree sampled in their own country according to a methodology adopted during the first preliminary meeting in Gembloux (26-27 September 1990) on which a complete agreement was obtained.

Each Team had to collect their own data on the sampling organized by themselves, including site description, silvicultural parameters and dendrometrical characteristics.

4. Progress Task meetings

Three main different meetings have taken place during the period of time allotted for Task 6, in view of a good orchestration of the work to be performed by each Team involved in the research programme on bark thickness (see first, second and third progress reports).

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

   - establishment of a sampling procedure for bark thickness;
   - establishment of the general methodology for bark thickness measurements.

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

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

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

   - first presentatation of a complete analysis on the Belgian data;
   - pointing out the difficulties generated by the differences in age of trees participating to the sampling in the different countries for a common data analysis procedure;
   - establishment by the Task leader Team of all the files of data collected in each country, with a first graphic treatment of the data received from each Team which was asked to check the final presentation of the data files;
   - main content of 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, these species have not been systematically investigated in each country involved in this Project, due to the fact that among these three sofwood species, one or the other could be less important in surface in one or several countries (cf. table 1).

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. It is clear that these index classes may vary to some extent according to the environmental conditions relevant to each country.

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

Moreover, it has to be noted that in some countries the stands selected are participating to experimental plots for which the silviculture applied (initial spacing, thinning intensity,thinning frequency) is well known.

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).

As the third part of the Project (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, 4, 5, 6, 9, 10 and 11 has been is cut off from the same trees.

2. Methodology

2.1. Tree cutting scheme

The raw material needed for modelling bark thickness consists in disks of 10 cm thickness cut off at different levels along the tree heigth outside whorls.

At least 6 disks per tree have been taken, corresponding to the following height levels: 1.3 m (dbh) and 15, 30, 45, 60 and 75 % of the total tree height (figure 1). Moreover, one disk located at the living crown base level (CBL) have been cut as far as that disk was not included inside the inter-whorl portion where the disks corresponding to the 45 % or 60 % height level are sampled.

Considering the special needs for realizing Tasks 10 (modelling young's modulus in commercial size boards) and 11 (modelling young's modulus in clear specimens) on Belgian Norway spruce, the previous procedure has not been followed in the same way. In that case, the disks used for Task 6 were taken on both sides of the logs required for Tasks 10 and 11, according to a specific cutting scheme (figure 1).

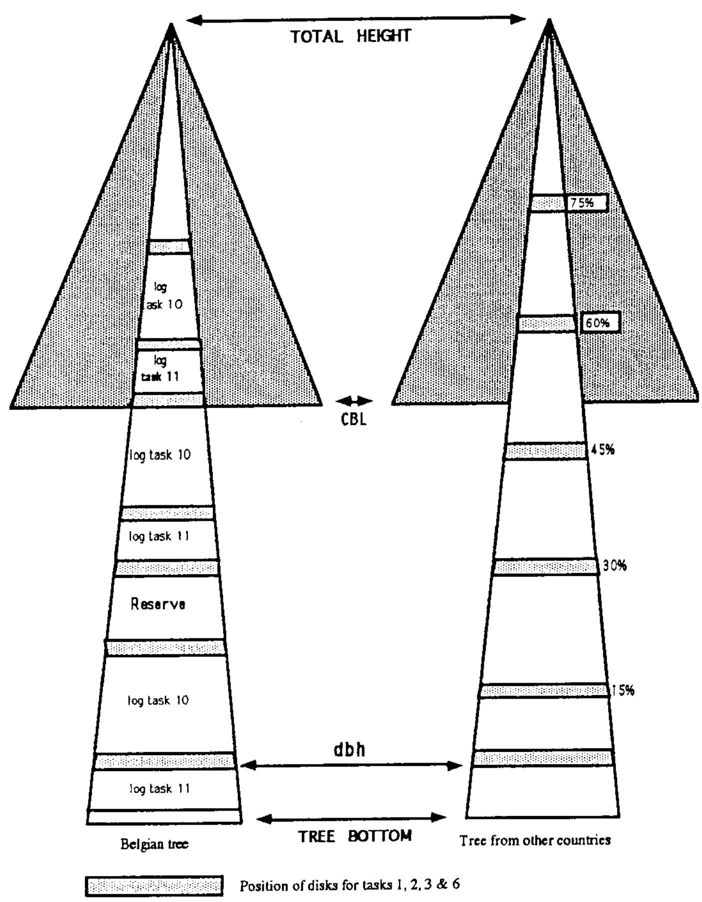


Figure 1. - *Tree cutting scheme for Belgium and other countries showing the disks position for bark measurements.*

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. Nevertheless, it has been asked to each Team participating to Task 6 to provide the following informations in their files in view of modelling bark thickness (see annex 1):

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

2.3. Bark thickness measuring procedure

On each disk sampled, bark thickness has been measured along four directions at right angle. These four directions were determined according to two different ways: on one hand, they are corresponding to the four cardinal orientations, on the other hand, they are corresponding to four perpendicular radii with an inclination of 12.5° clockwise from the largest diameter.

Bark thickness measurement in laboratory was performed on fresh disks either with a stereomicroscope coupled with a micrometric table or with a caliper square. The accuracy requested was fixed at 0.1 mm.

The direct measurement on the field with a bark gauge has definitely been forgotten due to the lack of accuracy observed, depending on the user itself and on the bark structure relevant to the species itself.

The raw material was kept fresh by stocking the disks in plastic bags inside an air-conditionned room.

Considering the specific experimental scheme used for Belgian trees, it was not allowed to cut the disks on the field. So, in order to prevent debarking during logging operations, it was decided to take 30 mm diameter bark patches with a pitch hole saw device on a drill. In order to avoid desiccation, these samples cut off every one meter length on the four cardinal orientations were directly stored in plastic bags on the field.

On the whole, nearly 6,000 bark thickness measurements were made on the 186 trees collected .

It must be already noted that a preliminary analysis (T-Test) concerning a limited number of Belgian samples has shown that there is no significant difference (T = 0,703 NS) between the two methods used for determining the four orientations of bark measurement (figure 2).

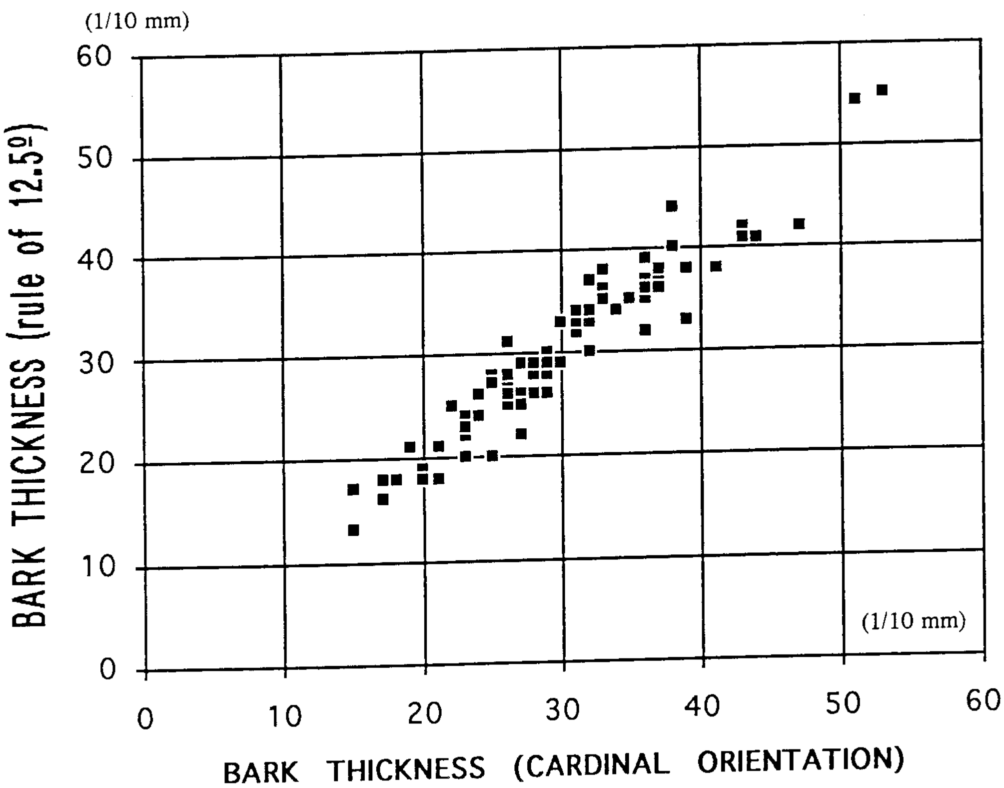


Figure 2. - *Relationship between bark thickness measured along four cardinal radii and bark thickness measured along four perpendicular radii with an inclination of 12.5° clockwise from the largest diameter.*

Moreover, with the objective of simplifying the modelling procedure, we have investigated the significance of the cardinal orientation on bark thickness in using a large sample for each species. It appears for Douglas fir and Sitka spruce that there is no significant difference in bark thickness according to the cardinal orientation (table 3).

On the other hand, the statistical analysis shows a significant difference (p = 0,05) for Norway spruce between the north position and the other cardinal orientations, with a thinner bark on the north direction.

Despite this observation, it was agreed to use the mean value calculated on the data observed on the four directions per height level as a reference for modelling bark thickness.

Table 3. - *Evolution of bark thickness according to the orientation for the three softwood species.*

Douglas fir				
Orientation	North	South	East	West
Bark thickness				
Min. value (mm)	0.2	0.5	0.8	0.9
Max. value (mm)	22.3	25.8	25.2	23.1
Mean value (mm)	5.14	5.17	5.13	5.17
Standard deviation	3.5	3.6	3.5	3.5
Number of observations	507	507	507	498
DF = 2015	F_{obs} = 0.02 NS		Pr = 0.998	

Sitka spruce				
Orientation	North	South	East	West
Bark thickness				
Min. value (mm)	1.6	1.8	0.3	1.8
Max. value (mm)	10	8.8	8.1	8.3
Mean value (mm)	4.3	4.3	4.4	4.4
Standard deviation	1.24	1.21	1.23	1.21
Number of observations	302	306	284	285
DF = 1172	F_{obs} = 0.65 NS		Pr = 0.584	

Norway spruce				
Orientation	North	South	East	West
Bark thickness				
Min. value (mm)	1.8	1.6	1.8	1.6
Max. value (mm)	9.7	9.6	9.3	11.7
Mean value (mm)	4.7	4.8	4.8	4.8
Standard deviation	1.24	1.16	1.24	1.21
Number of observations	651	649	637	635
DF = 2568	F_{obs} = 3.24 *		Pr = 0.021	

2.4. Data file organization

During the meeting hold in Bangor (20-23 March 1992), a proposal of a common spreadsheet data base has been presented, discussed and improved with all the Teams involved. One example of data presentation, common to each Team, is given in table 4.

All the informations collected by each Team and presented in a same way were recorded with an EXCEL® software on floppy disks. These floppy disks were sent by each Team 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.

Different data verifications were made as well by the Task Leader Team as by each Team concerned in view to prepare the final data files.

Two kinds of files were set up: the first one is dealing with bark thickness and the second one concerns bark volume. Each of them were subdivided into five groups of criteria:

- identification criteria giving general informations on the country, the species, the stands and the trees;

- description criteria detailing the stands and tree characteristics: Social position, productivity class and thinning intensity;

- measured criteria on the trees: total height, girth, level, bark thickness, ...;

- estimated criteria which concern variable transformation;

- uzed formulas for calculating the estimated criteria.

Table 5 is shows the kind of files used for bark thickness and table 6 is recapitulating the kind of files used for bark volume.

Table 4. - *Common spreadsheet data base*

PROPOSAL FOR A COMMON SPREADSHEET DATA BASE

Species	Station	N° tree	Site class (*)	Thinning intensity (**)	Social position (***)	Height Level (****) (%)	Height (cm)	Age (year)	Radius North (1/10mm)	Radius East (1/10mm)	Radius South (1/10mm)	Radius West (1/10mm)	Bark thickness North (1/10mm)	Bark thickness East (1/10mm)	Bark thickness South (1/10mm)	Bark thickness West (1/10mm)
Norway s.	S	1	high	high	dominant	DBH	160	69	2045	1793	2132	1709	51	43	44	48
"	W	4	high	low	suppressed	CBL	1440	22	"	"	"	"	"	"	"	"
"	T	2	low	low	co-dominant	30%	1052	44	"	"	"	"	"	"	"	"
"	D	6	low	high	dominant	15%	330	65	"	"	"	"	"	"	"	"

(*) Site class: high, low

(**) Thinning intensity: high, low

(***) Social position: dominant tree, co-dominant tree, suppressed tree

(****) height level: dbh, 15%, 30%, 45%, 60%, 75%, CBL

Table 5. - *Bark thickness data file.*

Identification criteria

Column	Name	Content
1	OBS	Number of observations
2	COUNTRY	B = Belgium; DK = Denmark; GB = Great Britain F = France; G = Germany; I = Italy
3	SPECIES	NS = Norway spruce; SS= Sitka spruce DF = Douglas fir
4	STAND	Number or letter of the stand
5	TREE	Number of the tree

Description criteria

Column	Name	Content	
6	POSITION	Social position	D = dominant tree Dd = co-dominant tree d = suppressed tree
7	PRODUCTIVITY	Site class	H = high L = low
8	THINNING	Thinning intensity	H = high L = low

Measured criteria

Column	Name	Content
9	LEVEL	dbh ; CBL ; 15 ; 30 ; 45 ; 60 ; 75 ; 90%
10	HEIGHT	Height where the measure is made
11	GIRTH*	Girth where the measure is made
12	THICK	Bark thickness
13	AGE	Total age of the tree (from the pith at 30 cm height)
14	HT	Total height of the tree
15	GIRTH13	Girth at 1.3 m
16	CBL	Height of the living crown base level
17	GIRTHCB	Girth at the living crown base level

* Remark: the girth is measured outside bark.

Estimated criteria

Column	Name	Content
18	GIRTH2	Girth square
19	HEIGHT2	Height square
20	HT2	HT square
21	HR	Relative height
22	GIRTHR	see used formulas

Formulas used

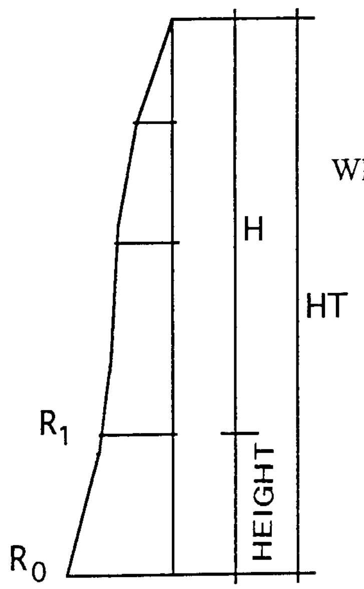
Name	Content
GIRTH2	GIRTH x GIRTH
HEIGHT2	HEIGHT x HEIGHT
HT2	HT x HT
HR	(HEIGHT / HT) x 100
GIRTHR	GIRTH13 x (HEIGHT / HT)
SURF/O/B	((GIRTH / 100) ^2) / (4 x π)
VOL/O/B	((SURF/O/B_o + SURF/O/B_1) / 2) x ($HEIGHT_1$ - $HEIGHT_o$)
DIAM/I/B	((GIRTH / 100) / π) - ((THICK / 1000) x 2)
SURF/I/B	(DIAM/I/B ^2) x π / 4
VOL/I/B	((SURF/I/B_o + SURF/I/B_1) / 2) x ($HEIGHT_1$ - $HEIGHT_o$)
RBWOOD	(VOL/O/B - VOL/I/B) / VOL/I/B x 100
RBTREE	(VOL/O/B - VOL/I/B) / VOL/O/B x 100
VOLB	VOL/O/B - VOL/I/B

The selected variables are expressed in the following units:

HEIGHT = meter (m)
GIRTH = centimeter (cm)
THICKNESS = millimeter (mm)
AGE = year
HR = percentage (%)
VOLB = cubic meter (m^3)
RBWOOD = percentage (%)
RBTREE = percentage (%)

Remark: The tree is assimilated to a sum of sawn off cones. Evaluation of the basic surfaces of each log is based on four measured radii. For the surface, at the bottom of the tree, the following formula was used:

$$\frac{R_0}{R_1} = \frac{HT}{HT - HEIGHT} \Rightarrow R_0 = R_1 \times \frac{HT}{HT - HEIGHT}$$



Where - R_0 = radius of the log at the bottom of the tree
- R_1 = radius of the log at one meter height
- HT = total height

Table 6. - *Bark volume data file.*

Identification criteria

Column	Name	Content
1	OBS	Number of observation
2	COUNTRY	B = Belgium; DK = Denmark; GB = Great Britain F = France; G = Germany; I = Italy
3	SPECIES	NS = Norway spruce; SS= Sitka spruce DF = Douglas fir
4	STAND	Number or letter of the stand
5	TREE	Number of the tree

Description criteria

Column	Name	Content	
6	POSITION	Social position	D = dominant tree Dd = co-dominant tree d = suppressed tree
7	PRODUCTIVITY	Site class	H = high L = low
8	THINNING	Thinning intensity	H = high L = low

Measured criteria

Column	Name	Content
9	HT	Total height of the tree
10	CBL	Height of the living crown base level
11	GIRTH13	Girth at 1.3 m
12	GIRTHCB	Girth at the living crown base level
13	AGE	Tree age at the bottom

Estimated criteria

Column	Name	Content
14	HT2	HT square
15	GIRTHT	see utilized formulas
16	RBWOOD	see utilized formulas
17	RBTREE	see utilized formulas
18	VOLB	Bark volume

Formulas used

Name	Content
HT2	HT x HT
GIRTHT	GIRTH13 x HT
VOL/O/B	Sum of VOL/O/B from individual file
VOL/I/B	Sum of VOL/I/B from individual file
RBWOOD	(VOL/O/B - VOL/I/B) / VOL/I/B x 100
RBTREE	(VOL/O/B - VOL/I/B) / VOL/O/B x 100
VOLB	VOL/O/B - VOL/I/B

CHAPTER 3 : RESULTS

1. Introduction
2. Bark thickness
3. Bark volume

1. Introduction

In computing the data files of all the Teams involved in Task 6, it appeared large differences between trees according to the species and the countries. Table 7 gives an overview of the mean values of girth at breast height, global age, age by productivity class and age by thinning intensity class per species and per country.

Table 7. - *General overview of main tree characteristics (girth and age) per species and country.*

Species	Countries	Mean girth at dbh (cm)	Mean age* (year)	Mean age (year) by Productivity H	Mean age (year) by Productivity L	Mean age (year) by Thinning H	Mean age (year) by Thinning L
Norway spruce	Belgium	102	58	47	69	55	67
	France	106	58	53	63	58	58
	Denmark	74	77	53	102	75	79
	mean	94	64	51	78	63	68
Sitka spruce	Great britain	85	43	28	58	43	43
	Denmark	76	54	46	63	61	48
	mean	81	49	37	61	52	46
Douglas fir	Italy	88	27	28	25	27	27
	Germany	99	39	39	40	42	37
	mean	94	33	33	33	34	32

* Remark: age measured from the pith at 30 cm height

It is clear that it is not possible to present in this report all the detailed data achieved by each Team so numerous they are. That is why we would like to present only in that part a general overview of the main data collected, on one hand for bark thickness and, on an other hand for bark volume.

2. Bark thickness

Tables 8, 9 and 10 record respectively for Norway spruce, Sitka spruce and Douglas fir the mean values of bark thickness in relationship with the height level in the tree, the site productivity, the thinning intensity and the Social position in the stand.

Some general trends may already been picked out from these 3 tables.

Table 8. - *Norway spruce bark thickness (in mm) per country in relationship with the tree height level, the site productivity, the thinning intensity and the Social position in the stand (mean values).*

Species NORWAY SPRUCE	Productivity		Thinning intensity		SOCIAL position			Mean bark thickness of 24 trees
	high	low	high	low	D	Dd	d	
Countries / *Height*								
Belgium								
height = 1.3 m	5.70	4.96	5.14	5.52	6.06	5.15	4.79	5.33
1.3 m < height <= CBL	4.85	3.74	4.50	4.75	5.37	4.80	3.82	4.63
height > CBL	4.08	3.18	3.93	3.84	4.33	3.87	3.01	3.88
France								
height = 1.3 m	6.02	6.20	6.41	5.82	6.40	6.16	5.77	6.11
1.3 m < height <= CBL	5.14	5.04	5.26	4.96	5.43	5.06	4.81	5.10
height > CBL	4.43	4.27	4.44	4.22	4.59	4.28	4.16	4.34
Denmark								
height = 1.3 m	5.05	6.58	6.19	5.45	5.99	5.91	5.50	5.82
1.3 m < height <= CBL	4.41	6.14	5.96	4.76	5.73	5.32	4.77	5.27
height > CBL	3.79	4.61	4.58	3.55	4.64	4.01	3.86	4.21
For the three countries								
height = 1.3 m	5.79	5.64	5.81	5.62	6.21	5.70	5.18	5.71
1.3 m < height <= CBL	4.83	5.04	5.02	4.81	5.47	5.01	4.28	4.90
height > CBL	4.07	3.98	4.20	3.85	4.43	3.97	3.49	4.04

For **Norway spruce,** whatever could be the country, the site productivity, the thinning intensity and the Social position of the tree in the stand, bark thickness appears to decrease from the bottom to the top of the tree.

On an other hand, whatever the height level in the tree could be, bark thickness seems to be for each country thinner when the thinning intensity is low and when the site productivity decreases, excepted in this last case for the Danish trees due to the big difference in age between site classes (± 50 years).

Moreover, bark thickness seems to be linked with the Social position of the tree in the stand, whatever the country and the tree height level could be, seeing that the dominant trees are characterized by a thicker bark, the suppressed trees by a thinner bark and co-dominant trees by intermediate values.

Broadly speaking, the French and Danish Norway spruce trees seem to have about the same bark thickness, as a mean, whilst the Belgian Norway spruce trees seem to be characterized by a thinner bark. As a whole, Norway spruce bark thickness varies between 1.7 mm and 10.1 mm.

For **Sitka spruce**, bark thickness is also decreasing from the bottom to the top of the tree for each criteria taken into account (country, site class, thinning intensity, Social position).

Table 9. - *Sitka spruce bark thickness (in mm) per country in relationship with the tree height level, the site productivity, the thinning intensity and the Social position in the stand. (mean value)*

Species SITKA SPRUCE	Productivity		Thinning intensity		SOCIAL position			Mean bark thickness of 24 trees
	high	low	high	low	D	Dd	d	
Countries / *Height*								
Denmark								
height = 1.3 m	4.94	5.34	5.54	4.94	5.70	5.08	5.03	5.25
1.3 m < height <= CBL	4.54	4.98	4.90	4.60	5.11	4.71	4.52	4.76
height > CBL	3.57	4.14	4.00	3.73	4.23	3.59	3.68	3.86
Great Britain								
height = 1.3 m	4.89	5.37	5.05	5.21	5.32	5.23	4.84	5.13
1.3 m < height <= CBL	3.62	4.70	4.19	4.21	4.57	4.40	3.72	4.20
height > CBL	3.34	4.08	3.52	3.71	3.92	3.66	3.02	3.62
For the two countries								
height = 1.3 m	4.92	5.45	5.29	5.08	5.50	5.14	4.93	5.19
1.3 m < height <= CBL	4.11	4.84	4.57	4.40	4.85	4.57	4.11	4.49
height > CBL	3.45	4.11	3.77	3.72	4.08	3.62	3.37	3.75

Whatever the height level in the tree could be, Sitka spruce bark thickness is increasing when the site productivity is lowering.

The effect of thinning intensity on Sitka spruce bark thickness is less important than for Norway spruce, but as a mean, the same trends could be observed. However, this effect is weak in Great Britain.

Concerning the Social position of the tree in the stand, Sitka spruce bark is thicker in dominant trees in comparison with co-dominant and suppressed trees which have the thinnest bark.

Sitka spruce is characterized by a bark thickness varying between 1.4 mm and 8.8 mm. These limits appear to be lower than those observed for Norway spruce, probably due to the fact that Sitka spruce trees are, as a mean, younger than Norway spruce trees (± 15 years).

For **Douglas fir**, the same trends as those observed for Norway spruce and Sitka spruce appear in what concerns the evolution of bark thickness along the tree height, i.e. a decreasing from the bottom to the top of the tree.

Table 10. - *Douglas fir bark thickness (in mm) per country in relationship with the tree height level, the site productivity, the thinning intensity and the Social position in the stand (mean values).*

Species **DOUGLAS FIR**	Productivity		Thinning intensity		SOCIAL position			Mean bark thickness of 24 trees
	high	low	high	low	D	Dd	d	
Countries / *Height*								
Germany *								
height = 1.3 m	11.88	14.55	14.76	11.61	14.33	12.56	13.34	13.41
1.3 m < height <= CBL	6.28	5.91	6.82	5.34	6.74	6.20	5.63	6.17
height > CBL	4.25	3.94	4.74	3.41	4.34	4.07	3.86	4.11
Italy								
height = 1.3 m	7.22	6.99	7.06	7.16	8.30	6.38	6.64	7.11
1.3 m < height <= CBL	4.02	3.79	4.12	3.72	4.13	3.86	3.76	3.91
height > CBL	2.09	2.04	2.14	1.98	2.04	2.03	2.12	2.07
For the two countries								
height = 1.3 m	10.02	12.03	12.19	9.83	12.14	10.31	10.90	11.12
1.3 m < height <= CBL	5.05	4.40	5.26	4.28	5.09	4.79	4.48	4.78
height > CBL	2.97	2.67	3.10	2.51	2.94	2.76	2.76	2.82

* : 42 trees instead of 24

As a whole, the site productivity seems to have a light effect on Douglas fir bark thickness considering that whatever the height level in the tree could be, the bark generally increases from low to high site productivity.

The thinning intensity has the same effect on Douglas fir bark thickness as for Norway spruce and Sitka spruce, that is to say a thicker bark when the thinning intensity becomes heavier.

The influence of the Social position of the tree in the stand on bark thickness is also the same for Douglas fir as for Norway spruce and Sitka spruce. Dominant trees have a thicker bark than co-dominant or suppressed trees, which ones being very similar.

It is interesting to observe that Douglas fir bark thickness is more or less two times larger in Germany than in Italy. The bark thickness of Douglas fir ranges from 0.6 mm to 24.1 mm.

If we compare the species between them, we may observe at breast height that Douglas fir has the thickest bark (11.1 mm) followed by Norway spruce (5.7 mm) and Sitka spruce (5.2 mm).

Between breast height level and crown base level, the three species have about the same bark thickness (Douglas fir: 4.8 mm, Norway spruce: 4.9 mm, Sitka spruce: 4.5 mm).

In addition, inside the living crown, Douglas fir has the thinnest bark (2.8 mm) in comparison with Norway spruce (4.0 mm) and Sitka spruce (3.8 mm).

3. Bark volume

Tables 11, 12 and 13 summarize for each species the mean values of bark volume as a function of the country, the site productivity, the thinning intensity and the Social position in the stand.

Bark volume ("*VOLB*") has been calculated according to the following formula:

VOLB = VOLUME OUTSIDE BARK - VOLUME INSIDE BARK

Table 11. - *Norway spruce bark volume (in m^3) per country in relationship with the site productivity, the thinning intensity and the Social position in the stand.*

Species NORWAY SPRUCE	Productivity		Thinning intensity		SOCIAL position			Mean bark volume of 24 trees
	high	low	high	low	D	Dd	d	
Countries **Belgium**	0.079	0.053	0.063	0.070	0.091	0.066	0.042	0.066
France	0.081	0.081	0.083	0.078	0.093	0.082	0.067	0.081
Denmark	0.052	0.053	0.066	0.038	0.065	0.052	0.038	0.052
For the three countries	0.070	0.062	0.071	0.062	0.083	0.066	0.049	0.066

For **Norway spruce**, only the Social position of the tree in the stand seems to have an influence on the bark volume produced. In fact, whatever the country could be, the dominant trees always have the larger bark volume, the suppressed trees the lowest one and the co-dominant trees having intermediate values.

Moreover, table 11 shows that the trees selected in France have the highest mean bark volume (0.081 m^3) in comparison with those collected in Belgium (0.066 m^3) or in Denmark (0.052 m^3).

Table 12. - *Sitka spruce bark volume (in m^3) per country in relationship with the site productivity, the thinning intensity and the Social position in the stand.*

Species SITKA SPRUCE	Productivity		Thinning intensity		SOCIAL position			Mean bark volume of 24 trees
	high	low	high	low	D	Dd	d	
Countries **Denmark**	0.052	0.054	0.067	0.040	0.072	0.048	0.040	0.053
Great Britain	0.033	0.050	0.047	0.036	0.040	0.049	0.036	0.041
For the two countries	0.043	0.052	0.057	0.038	0.061	0.045	0.036	0.047

For **Sitka spruce**, the bark volume appears to be larger on low site productivity and when the thinning intensity becomes heavier.

The Social position of the tree in the stand has the same effect on Sitka spruce bark volume as on Norway spruce bark volume, dominant trees having the biggest bark volume compared to co-dominant and suppressed trees. Being younger, the British trees generated a lower bark volume (0.041 m^3) than the Danish ones (0.053 m^3).

Table 13. - *Douglas fir bark volume (in m^3) per country in relationship with the site productivity, the thinning intensity and the Social position in the stand.*

Species **Douglas fir**	Productivity		Thinning intensity		SOCIAL position			Mean bark volume of 24 trees
	high	low	high	low	D	Dd	d	
Countries								
Germany *	0.088	0.083	0.100	0.066	0.095	0.083	0.079	0.085
Italy	0.052	0.039	0.047	0.043	0.052	0.042	0.043	0.045
For the two countries	0.074	0.068	0.082	0.057	0.079	0.068	0.066	0.071

* : mean of 42 trees

Concerning **Douglas fir**, the volume of bark is larger on high site productivity and also when the thinning intensity is increasing.

Co-dominant and suppressed trees prove to be very similar by their amount of bark produced which is always lower than that of dominant trees.

Being far younger, the Italian Douglas fir trees produce more or less half the amount of bark (0.045 m^3) compared with the German trees (0.085 m^3).

It must also be pointed out that the volume of bark varies greatly with the softwood species itself. Douglas fir produces indeed the highest amount of bark compared with Norway spruce and mainly Sitka spruce as it clearly appears through the range of values given hereafter:

Species	Bark volume (m^3)			
	min	Mean	max	Standard deviation
Douglas fir	0.028	0.071	0.132	0.029
Norway spruce	0.017	0.066	0.119	0.025
Sitka spruce	0.014	0.047	0.103	0.021

An other way to appraise the importance of bark production per species, country, site productivity, thinning intensity and Social position of the tree is to translate the bark volume as a function of the timber volume. This criteria is indeed quite important as well for the forester as for wood processing and users (Smith 1967, 1971).

Then, the relative bark volume is calculated according to the following formula:

$$\mathbf{RBTREE\ (\%)} = \frac{\mathbf{Vol\ outside\ bark - Vol\ inside\ bark}}{\mathbf{Vol\ outside\ bark}} \cdot \mathbf{100}$$

Table 14 gives the mean values of the relative bark volume (%) for each species per country in connection with the site productivity, the thinning intensity and the Social position of the tree in the stand.

It appears that the production of bark compared to the total tree volume becomes bigger when the site productivity is lowering.

The species behave differently with the thinning intensity. The relative bark volume produced by Norway spruce and Sitka spruce is increasing when the thinning intensity is lowering, while for Douglas fir, the relative bark volume is decreasing when the thinning intensity becomes lower.

The Social position occupied by the tree in the stand scarcely influences the bark proportion whatever the species could be. The bark proportion seems to be slightly higher in suppressed trees than in co-dominant trees and above all in dominant trees.

In a same species, big differences appear from one country to another. Broadly speaking, the bark production compared to the total tree volume is higher for Douglas fir (12.7 %) than for Sitka spruce (10.5 %) and Norway spruce (10.2 %).

The range of variation of relative bark volume is given hereafter:

Species	Relative bark volume (%)			
	min	Mean	max	Standard deviation
Douglas fir	6.70	13.69	22,00	3.97
Norway spruce	5.24	10.17	23.80	3.83
Sitka spruce	6.28	10.45	15.31	2.32

Table 14. - *Relative bark volume (in %) per species and per country in relationship with the site productivity, the thinning intensity and the Social position.*

Species	Productivity		Thinning intensity		SOCIAL position			Mean value of 24 trees
countries	high	low	high	low	D	Dd	d	
NORWAY SPRUCE								
Belgium	8.28	6.33	7.11	7.50	7.02	7.49	7.41	7.31
France	9.77	8.76	9.30	9.24	8.95	9.09	9.76	9.27
Denmark	10.55	17.33	12.20	15.68	13.53	13.25	15.29	13.94
For the three countries	9.53	10.80	9.53	10.81	9.89	9.94	10.82	10.17
SITKA SPRUCE								
Denmark	11.46	11.73	10.60	12.60	9.89	12.21	12.77	11.60
Great Britain	8.81	9.78	8.63	9.96	10.57	8.83	8.49	9.30
For the two countries	10.14	10.76	9.61	11.28	9.56	10.57	11.25	10.45
Douglas fir								
Germany *	13.21	16.21	15.14	14.64	14.98	14.44	15.35	14.92
Italy	8.84	8.71	8.82	8.73	9.21	8.63	8.48	8.77
For the two countries	11.47	13.71	13.03	12.28	12.89	12.33	12.85	12.69

* : mean of 42 trees

CHAPTER 4 : ANALYSIS

1. Introduction

2. Bark thickness evolution

3. Bark thickness modelling

4. Bark volume evolution

5. Bark volume modelling

1. Introduction

In the Technical Annex of the contract, Task 6 has to deal with the setting up of models for bark thickness describing the evolution of this parameter in the tree in relation to silvicultural treatment.

However, before realizing this work, it appears very interesting to know the evolution of bark thickness not only inside a given tree but also according to the selecting criteria used for the sampling: site productivity, thinning intensity and Social position in the stand. These steps constitute a good approach of modelling.

On an other hand, the amount of bark produced has been determined for each tree sampled because of an obvious interest for practice, and the evolution of this parameter as a function of the selecting criteria has also been analysed before modelling.

2. Bark thickness evolution

2.1. Variance components analysis

In order to identify the main sources of variation, a variance components analysis has been realized species by species for the three factors *"stand"*, *"tree"* and *"samples in the tree"* in connection with the *"Social position"* of the tree in the stand. The target is to point out the factor contributing the most to the total variability observed. It has to be noted that the factor *"stand"* means the cumulated effect of site productivity and thinning intensity and the factor *"tree"* means the differences between trees belonging to a same couple. In each country, the trees have been indeed sampled by couple for each Social position in a given stand as beeing replicates. The factor *"samples in the tree"* means intra-tree differences.

Table 15 gives the values of variance components for each factor and each Social position expressed in relative value of the residual variance which is corresponding to the component *"samples in the tree"*.

The most influential source of variability is due to the factor *"samples in the tree"*, whatever the species could be. In this context, it must be observed that the dominant trees have the highest variability in bark thickness.

Table 15.- *Variance components analysis ("stand", "tree", "samples in the tree") per Social position for each species (the figures are corresponding to the ratio of the vriance of the considered factor to the residual variance)*

Norway spruce			
Social position	Factors		
	Stand	Tree	Sample in the tree
Dominant trees	0,51	0,16	0,89
Co-dominant trees	0,38	0,12	0,68
Suppressed trees	0,40	0,04	0,58
Sitka spruce			
Social position	Factors		
	Stand	Tree	Sample in the tree
Dominant trees	0,07	0,10	0,74
Co-dominant trees	0,35	0,20	0,62
Suppressed trees	0,65	0,14	0,63
Douglas fir			
Social position	Factors		
	Stand	Tree	Sample in the tree
Dominant trees	0,14	0	11,72
Co-dominant trees	0,15	0	7,24
Suppressed trees	1,73	0	8,88

The second most important source of variability is identifying with the factor "*stand*". For this factor, integrating the effects of "*site productivity*" and "*thinning intensity*", it appears that the suppressed trees of Douglas-fir and Sitka spruce are the most variable.

Finally, the factor "*tree*" has the weakest contribution to the total variance which means that each tree belonging to a given couple per Social position in the stand may be considered as **true replicates.**

2.2. Intra tree variability

2.2.1. Effect of the orientation on bark thickness

As previously examined (table 3), the differences in bark thickness according to four directions at right angle (cardinal orientations or not) are not significant for Sitka spruce and Douglas fir. Only the bark of Norway spruce is slightly thinner on the north position compared to the three other directions, but the difference, if significant, is very small. In view of simplifying the modelling procedure, it was decided to use the mean value of the four directions per height level, as a reference.

2.2.2. Evolution of the bark thickness as a function of the relative height

As an example, figure 3 shows the distribution of the mean bark thickness (mean of four orientations at a given level) of **Norway spruce** in connection with the relative height of the tree.

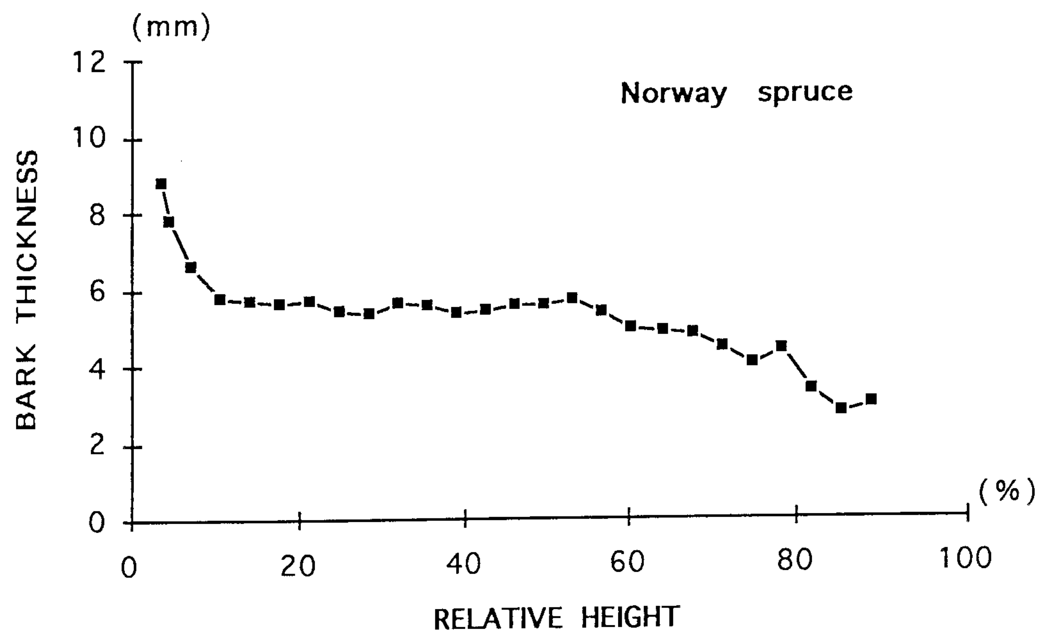


Figure 3. - *Mean bark thickness of Norway spruce as a function of the relative height in the tree (Belgian dominant tree number 2, Wellin stand, site productivity qualified high, thinning intensity qualified low).*

As the phenomena observed for Norway spruce is more or less the same in each country, figure 3 concerns a Belgian tree (tree n^r 2, Wellin stand) coming from a high site productivity characterized by a low thinning intensity. The choice of a Belgian tree for illustrating the evolution of bark thickness with the relative height in the tree is resulting from a larger number of observations along the stem than in other countries.

Figure 3 points out that the Norway spruce bark thickness is far from being constant along the stem. The bark thickness is maximum at the bottom of the tree in decreasing steeply on the first 3 up to 4 meters, then becomes more constant up to the crown base level and decreases inside the living crown for reaching a minimum at the top of the tree.

As a conclusion, the evolution of bark thickness according to the relative height along the tree is characterized, in the case of Norway spruce, by a tremendous footing effect and an obvious living crown base level effect.

For **Sitka spruce**, figure 4 shows almost the same trends with an obvious footing effect and crown base level effect but between these limits the bark thickness looks like to be a little bit less constant.

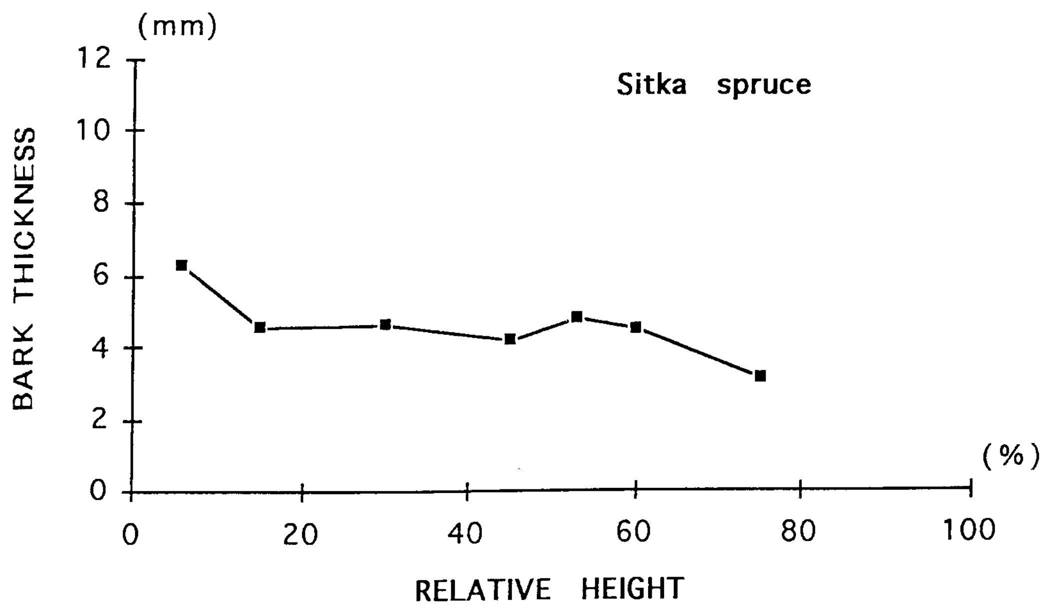


Figure 4. - *Mean bark thickness of Sitka spruce as a function of the relative height in the tree (British dominant tree number B, G1 stand, site productivity qualified high, thinning intensity qualified low).*

For **Douglas fir,** figure 5 also points out an important footing effect extending from the bottom of the tree up to 30 % of the total tree height and beyond that point the bark thickness is slightly decreasing.

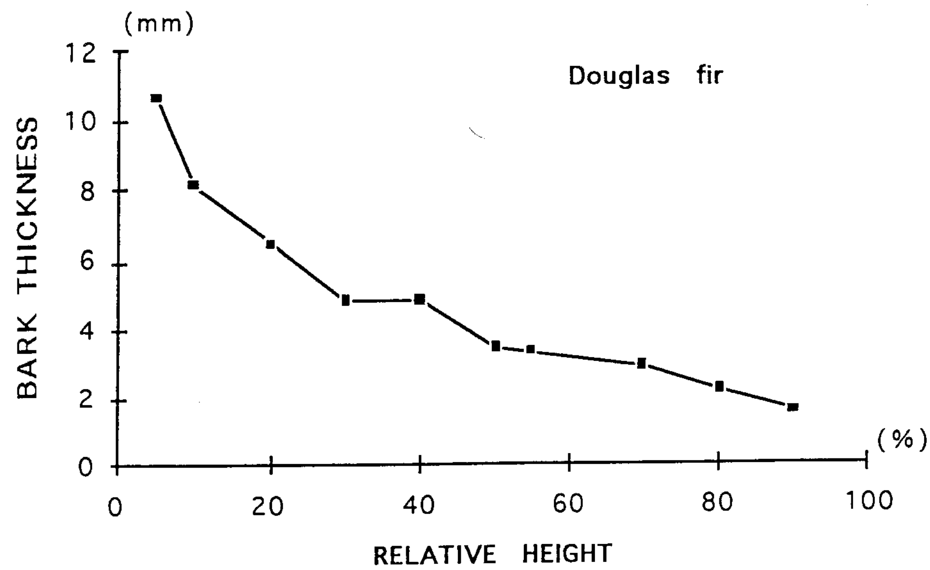


Figure 5. - *Mean bark thickness of Douglas fir as a function of the relative height in the tree (Italian dominant tree number 2, stand 4, site productivity qualified high, thinning intensity qualified low).*

2.3. Inter tree variability

2.3.1. Effect of the Social position in the stand on tree bark thickness

In order to appraise the influence of the Social position of the tree in the stand on the tree bark thickness, the mean bark thickness values per Social position in the stand whatever the productivity and the thinning intensity could be, are presented in figure 6 per species and country. Each stick represents 8 trees.

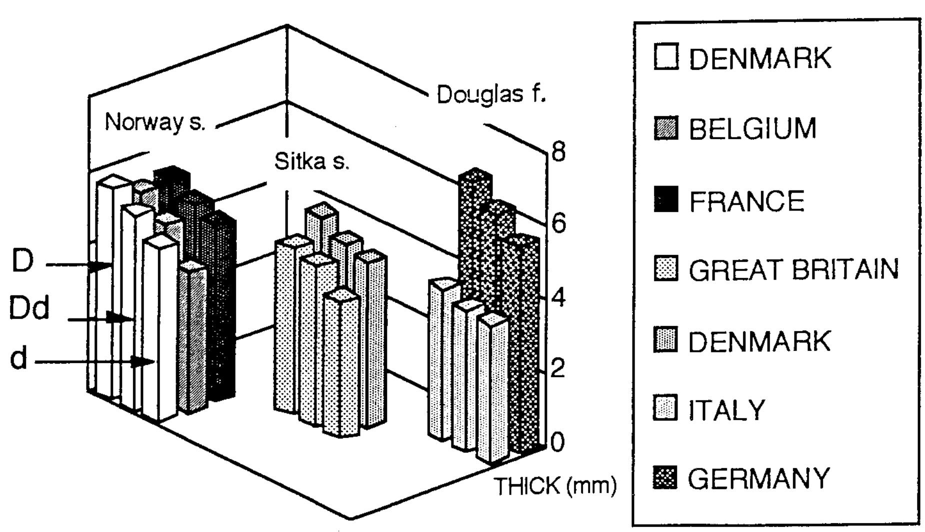


Figure 6. - *Mean bark thickness values (in mm, between 1.3 m and living crown base level) per species, per country in relationship with the Social position in the stand.*

The graph has been constructed in using the bark thickness data only coming from the tree portion when the bark remains more or less constant (ouside the footing place and the living crown), i.e. between 1.3 m level and the living crown base level.

For each species in the different countries, the Social position of the tree in the stand influences bark thickness in the same way. In all cases, dominant trees have indeed the thickest bark while the suppressed trees are characterized by the thinnest bark. The co-dominant trees range in an intermediate position.

On a statistical point of view, a four criteria (country, site productivity, thinning intensity and Social position) variance analysis, applied to the data relevant to the tree portion between 1.3 m and the crown base level, shows that the effect of the Social position in the stand is at least highly significant for the three species (Norway spruce: $F_{obs} = 91.4$ *** (DF = 2); Sitka spruce: $F_{obs} = 11.5$ *** (DF = 2) ; Douglas fir: $F_{obs} = 4.9$ ** (DF = 2)).

The deviations in bark thickness according to the Social position for a tree portion could be also observed at each tree height level. As an illustration of that phenomena, figures 7a, 7b, 7c, represent the evolution of bark thickness along the tree height per species, country and Social position.

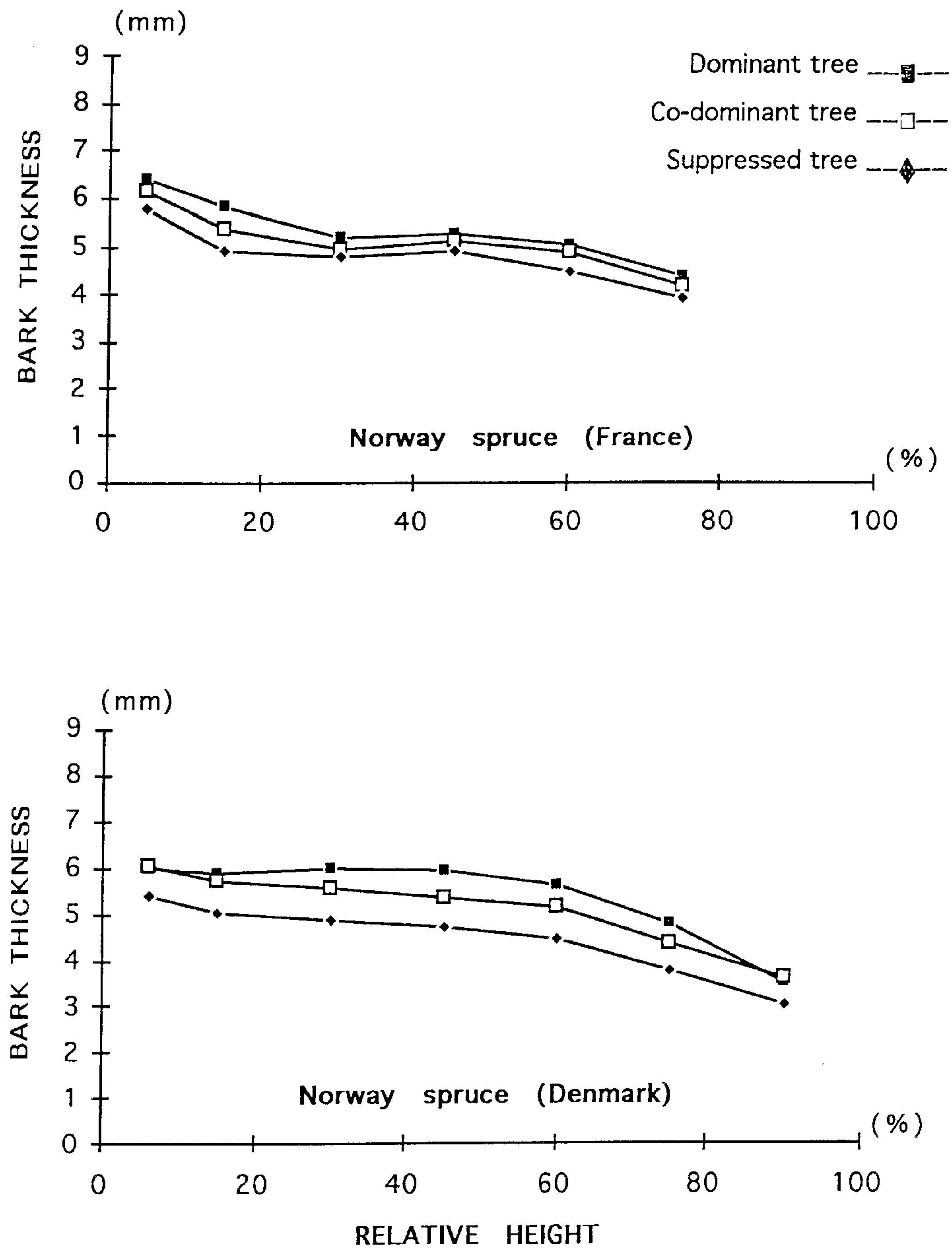
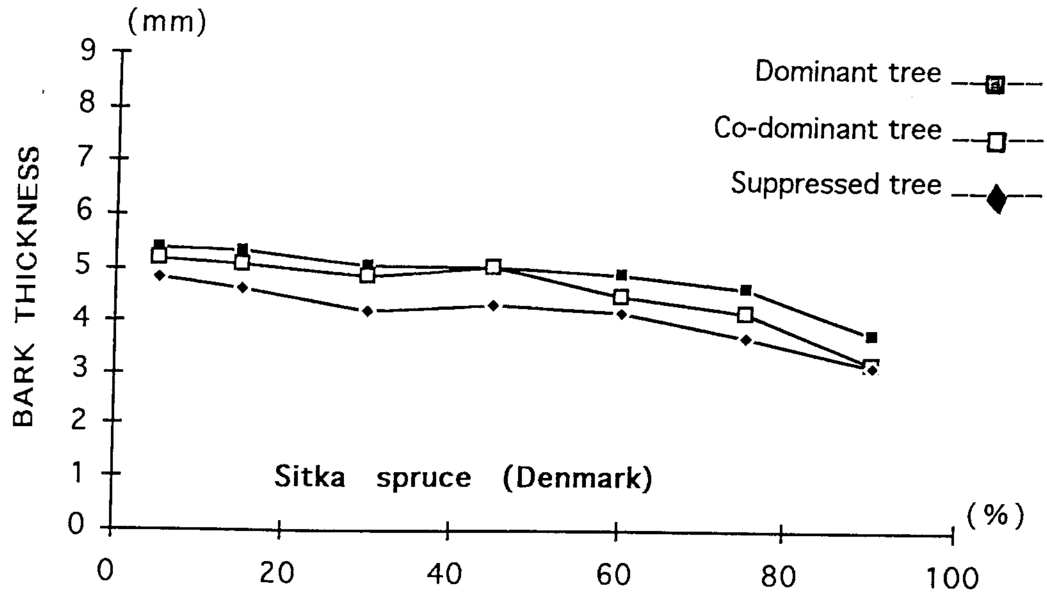


Figure 7a. - *Evolution of Norway spruce bark thickness along the stem in connection with the Social position of the tree in the stand.*



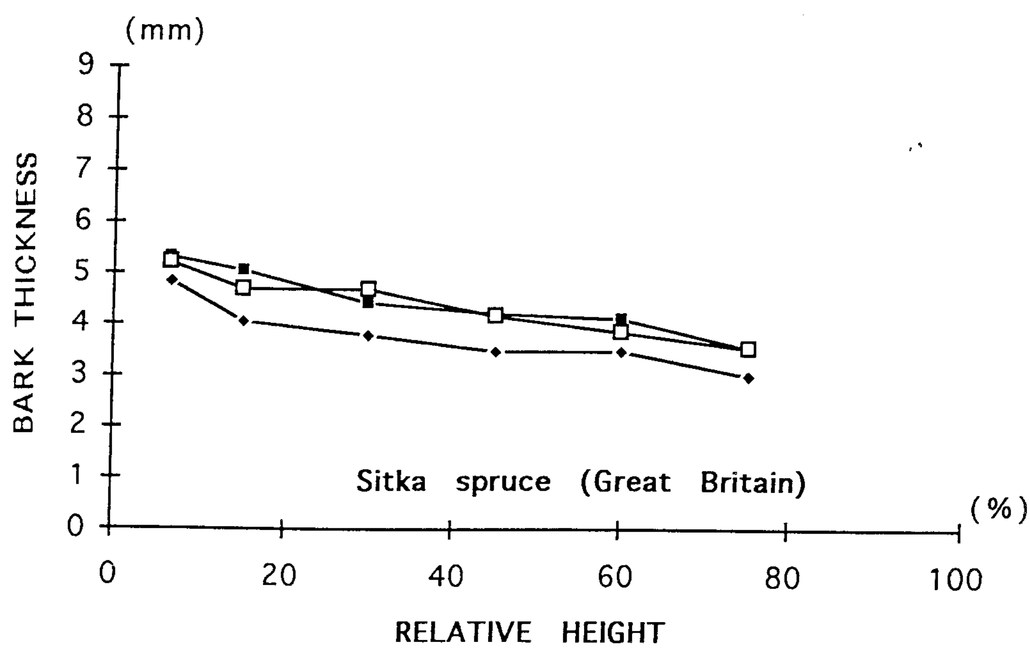


Figure 7b. - *Evolution of Sitka spruce bark thickness along the stem in connection with the Social position of the tree in the stand.*

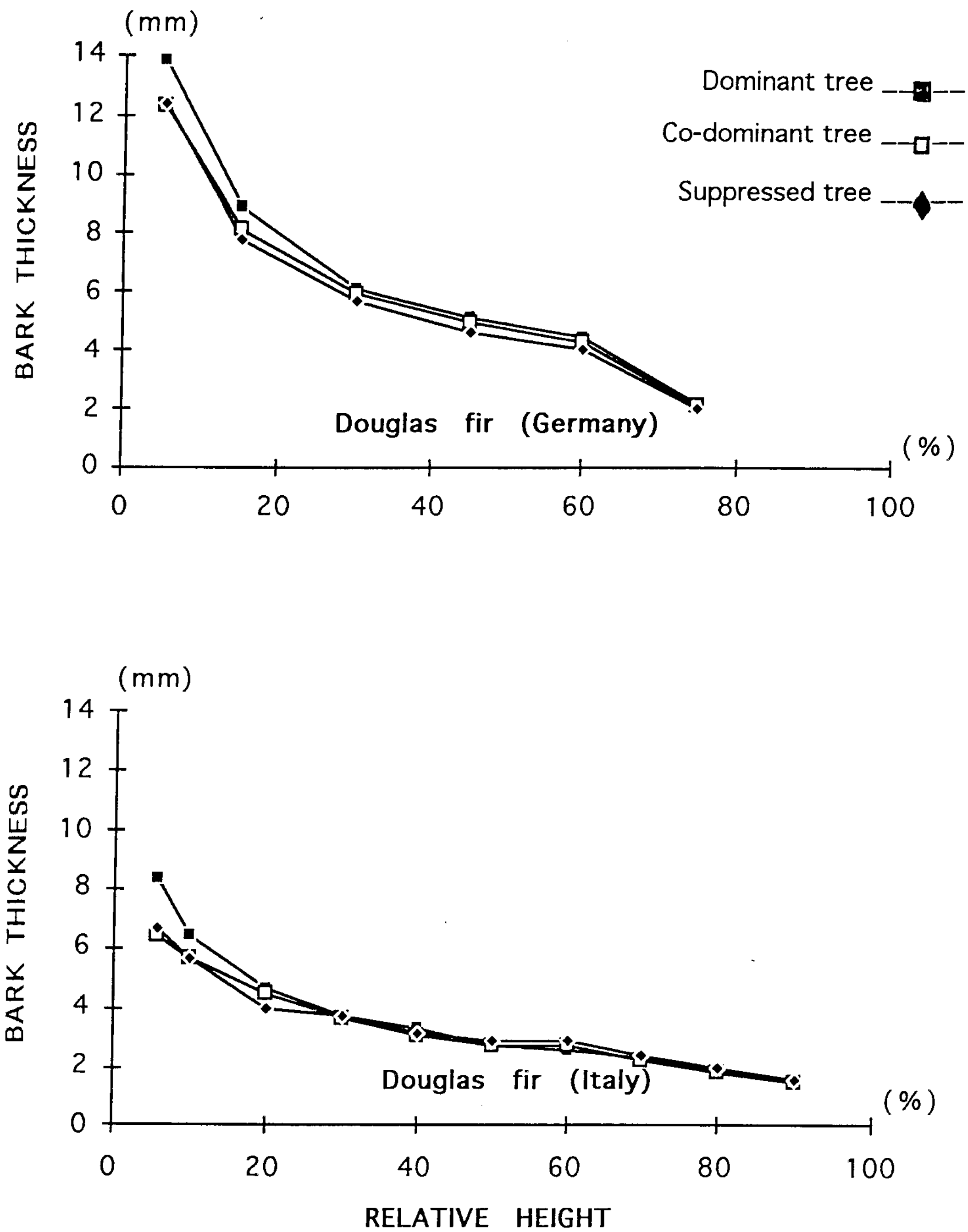


Figure 7c. - *Evolution of Douglas fir bark thickness along the stem in connection with the Social position of the tree in the stand.*

2.3.2. Effect of the site productivity on tree bark thickness

Figure 8 represents the mean bark thickness values per species and country according to the site productivity. Each stick concerns the mean value of the data observed on the stem portion between 1.3 m and the crown base level for 12 trees.

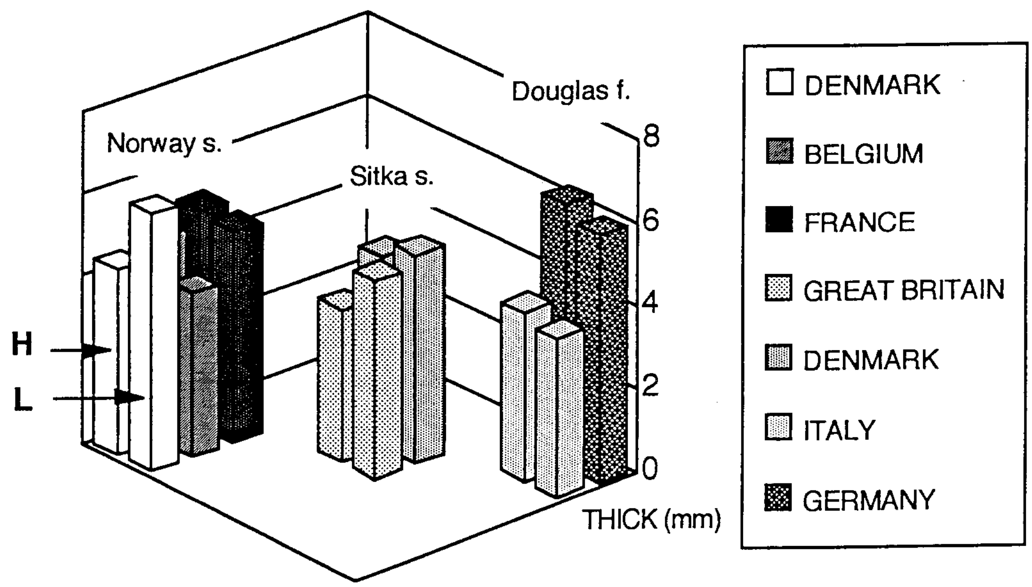


Figure 8. - *Mean bark thickness values (in mm, between 1.3 m and living crown base level) per species and country in relationship with the site productivity.*

For Norway Spruce, in Belgium and France, the bark thickness is decreasing when the site productivity is lowering. The Danish Norway spruces react in an opposite way, probably because of a large age difference between the trees selected within the two kinds of site productivity (more than 50 years).

For Sitka spruce, an opposite trend is observed. The bark thickness is increasing when the site productivity is lowering. For both countries concerned, it has to be noted that a noticeably age difference appears between the trees belonging to each kind of site productivity. The differences are indeed corresponding to 30 years in Great Britain and to 17 years in Denmark. So, the real impact of site productivity on bark thickness is masked by the age differences in both countries because it is well known that older trees possess a thicker bark than younger ones.

For Douglas fir, while the trees sampled have about the same age in the different site productivity classes, it appears that bark thickness is slightly decreasing when the site productivity is lowering.

The statistical analysis clearly reveals a highly significant effect of site productivity (F_{obs} = 8.9** (DF = 1)) on Norway spruce bark thickness with also a strong interaction between country and site productivity (F_{obs} = 144.2*** (DF = 6)).

The following table shows indeed that the site productivity effect is not the same in each country:

Mean bark thicness (mm) (Between 1.3 and CBL)

	Site productivity	
Country	High	Low
Belgian	4.85	3.74
Denmark	4.41	6.14
France	5.14	5.04

For Sitka spruce, the site productivity influences very highly significantly bark thickness (F_{obs} = 39.7 *** (DF = 1)) without any noticeably interaction between the country and the site productivity.

In the case of Douglas fir, there is no significant effect of the site productivity on bark thickness (F_{obs} = 1.5 NS (DF = 1)).

On an other hand, the bark thickness differences noted here above according to the site productivity are reflected back all along the tree height, as illustrated in figures 9a, 9b, 9c, which present the evolution of bark thickness along the stem per site productivity for each species and country.

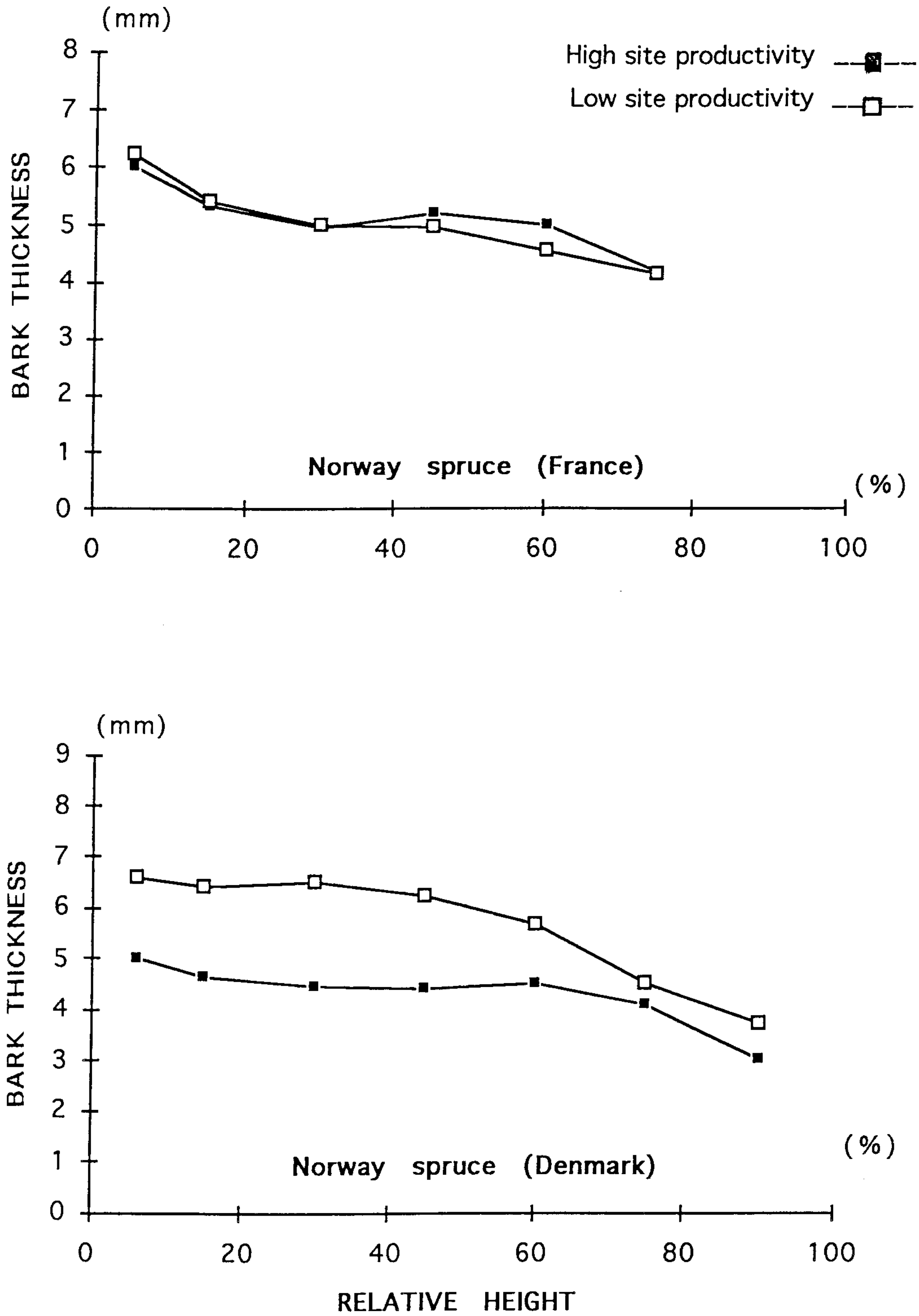


Figure 9a. - *Evolution of Norway spruce bark thickness along the stem in connection with the site productivity.*

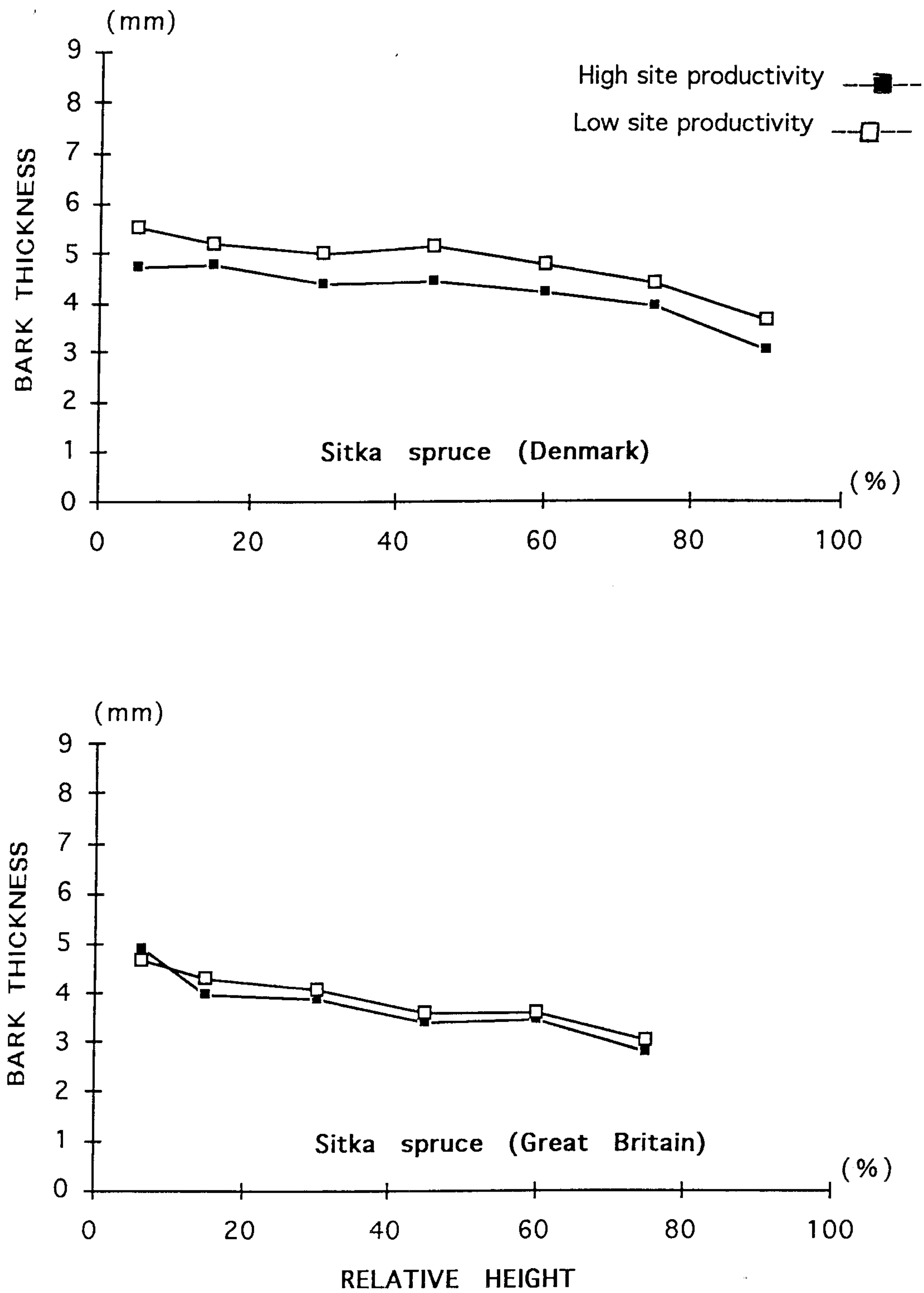
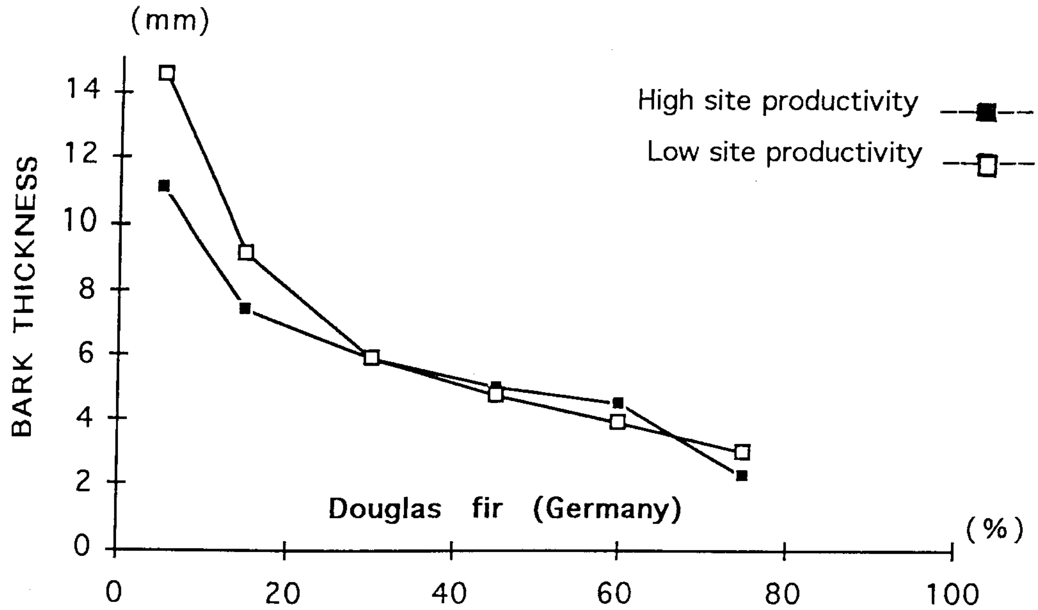


Figure 9b. - *Evolution of Sitka spruce bark thickness along the stem in connection with the site productivity.*



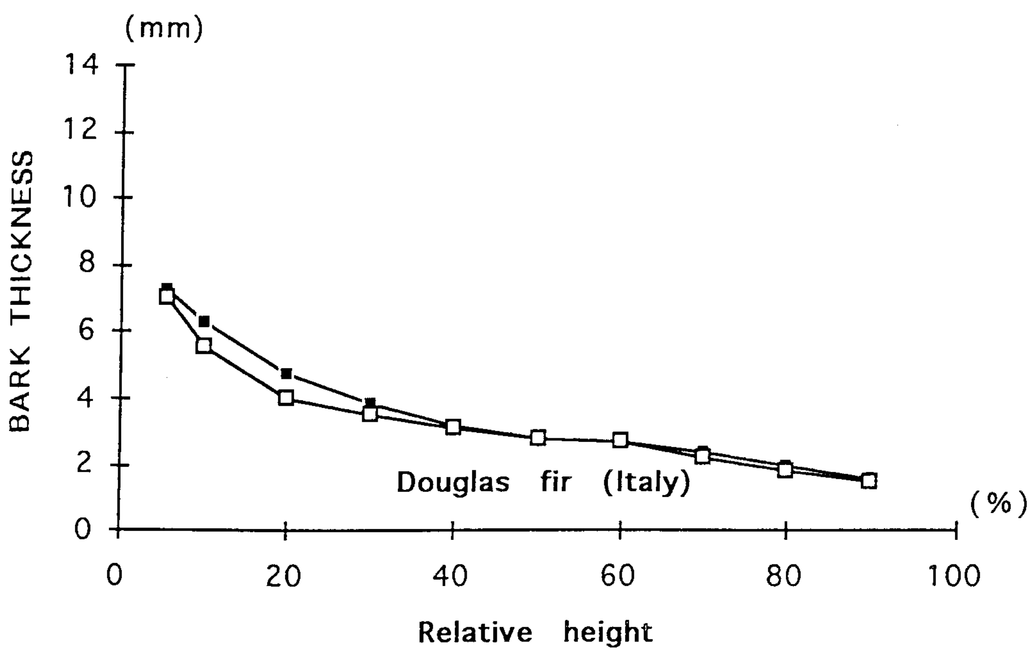


Figure 9c. - *Evolution of Douglas fir bark thickness along the stem in connection with the site productivity.*

2.3.3. Effect of the thinning intensity on tree bark thickness

The effect of the thinning intensity on tree bark thickness per species and country could be seen through figure 10. Each stick in that figure represents the mean bark thickness of 12 trees for which only the stem part included between 1.3 m and the living crown base level has been taken into account.

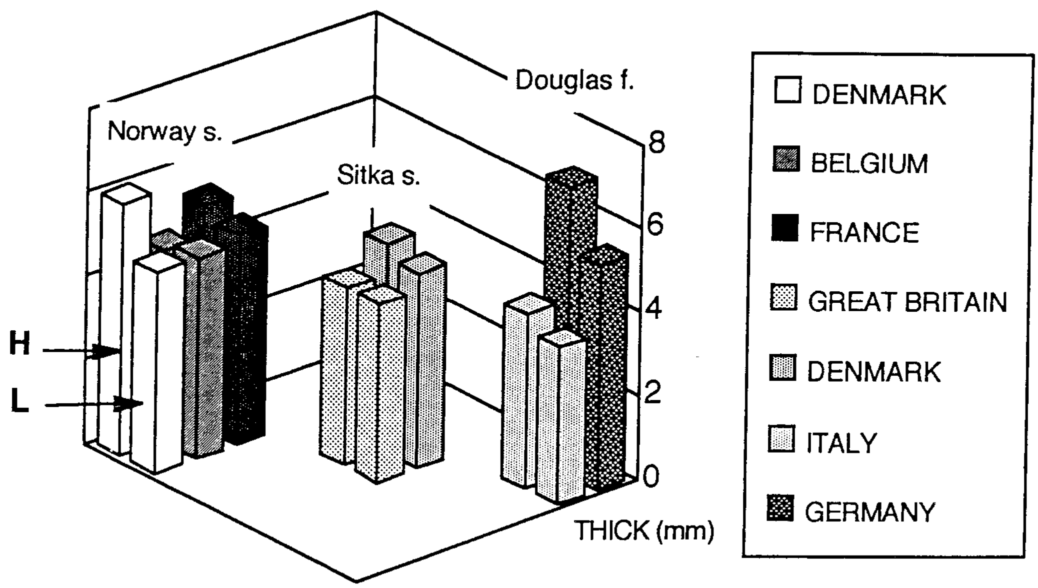


Figure 10. - *Mean bark thickness values (in mm, between 1.3 m and living crown base level) per species, per country in relationship with the thinning intensity.*

Broadly speaking, the thinning intensity seems to influence in a same way the bark thickness of the three species: a thinner bark is produced when the thinning intensity is decreasing.

Nevertheless, this trend is not observed in the case of Norway spruce in Belgium and Sitka spruce in Great Britain for which the tree bark thickness looks like to be similar whatever the thinning intensity could be.

The statistical analysis points out that the thinning intensity significantly affects the bark thickness of Norway spruce ($F_{obs} = 36.7$ *** (DF = 1)) and Douglas fir ($F_{obs} = 22.4$ *** (DF = 1)) with a pronounced interaction between the thinning intensity and the country as appearing from the following table:

Mean bark thickness (mm) (between 1.3m and CBL)

Norway spruce	*Country*	*Thinning intensity*	
		High	Low
	Belgium	4.5	4.8
	Denmark	5.9	4.8
	France	5.3	5.0

Mean bark thickness (mm) (between 1.3m and CBL)

Douglas fir	*Country*	*Thinning intensity*	
		High	Low
	Germany	6.8	5.3
	Italy	4.1	3.7

Concerning Sitka spruce, the statistical analysis shows no effect of the thinning intensity on bark thickness.

These trends are also illustrated in figure 11a, 11b, 11c, which show for each species and country the evolution of bark thickness according to the thinning intensity all along the tree height.

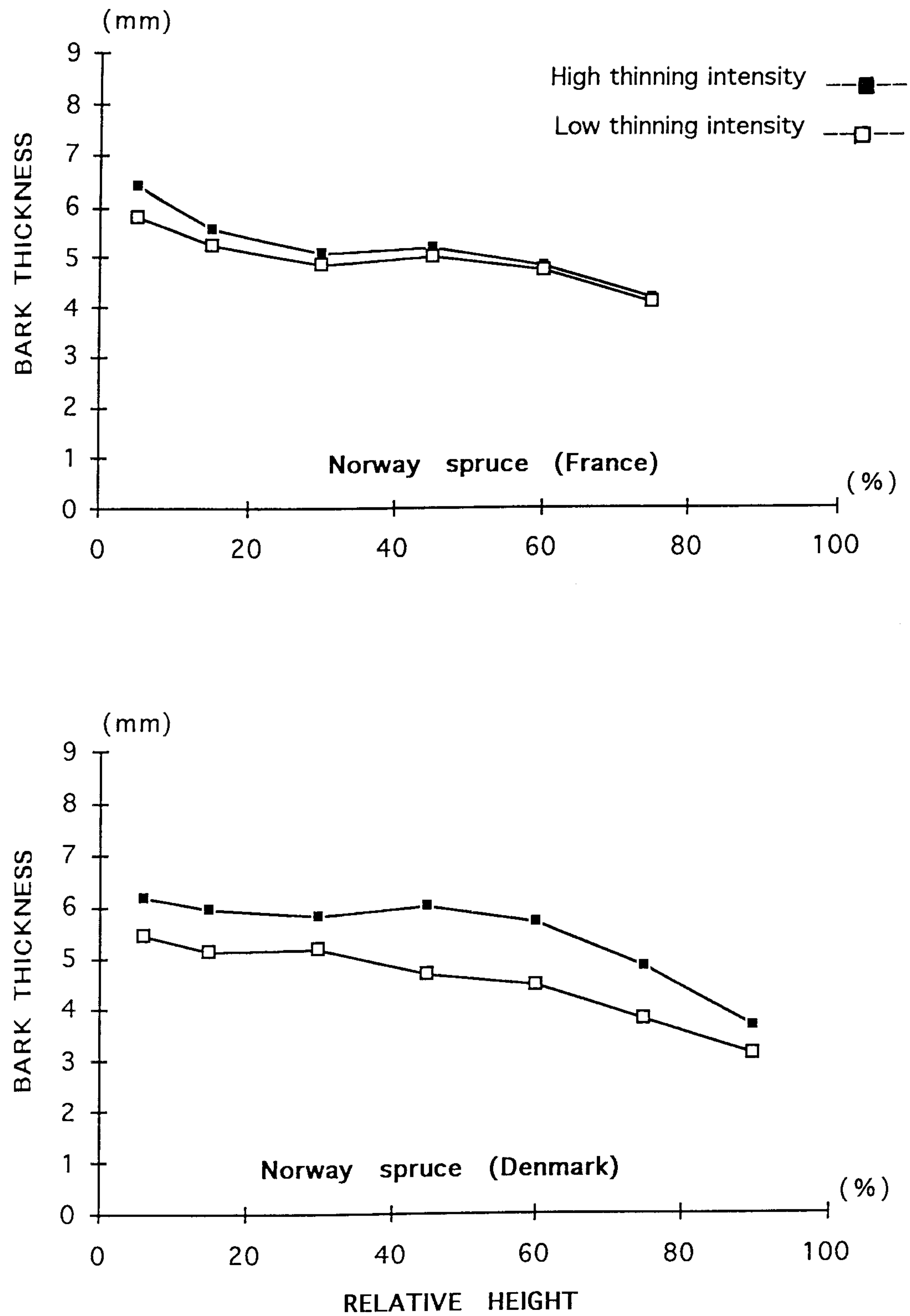


Figure 11a. - *Evolution of Norway spruce bark thickness along the stem in connection with the thinning intensity.*

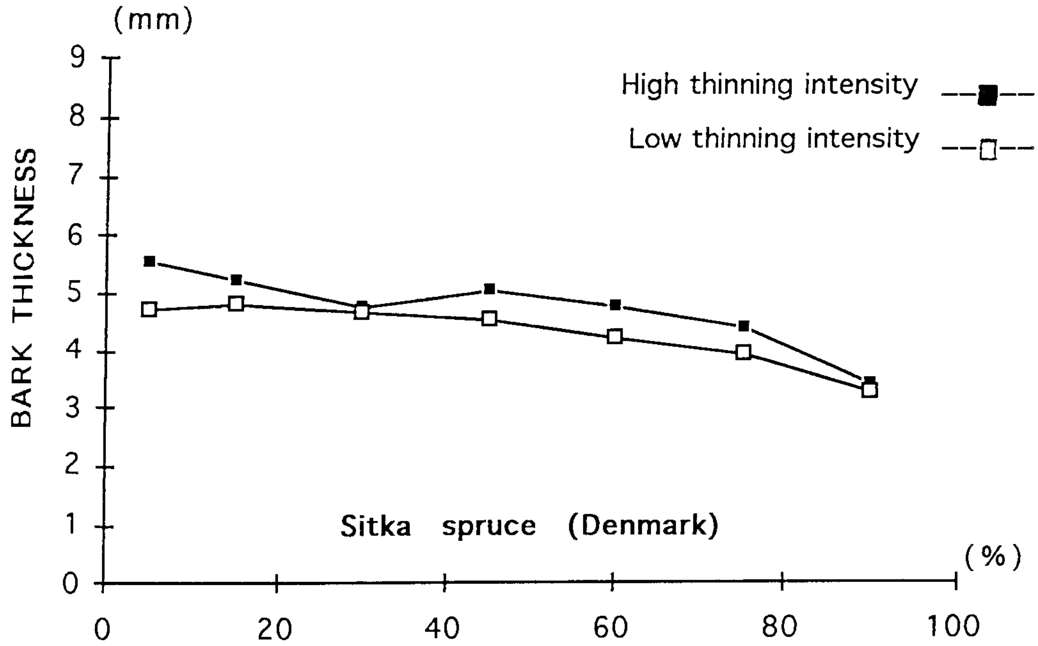


Figure 11b. - *Evolution of Sitka spruce bark thickness along the stem in connection with the thinning intensity.*

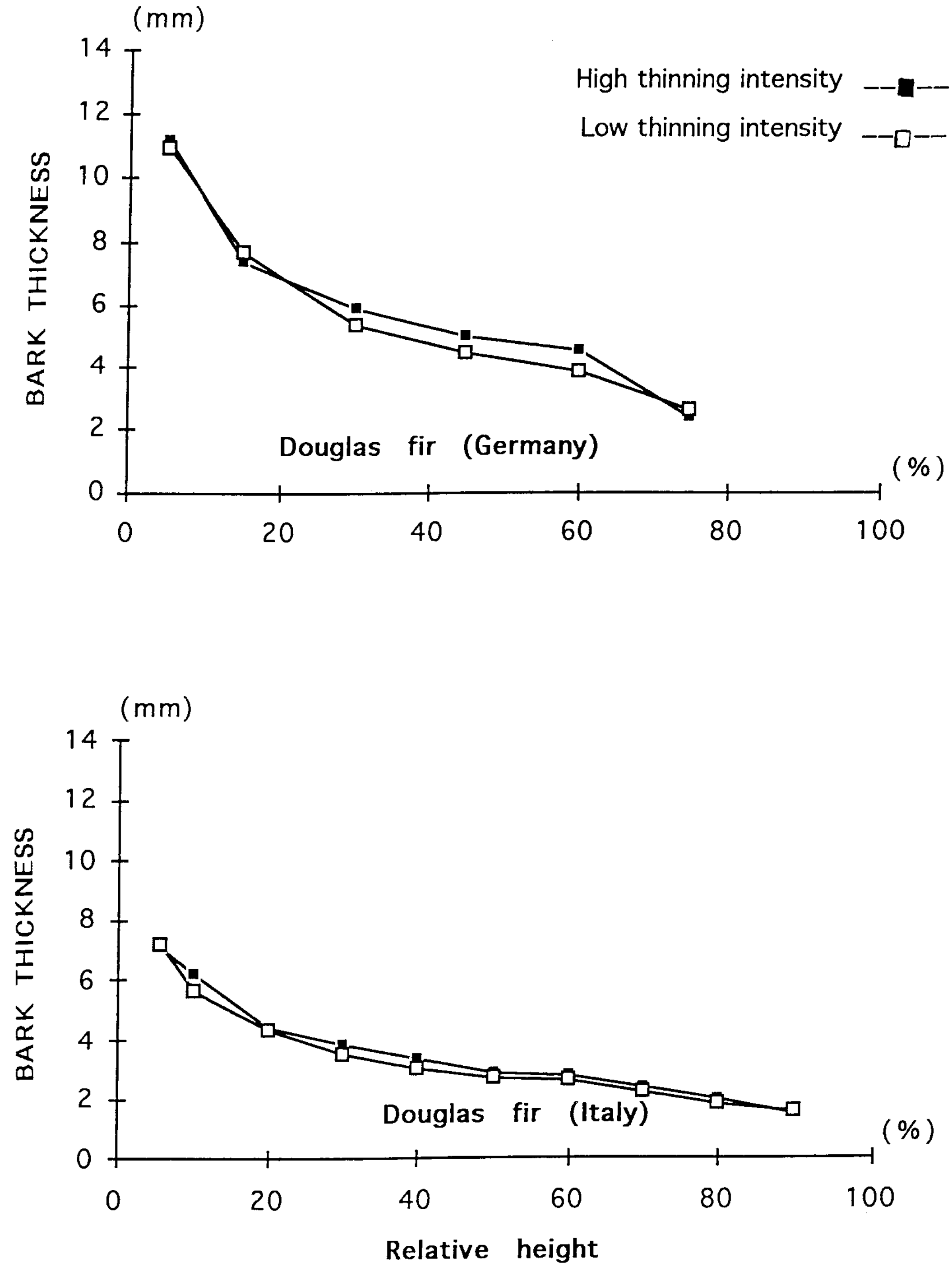


Figure 11c. - *Evolution of Douglas fir bark thickness along the stem in connection with the thinning intensity.*

2.3.4. Effect of the country on bark thickness

As pointed out previously in the different statistical analysis, the country itself exercices a strong influence on bark thickness of each species ($F_{obs\ Norway\ spruce} = 86.1$ *** (DF = 2); $F_{obs\ Sitka\ spruce} = 26.6$ *** (DF = 1); $F_{obs\ Douglas\ fir} = 103.7$ *** (DF = 1)). This could result from a cumulative action of environmental conditions, genetical origin, silvicultural technics, stand age and tree girth... relevant to each country.

The Newman & Keuls test applied to the mean bark thickness values (observed on the stem part between 1.3m and CBL) is summarized for each species hereafter, showing within a given species the differences between countries:

Species	*Country*	*Mean bark thickness* (mm)	*Group(*)*
Norway spruce	**Denmark**	5.3	A
	France	5.1	A
	Belgium	4.6	B
Sitka spruce	**Denmark**	4.8	A
	Great-Britain	4.2	B
Dougla fir	**Germany**	6.2	A
	Italy	3.9	B

* Within each species, the countries characterized by a same letter symbol belong to a same group.

2.3.5. Conclusion

The results examined in relationship with each criterion used for the sampling in each country showed that the evolution of bark thickness as a function of each stand selection criteria ("*site productivity*", "*thinning intensity*") is far to be constant or to point up a same trend as well for a given species as for the three species.

On the other hand, the tree selection criteria ("*Social position*" in the stand) acts in a same manner on the bark thickness of each species.

These observations will have to be taken in mind for modelling.

3. Bark thickness modelling

3.1. General procedure for modelling bark thickness

The problem of connections between bark thickness and dendrometrical characteristics measured on the trees has been solved by the multiple regression analysis (PROC REG on SAS®) as this method consists in putting into close relationship a dependent variable as bark thickness with two or several independent variables as each dendrometrical characteristic (DAGNELIE, 1969; 1970).

The choice of independent variables is realized systematically 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).

This procedure is only valid for linear models that we have presently adopted considering the general evolution of bark thickness per species in connection with the relative height (figures 3, 4, 5).

The choice of **linear models** are deliberately limited to those including at the most three independent variables. In some cases, the model chosen is not the best one based on the highest value for the determination coefficient (R^2) but that composed of the most accessible variables, i.e. those very easily measurable on the field by the forester.

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

In a first step, the regression analysis is based on the whole data related to each species in order to find out if a general model could be convenient for each species. These models are called "***General models***".

In a second step, the regression analysis has been realized on the data per country for each species. These models are called "***Country models***".

In a third and final step, the regression analysis was dealing with the same combination of independent variables for each country inside a same species. These last models are called "***Common models***".

This three steps procedure has been adopted for taking care of models homogeneity for feeding SIMQUA software.

3.2. Main variables considered for bark thickness modelling

The main independent variables taken into account for tree bark thickness modelling are:

- height level of bark measurement	**HEIGHT**
- girth at the level of bark measurement	**GIRTH**
- total height of the tree	**HT**
- girth at breast height	**GIRTH13**
- living crown base level	**CBL**
- girth at the living crown base level	**GIRTHCB**
- total age of the tree	**AGE**
- square height level of bark measurement	**HEIGHT2**
- square girth at the level of bark measurement	**GIRTH2**
- square total height of the tree	**HT2**
- relative height level of bark measurement	**HR**
- girth at breast height times relative height level of bark measurement	**GIRTHR**

3.3. Generals models

According to the detailed procedure adopted hereabove, the best general models selected per species are presented hereafter.

3.3.1. Norway spruce

a. Regression equation

$$\mathbf{THICK = 0.335 + 0.040\ AGE + 0.005\ HT2 - 0.024\ HR}$$

$R^2 = 0.53$ $S = 0.79$ $N = 696$

b. Analysis of residuals

The results of the analysis of residues calculated from the selected model show at least a significant effect of the "*Country*" (F_{obs} = 68.0 *** (DF = 2)), of the "*Stand*" (F_{obs} = 37.9 *** (DF = 9)), of the "*Social position* "(F_{obs} = 13.1*** (DF = 2)) and of the interaction "*Stand x Social position* " (F_{obs} = 3.7*** (DF = 18)) on the model. Among all these parameters, the most implicated factor on the model is the "*Country*". That means that a best prediction of bark thickness requires the establishment of separated models by country.

Table 16 presents the results of the variance analysis of residues for the variable "*Country*" and the results of the Newman & Keuls test.

Table 16. - *Variance analysis of residues for Norway spruce general model*

Mean residuals (mm)	Number of observations N	Variable "*COUNTRY*"	Group
+ 0.3299	167	Denmark	A
- 0.0521	365	Belgium	B
- 0.2201	164	France	C

The variance analysis of residues shows that each country behaves differently and has to be treated by distinct models. This conclusion confirms the observations made previously.

Figure 12 gives the distribution of residuals for the three countries as a function of the bark thickness predicted value from the model.

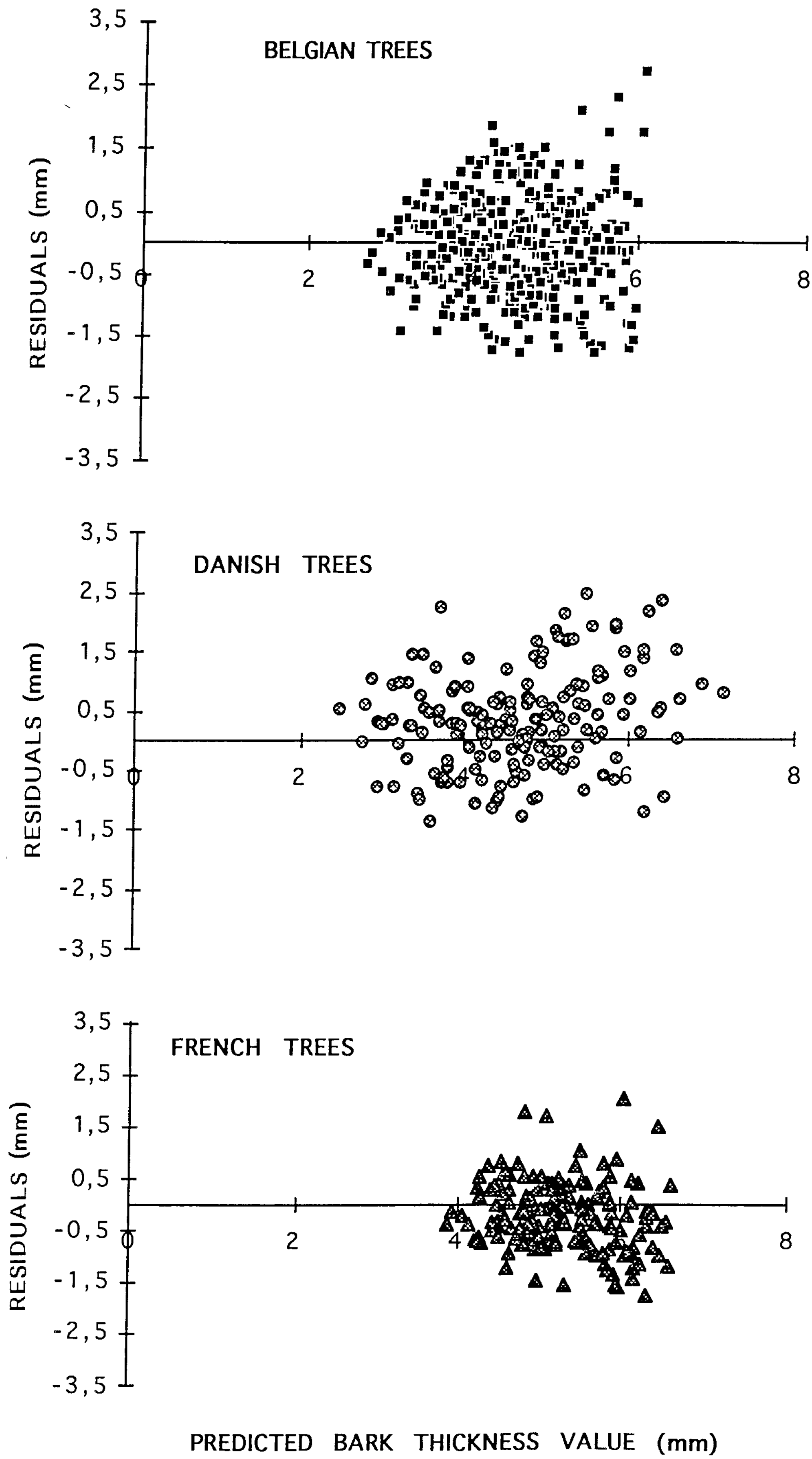


Figure 12. - *Distribution of bark thickness residuals for Norway spruce general model.*

3.3.2. Sitka spruce

a. Regression equation

$$\textbf{THICK} = 2.595 + 0.013\ \textbf{GIRTH13} + 0.033\ \textbf{AGE} - 0.02\ \textbf{HR}$$

$R^2 = 0.54$ $S = 0.74$ $N = 319$

b. Analysis of residues

The results of the analysis of residues show at least a significant effect of the "*Country*" ($F_{obs} = 4.16^*$ (DF = 1)), of the "*Stand*" ($F_{obs} = 6.87^{***}$ (DF = 6)), of the "*Social position* " ($F_{obs} = 8.98^{***}$ (DF = 2)) and of the interaction "*Stand x Social position* " ($F_{obs} = 3.26^{***}$ (DF = 12)).

Taking care of an homogeneous presentation of the results, the variance analysis of residues and Newman & Keuls test were made for the variable "*Country*" (table 17). The same observations as for Norway spruce can be made.

Table 17. - *Variance analysis of residues for Sitka spruce general model.*

Mean residues (mm)	Number of observations N	Variable "*COUNTRY*"	Group
+0.1108	164	Denmark	A
- 0.1172	155	Great Britain	B

Figure 13 shows the distributions of residues in connection with the bark thickness predicted value from the model for both countries. The selected model slightly over-estimates the predicted value of bark thickness for the Danish trees, but under-estimates those for the British trees.

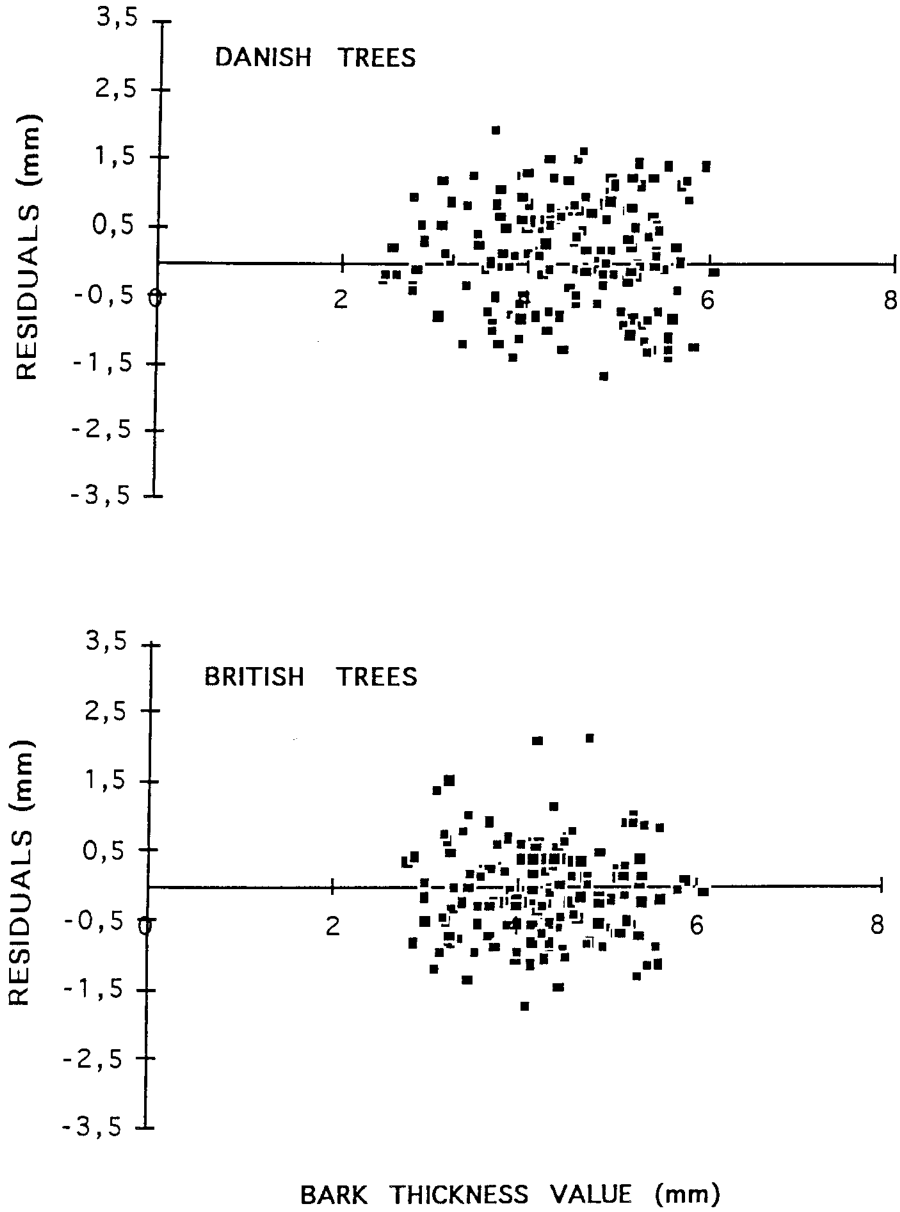


Figure 13. - *Distribution of bark thickness residues for Sitka spruce general model.*

3.3.3. Douglas fir

a. Regression equation

$$\textbf{THICK} = -0.550 + 0.002\ \textbf{AGE} + 0.001\ \textbf{GIRTH2} + 0.023\ \textbf{GIRTHR}$$

$R^2 = 0.74$ $S = 1.85$ $N = 414$

b. Analysis of residuals

The results of the analysis of residuals only show a significant effect of the "*Country*" (F_{obs} = 17.1*** (DF = 1)). It must be observed that the standard deviation related to the model is more than two times higher than for the two Spruce species, indicating a higher bark thickness variability for Douglas fir.

The results of the variance analysis of residues and the Newman & Keuls test are presented in table 18 for the variable "*Country*" which is this time the only one to influence in a large extent the selected model.

Table 18. - *Variance analysis of residues for Douglas fir general model.*

Mean residues (mm)	Number of observations N	Variable "*COUNTRY*"	Group
+ 0.4627	174	Germany	A
- 0.3354	240	Italy	B

Figure 14 which gives the distribution of residues shows that the selected model is convenient for the Italian Douglas fir trees but does not fit quite well on the German douglas fir trees, when the predicted values of bark thickness exceed 5 mm.

The extent of variability of residues is justified by a larger variability of bark thickness when the girth at the measured level exceeds 60 cm (figure 15).

That means that a higher variability of bark thickness residues is generated by the footing effect because the largest girth at the measured level is indeed corresponding to the bottom part of the tree.

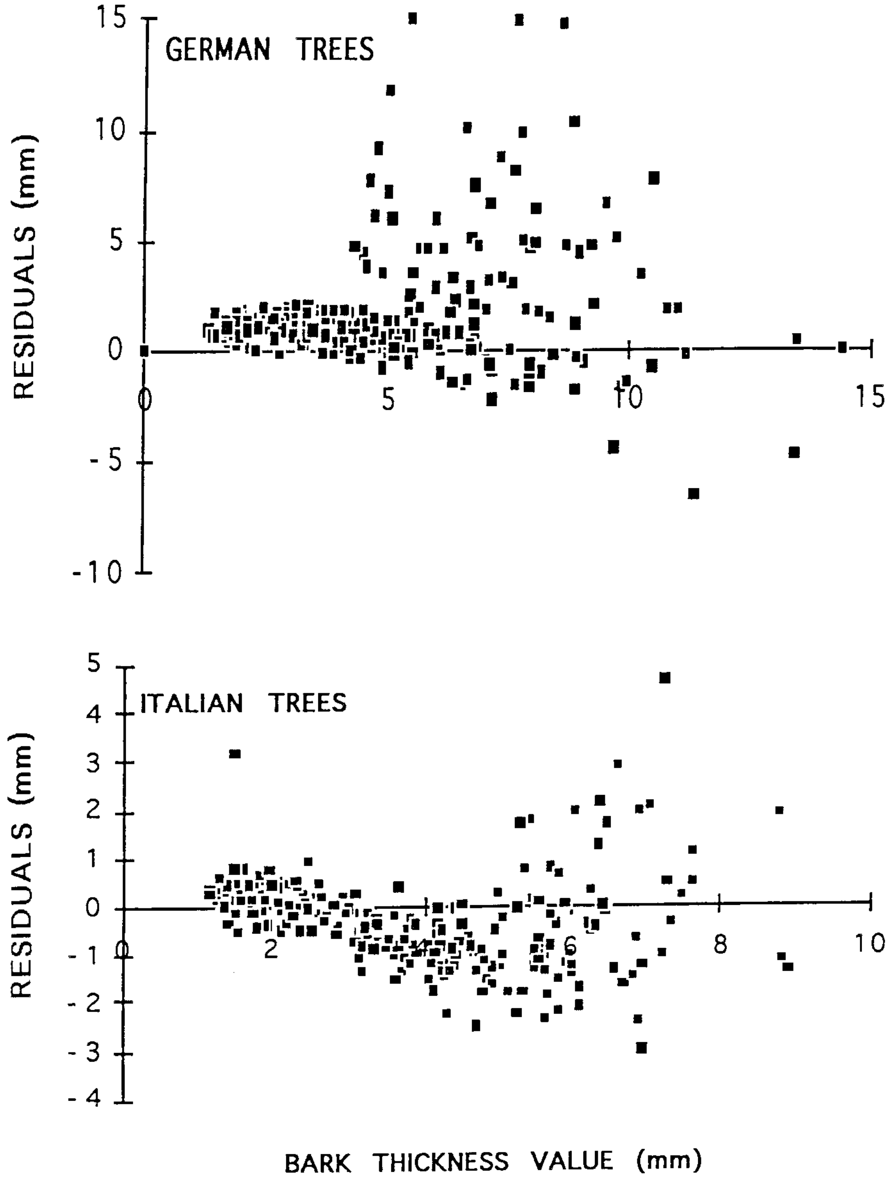


Figure 14. - *Distribution of bark thickness residues for Douglas fir general model.*

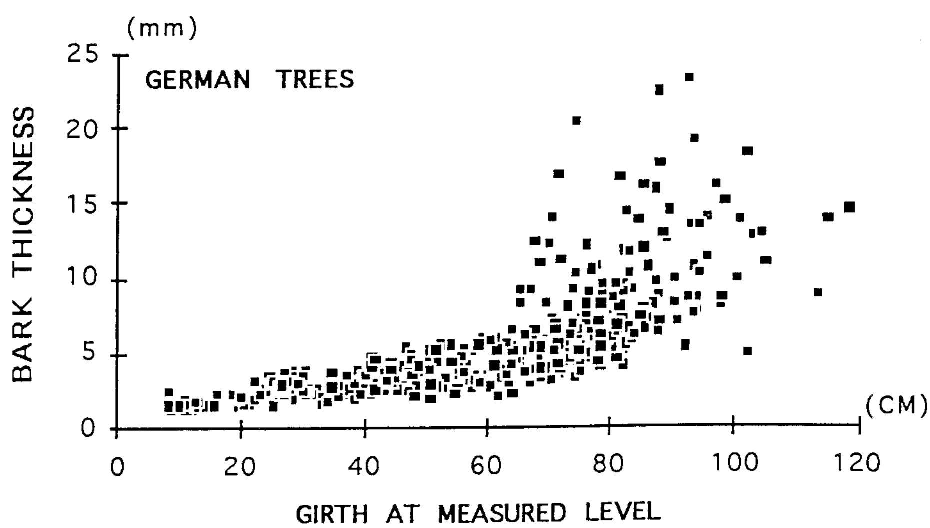


Figure 15. - *Bark thickness distribution versus girth at the measured level.*

3.3.4. Conclusion

Whatever the species could be, the variables taken into account by the general model may be separated into three groups:

- the total age of the tree (AGE)

- the variables referring to tree growth in diameter (GIRTH 13, GIRTH 2, GIRTHR);

- the variables referring to tree height growth (HT2, HR).

When using only one variable model, the best explaining parameter is always the girth at the measured level, clearly indicating that bark thickness is above all linked to tree growing in diameter.

3.4. Country model

As the variable "*Country*" interacts to a large extent on the predicting values given by general models, a higher accuracy in prediction could be expected when using models established country by country for each species.

3.4.1. Norway spruce

3.4.1.1. In Belgium

a. Regression equation

$$\mathbf{THICK = + 0.924 + 0.030\ GIRTH - 0.015\ AGE + 0.003\ HT2}$$

R^2= 0.74 S = 0.56 N = 365

b. Analysis of residues

The results from the analysis of residues show a significant effect of the "*Stand*" (F_{obs} = 31.3*** (DF = 3)) and of the interaction "*Stand x Social position*" (F_{obs} = 10.5*** (DF = 6)). That means that a better accuracy in predicting bark thickness could be obtained in using models stand by stand, but this next step has not been considered in the framework of this study because the target is to achieve models as general as possible.

The results of the variance analysis of residues with the corresponding results from a Newman & Keuls test are presented in table 19. Figure 15 shows the distribution of residues without any bias.

Table 19. - *Variance analysis of residues for Belgian Norway spruce country model.*

Mean residues (mm)	Number of observations N	Variable "*STAND*"	Group
+0.2941	44	Solwaster (S)	A
+0.1579	136	Dohan (D)	A
-0.0772	142	Wellin (W)	B
-0.5456	43	Ternell (T)	C

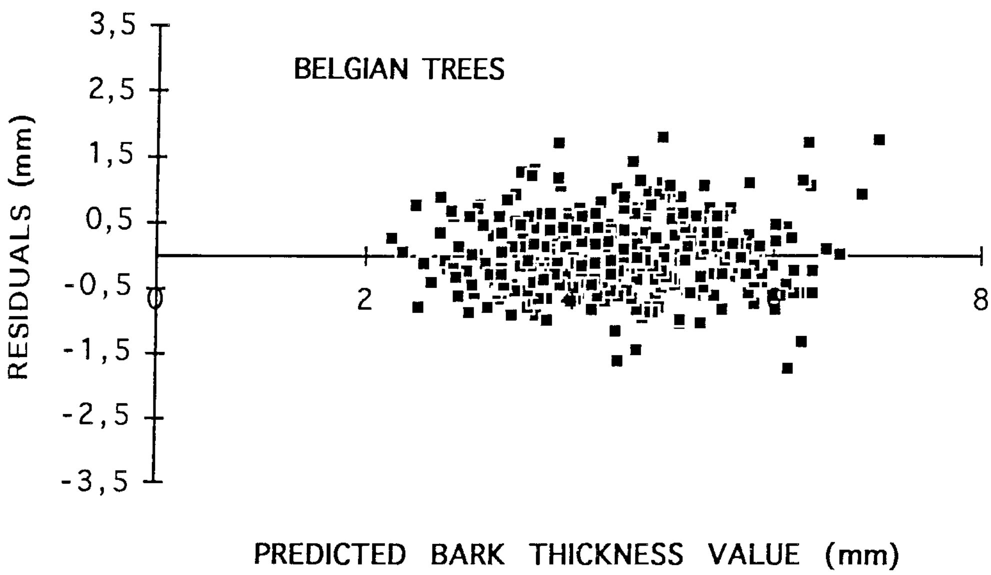


Figure 16. - *Distribution of bark thickness residues for Belgian Norway spruce country model.*

3.4.1.2. In France

a. Regression equation

$$\text{THICK} = + 3.267 + 0.046\ \text{GIRTH} - 0.031\ \text{AGE} + 0.002\ \text{HEIGHT2}$$

$R^2 = 0.59$ $S = 0.55$ $N = 164$

b. Analysis of residues

Only the effect of the interaction *"Stand x Social position"* is significant on the selected model ($F_{obs} = 7.1$ *** (DF = 6)). Figure 17 illustrates the distribution of residues calculated from the selected model.

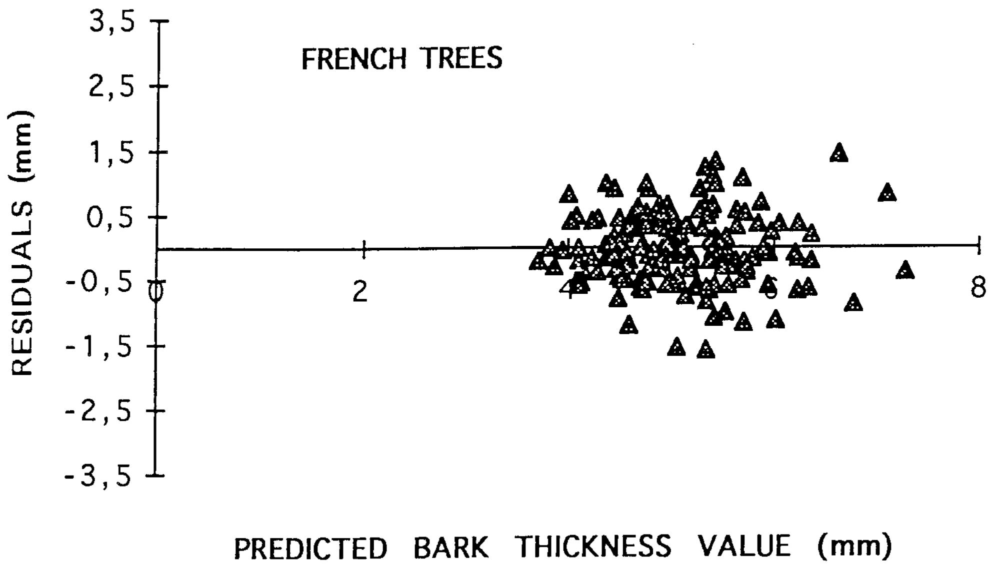


Figure 17. - *Distribution of bark thickness residues for French Norway spruce country model.*

3.4.1.3. In Denmark

a. Regression equation

$$\text{THICK} = -0.825 + 0.101\ \text{GIRTH} + 0.034\ \text{AGE} - 0.001\ \text{GIRTH2}$$

$R^2 = 0.78$ $S = 0.66$ $N = 167$

b. Analysis of residues

The variables "*Stand*" ($F_{obs} = 9.2$ *** ($DF = 3$)) and "*Social position*" ($F_{obs} = 5.2$ ** ($DF = 2$)) act significantly on the selected model.

Table 20 gives the results of the variance analysis of residues and of the Newman & Keuls test. It appears that the two stands belonging to high site productivity classes may be grouped in a same model. Figure 18 illustrates the distribution of residues relevant to the selected model.

Table 20. - *Variance analysis of residues for Danish Norway spruce country model.*

Mean residues (mm)	Number of observations N	Variable "*STAND*"	Group
0.3508	42	IS	A
0.0366	42	KN	B
-0.0629	42	RU	B
-0.3325	41	GL	C

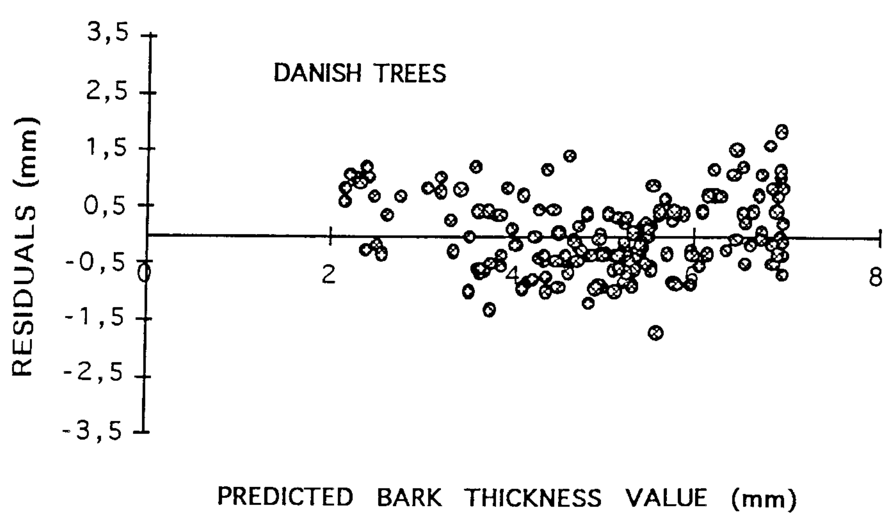


Figure 18. - *Distribution of bark thickness residues for Danish Norway spruce country model.*

3.4.1.4. Conclusion

The "***country models***" for Norway spruce are far more accurate than the general model, taking into account the higher values of R^2, excepted for France. This observation is confirmed by the decrease of the standard deviation values of the models.

3.4.2. Sitka spruce

3.4.2.1. In Denmark

a. Regression equation

THICK = + 1.182 + 0.052 GIRTH + 0.028 AGE - 0.0002 GIRTH2

$R^2 = 0.56$ S = 0.74 N = 164

b. Analysis of residues

There is a significant effect of the variable ""*Stand*" (F_{obs} = 13.6 *** (DF = 3)) and of the interaction "*Stand x Social position*" (F_{obs} = 2.8 * (DF = 6)) on the selected model.

The results of the variance analysis of residues and those from the Newman & Keuls test are presented in table 21, and figure 19 illustrates the distribution of the residues from the model.

Table 21. - *Variance analysis of residues for Sitka spruce country model.*

Mean residues (mm)	Number of observations N	Variable "*STAND*"	Group
0.3947	41	FE	A
0.1434	42	FR	A B
-0.0724	39	LH	B
-0.4615	42	UG	C

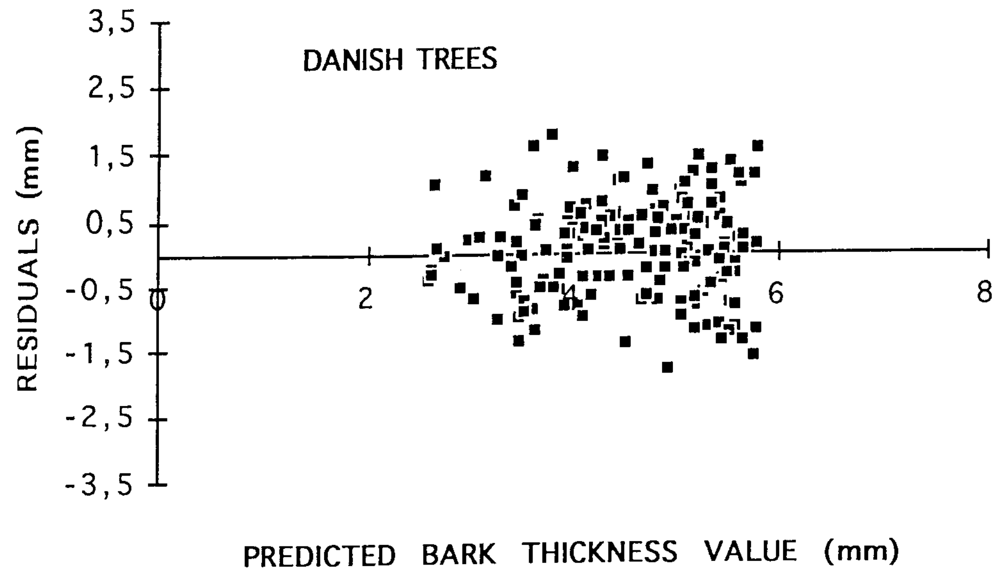


Figure 19. - *Distribution of bark thickness residues for Danish Sitka spruce country model.*

3.4.2.2. In Great Britain

a. Regression equation

$$THICK = + 2.234 - 0.117\ HEIGHT + 0.019\ GIRTH13 + 0.028\ AGE$$

$R^2 = 0.58$ $S = 0.66$ $N = 155$

b. Analysis of residues

The variable "*Social position*" ($F_{obs} = 21.8$ *** (DF = 2)) and the interaction "*Stand x Social position*" ($F_{obs} = 5.2$ *** (DF = 6)) act significantly on the selected model.

Table 22 gives the results of the variance analysis of residues and those of the Newman & Keuls test. It appears that a more accurate prediction of bark thickness needs the establishment of models per Social position in the stand.

Table 22. - *Variance analysis of residues for Sitka spruce country model.*

Mean residues (mm)	Number of observations N	Variable "*Social position*"	Group
+0.3118	52	D	A
+0.0727	53	Dd	B
-0.4013	50	d	C

The distribution of residues calculated from the model is illustrated in figure 20.

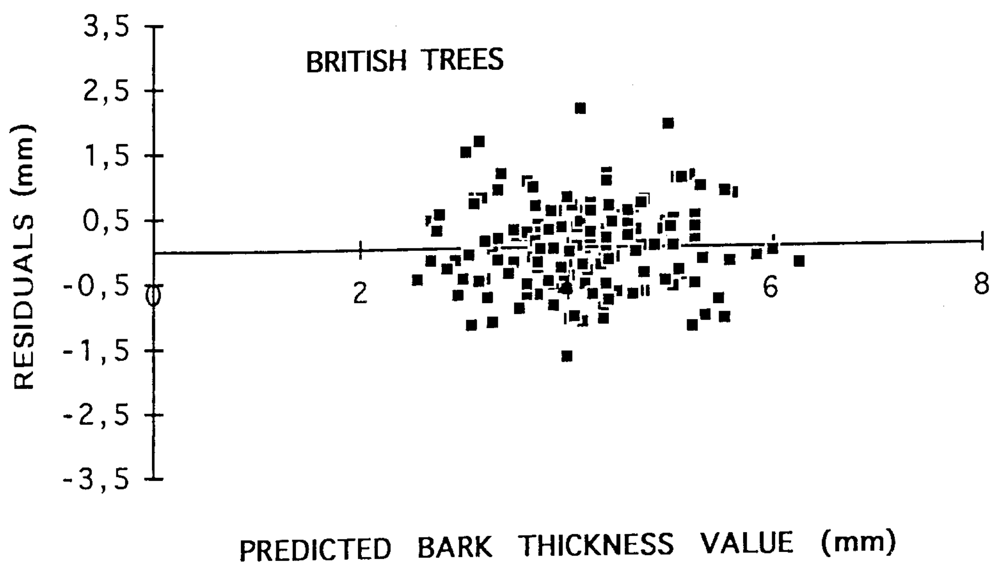


Figure 20. - *Distribution of bark thickness residues for British Sitka spruce country model.*

3.4.2.3. Conclusion

The improvement of the predicting value of bark thickness from the models per country is weak in comparison with the accuracy given by the general model. For Great Britain, the weakness of prediction is due to the fact that the best model ($R^2 = 0.61$) has not been chosen because we preferred models with easier measurable variables on the field.

3.4.3. Douglas fir

3.4.3.1. In Germany

a. Regression equation

$$THICK = + 10.196 + 0.0004\ AGE - 0.162\ HR + 0.062\ GIRTHR$$

$R^2 = 0.68$ S = 2.40 N = 174

b. Analysis of residues

The variable "*Stand*" (F_{obs} = 6.23 *** (DF=3)) significantly interfers on the selected model.

Table 23 gives the results of the variance analysis of residues and the results of the Newman & Keuls test. The distribution of residues is illustrated by figure 21.

Table 23. - *Variance analysis of residues for Douglas fir country model.*

Mean residues (mm)	Number of observations N	Variable "*STAND*"	Group
+0.8172	36	C	A
+0.5683	60	A	A
-0.6872	36	D	B
-0.9233	42	B	B

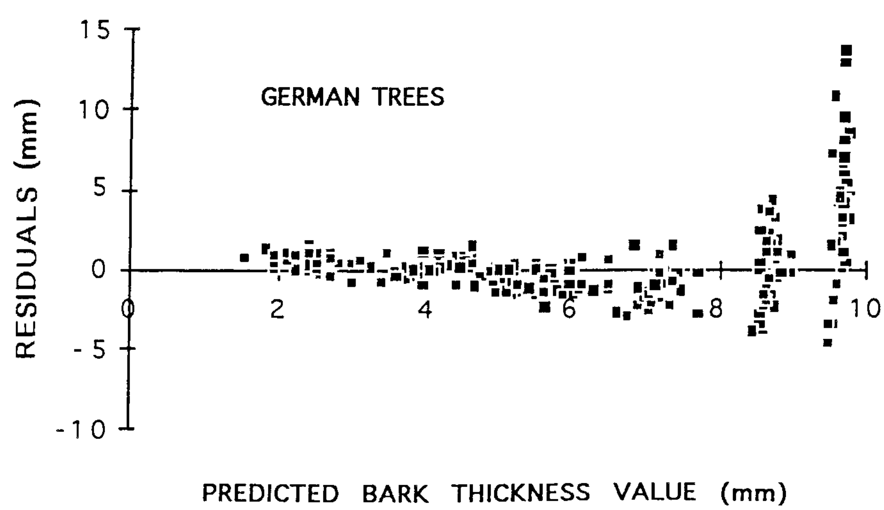


Figure 21. - *Distribution of bark thickness residues for German Douglas fir country model.*

3.4.3.2. In Italy

a. Regression analysis

$$THICK = +2.660 - 0.259\ HEIGHT + 0.001\ GIRTH2 + 0.01\ HEIGHT2$$

$R^2 = 0.80$ $S = 0.86$ $N = 240$

b. Analysis of residues

There is no significant effect of the variables.

In figure 22 which illustrates the distribution of residues, no bias is observed as for the German Douglas fir because the bark remains below a predicted thickness of 8 mm corresponding to younger trees (Italian trees: 27 years old; German trees: 39 years old). In Germany, the bias is obvious when the predicted bark thickness exceeds 8 mm.

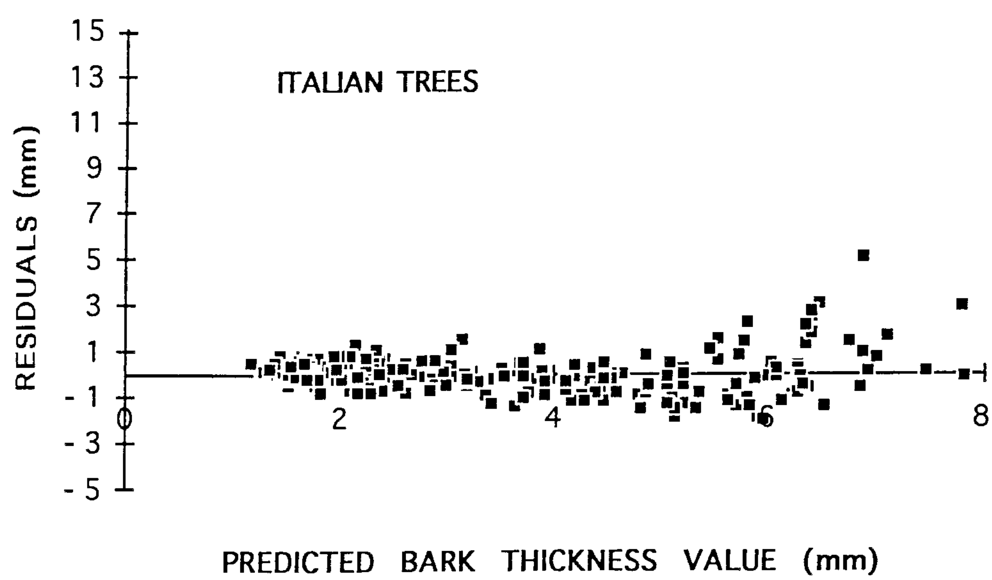


Figure 22. - *Distribution of bark thickness residues for Italian Douglas fir country model.*

3.4.3.3. Conclusion

The "***country models***" instead of a general model only give rise to a best prediction of bark thickness for the Italian Douglas fir. That means that a linear model is convenient for the Italian sampling, while in Germany a non linear model could improve the prediction (cf.Chap.4 § 3.7). The same conclusions may be infered from the evolution of the standard deviations. The standard deviation for the general model is equal to 1.85 mm whilst for the country models the standard deviation is equivalent to 0.86 mm for Italian trees but increases up to 2.4 mm for German trees.

3.5. Common models

By common model it must be understood a **model per species** including the **same combination of independent variables** for each country. Only the coefficients of the regression equation are varying from one country to another for the same species. This procedure is followed in view to get a modelling homogeneity for each species in taking care of differences between countries.

The choice of variables is based on the residual variance calculation of the five best models in each country. By best models it must be understood the models having the lowest residual variance. The five best models selected by this method for one country are applied to the others with the calculation of the corresponding residual variance.

Thus, if a species is present in three countries, a maximum of 15 models are selected with their corresponding residual variance in each country. From this listing, the best model is selected according to its lowest mean residual variance calculated for the three countries (see Annex 3).

3.5.1. Norway spruce

3.5.1.1. In Belgium

a. Regression equation

THICK = + 2.063 + 0.050 GIRTH - 0.034 AGE + 0.003 HEIGHT2

$R^2 = 0.74$ $S = 0.56$ $N = 365$

b. Analysis of residues

The variables "*Stand*" (F_{obs} = 53.2 *** (DF = 3)), "*Social position*" (F_{obs} = 6.4 ** (DF = 2)) and the interaction "*Stand x Social position*" (F_{obs} = 17.9 *** (DF = 6) are acting significantly on the model.

Table 24 summarizes the complete results of the variance analysis of residues. The illustration of the distribution of these last ones is given in figure 23.

Table 24. - *Variance analysis of residues for Belgian Norway spruce common model.*

Mean residues (mm)	Number of observations N	Variable "*STAND*"	Group
0.3613	44	Solwaster (S)	A
0.1275	136	Dohan (D)	B
-0.0204	142	Wellin (W)	C
-0.7055	43	Ternell (T)	D

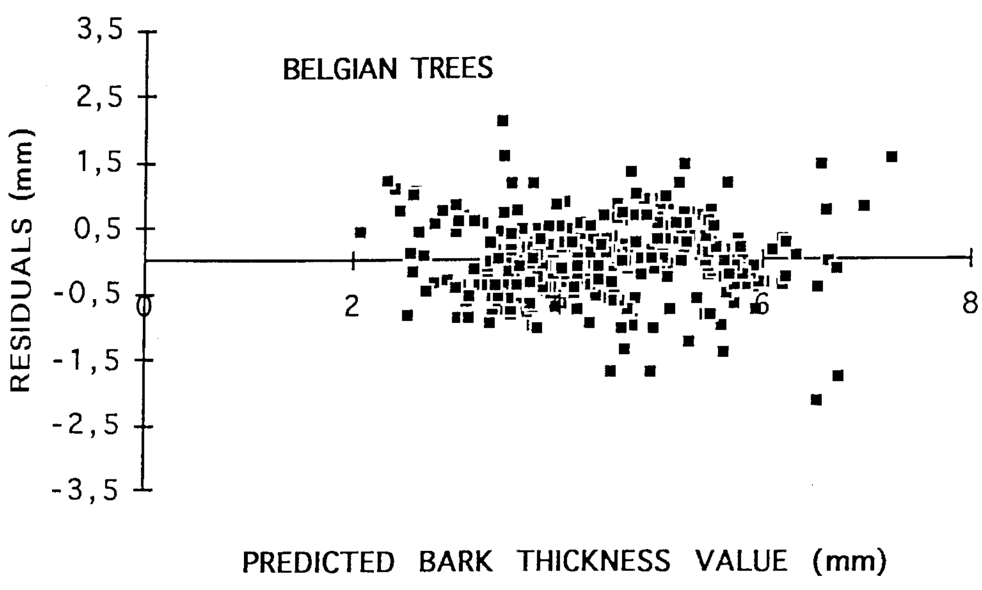


Figure 23. - *Distribution of bark thickness residues for Belgian Norway spruce common model.*

b. Analysis of residues

The variables "*Stand*" (F_{obs} = 53.2 *** (DF = 3)), "*Social position*" (F_{obs} = 6.4 ** (DF = 2)) and the interaction "*Stand x Social position*" (F_{obs} = 17.9 *** (DF = 6) are acting significantly on the model.

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-0.7055	43	Ternell (T)	D

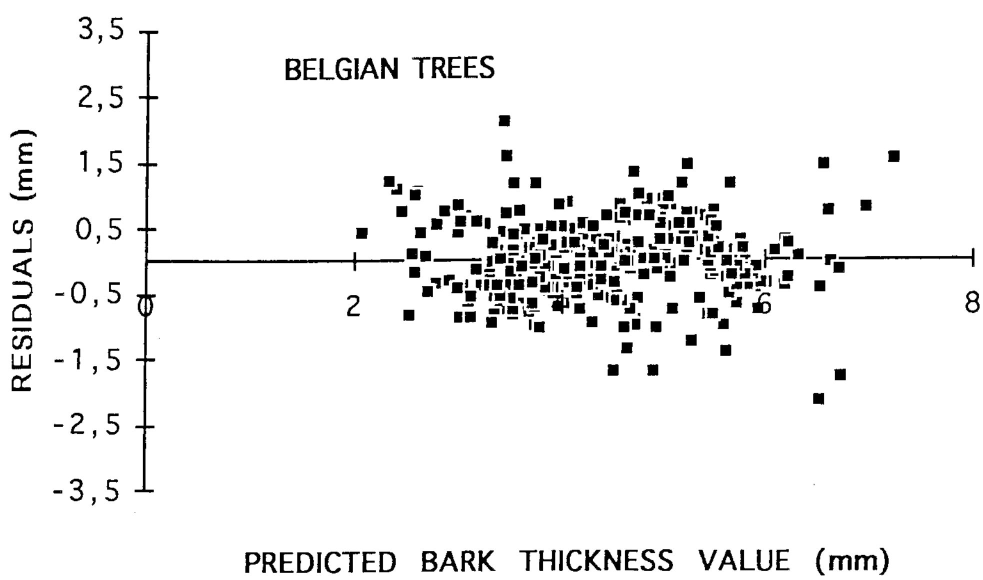


Figure 23. - *Distribution of bark thickness residues for Belgian Norway spruce common model.*

3.5.1.2. In France

a. Regression equation

$$\textbf{THICK} = +\ 3.267 + 0.046\ \textbf{GIRTH} - 0.031\ \textbf{AGE} + 0.002\ \textbf{HEIGHT2}$$

$R^2 = 0.59$ $S = 0.55$ $N = 164$

b. Analysis of residuals

Only the interaction "*Stand x Social position*" has a significant effect ($F_{obs} = 7.1$ *** (DF = 6)) on the model. Figure 24 shows the distribution of the residuals calculated from the model.

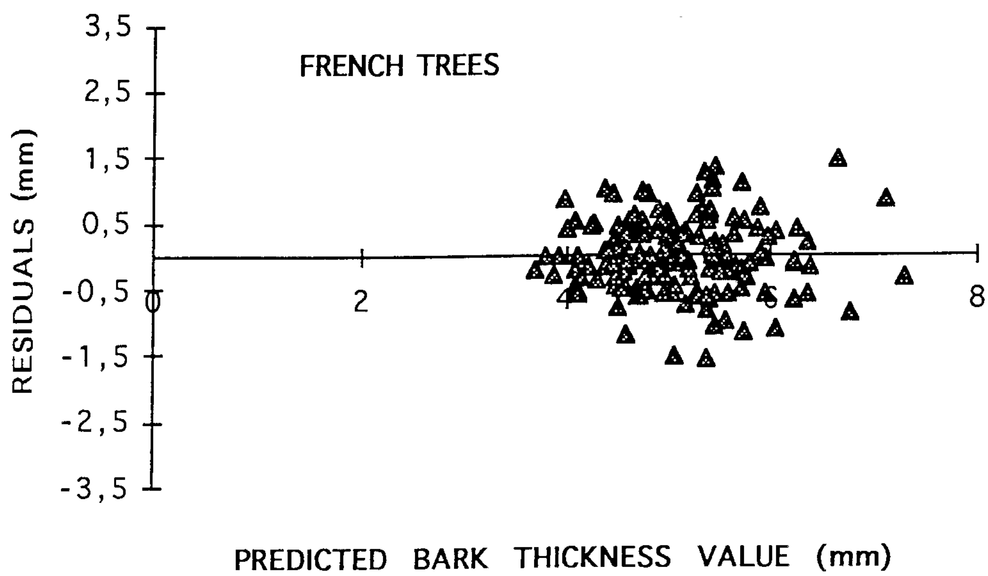


Figure 24. - *Distribution of bark thickness residues for French Norway spruce common model.*

3.5.1.3. In Denmark

a. Regression equation

$$\textbf{THICK = - 0.839 + 0.054 GIRTH - 0.038 AGE + 0.002 HEIGHT2}$$

$R^2 = 0.76$ $S = 0.70$ $N = 167$

b. Analysis of residuals

There is no significant effect of the variables on the model. Figure 25 gives an illustration of the distribution of residuals.

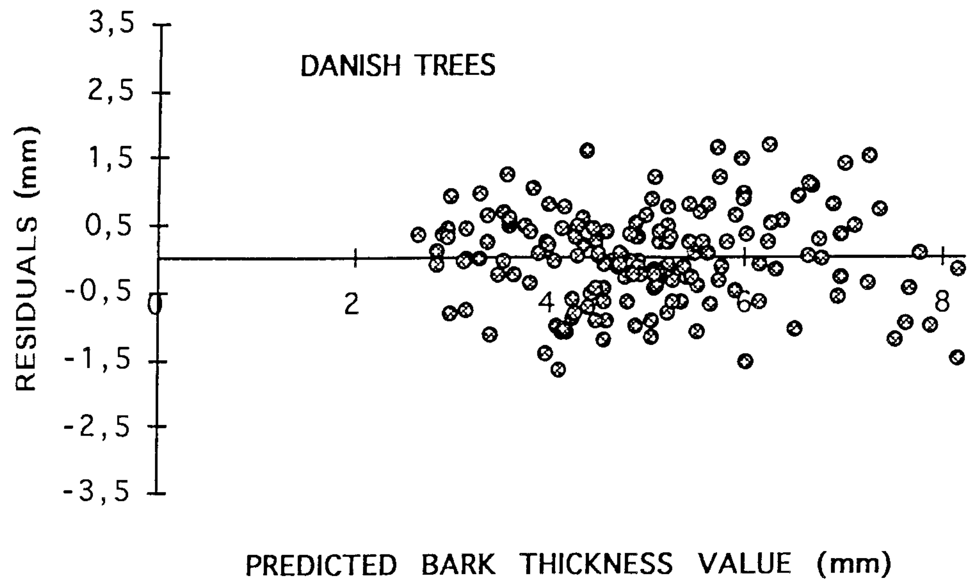


Figure 25. - *Distribution of bark thickness residues for Danish Norway spruce common model.*

3.5.1.4. Conclusion

For Norway spruce the fact to choose a common model for the three countries does not effect the prediction of bark thickness in comparison with the accuracy given by the country models (Chap. 4 § 3.4.1).

3.5.2. Sitka spruce

3.5.2.1. In Denmark

a. Regression equation

$$\text{THICK} = + 2.001 + 0.027\ \text{GIRTH} - 0.026\ \text{CBL} + 0.029\ \text{AGE}$$

$R^2 = 0.54$ $S = 0.76$ $N = 164$

b. Analysis of residues

The variable "*Stand*" (F_{obs} = 11.8 *** (DF = 3)) and the interaction "*Stand x Social position*" (F_{obs} = 2.5 * (DF = 6)) affect significantly the model.

Table 25 gives the results of the variance analysis of residuals and figure 26 shows the distribution of residuals.

Table 25. - *Variance analysis of residues for Danish Sitka spruce common model.*

Mean residues (mm)	Number of observations N	Variable "*STAND*"	Group
+0.3310	41	FE	A
+0.2093	42	FR	A B
-0.0799	39	LH	B
-0.4583	42	UG	C

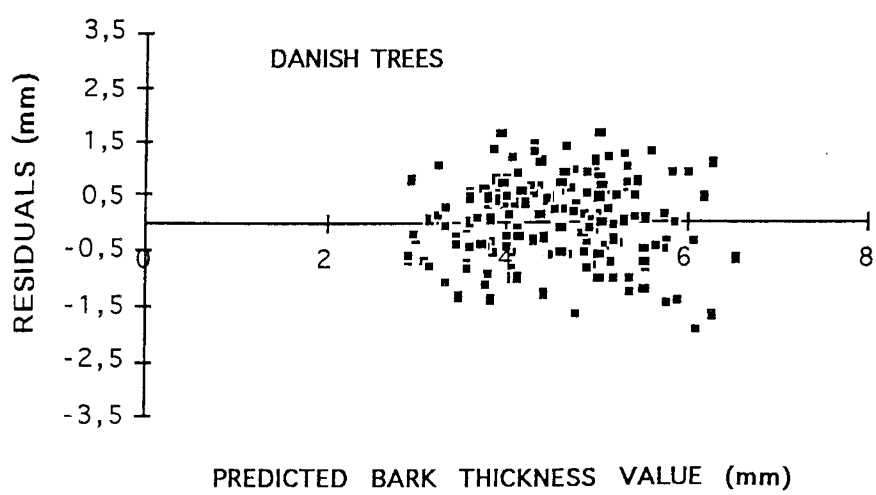


Figure 26. - *Distribution of bark thickness residues for Danish Sitka spruce common model.*

3.5.2.2. In Great Britain

a. Regression equation

$$\mathbf{THICK = + 2.944 + 0.032\ GIRTH - 0.208\ CBL + 0.038\ AGE}$$

$R^2 = 0.61$ $S = 0.63$ $N = 155$

b. Analysis of residues

Only the interaction *"Stand x Social position"* ($F_{obs} = 6.3$ *** (DF = 6)) affects significantly the model. Figure 27 illustrates the distribution of residuals.

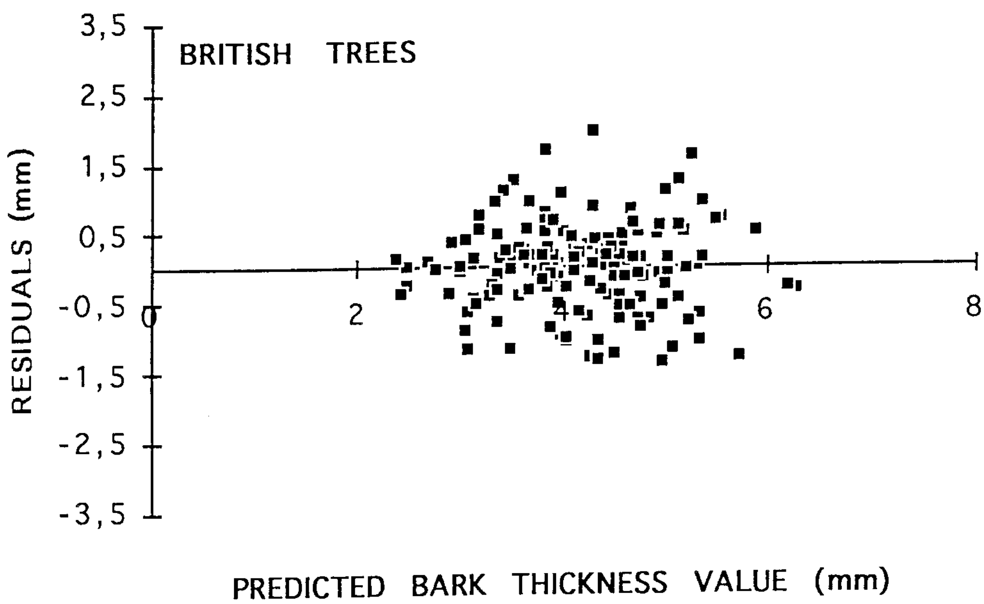


Figure 27. - *Distribution of bark thickness residues for British Sitka spruce common model.*

3.5.2.3. Conclusion

The prediction of bark thickness is as accurate with a common model as with a country model for Sitka spruce.

3.5.3. Douglas fir

3.5.3.1. In Germany

a. Regression equation

$$THICK = + 4.966 - 0.780\ HEIGHT + 0.015\ HEIGHT2 + 0.012\ HT2$$

$R^2 = 0.68$ $S = 2.42$ $N = 174$

b. Analysis of residuals

There is no significant effect of the variables on the model. Figure 28 shows the distribution of residuals with an evident bias previously explained (Chap. 4 § 3.3.3).

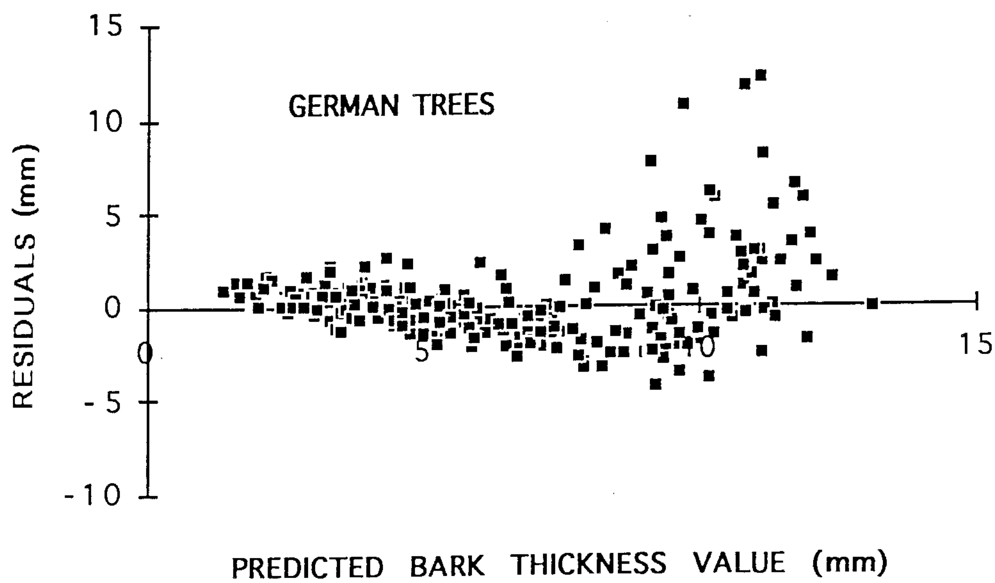


Figure 28. - *Distribution of bark thickness residues for German Douglas fir common model.*

3.5.3.2. In Italy

a. Regression equation

$$THICK = + 5.629 - 0.523\ HEIGHT + 0.013\ HEIGHT2 + 0.003\ HT2$$

$R^2 = 0.76$ $S = 0.95$ $N = 240$

b. Analysis of residues

There is no significant effect of the variables on the model. Figure 29 illustrates the distribution of residues and shows an increasing of residual variability when the predicted bark thickness becomes higher than 5 mm.

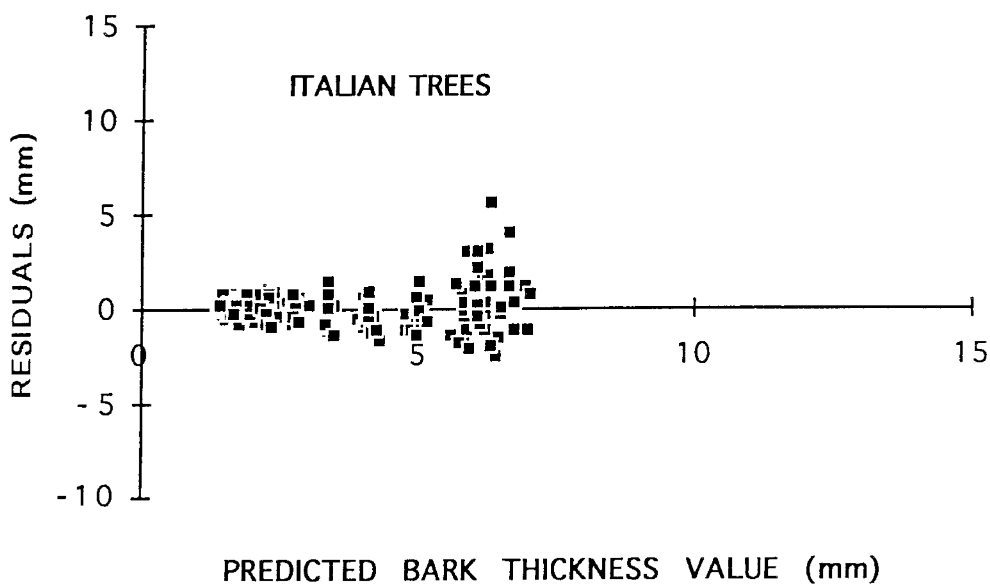


Figure 29. - *Distribution of bark thickness residues for Italian Douglas fir common model.*

3.5.3.3. Conclusion

The prediction of Douglas fir bark thickness is as accurate when using a common model as when using a country model.

3.6. Summary of the linear models

Table 26 gives for each species and for each category of models the best combination of variables with the associated accuracy.

Table 26. - *Summary of the linear models for predicting bark thickness.*

SPECIES	*GENERAL MODEL*	*COUNTRY MODEL*	*COMMON MODEL*
Norway spruce	AGE - HT2 - HR $R^2 = 0.53$	GIRTH - AGE - HT2 (Belgium) $R^2 = 0.74$ GIRTH - AGE - HEIGHT2 (France) $R^2 = 0.59$ GIRTH - AGE - GIRTH2 (Denmark) $R^2 = 0.78$	GIRTH - AGE - HEIGHT2 (Belgium) $R^2 = 0.74$ (France) $R^2 = 0.59$ (Denmark) $R^2 = 0.76$
Sitka spruce	GIRTH13 - AGE - HR $R^2 = 0.54$	GIRTH - AGE - GIRTH2 (Denmark) $R^2 = 0.56$ HEIGHT - GIRTH13 - AGE (Great Britain) $R^2 = 0.58$	GIRTH - CBL - AGE (Denmark) $R^2 = 0.54$ (Great Britain) $R^2 = 0.61$
Douglas fir	AGE - GIRTH2 - GIRTHR $R^2 = 0.74$	AGE - HR - GIRTHR (Germany) $R^2 = 0.68$ HEIGHT - GIRTH2 - HEIGHT2 (Italy) $R^2 = 0.80$	HEIGHT - HEIGHT2 - HT2 (Germany) $R^2 = 0.68$ (Italy) $R^2 = 076$

It appears that the choice of a common model per species (based upon the same independent variables for each country) only leads to a very slight decrease of accuracy of bark thickness estimation with a very slight increase of the standard deviation. The final choice between a common model or a country model is mainly depending on minima needs of "*SIMQUA*" software.

3.7. Non linear model for Douglas fir

Referring to the distribution of Douglas fir bark thickness in Germany in connection with the girth at the measured level (figure 15) and to the analysis of residuals calculated by linear models which show an important bias for bark thickness predicted beyond 5 mm, it seems desirable to experiment a non linear model.

This particular study has been made by Prof. BECKER Team (Team 4 - Subtask 6.1) and the whole document written by Team 4 is reproduced in Annex 2. In the following section, we just present a summary dealing with a general model and a common model.

The general principle adopted for setting up a non linear model is referring to the GOMPERTZ function which is often used for describing natural growth processes.

$$y = b * e^{-c * a^{n}}$$

For improving the model, a linear function for the variable "*GIRTH*" (Girth at the measured level) and a square function for the variable "*HR*" (Relative height) were added for integrating tree shape, height and footing effect.

3.7.1. General non linear model

a. Regression equation

$$\mathbf{THICK} = +3 * e^{-5.447 * 0.987^{\mathbf{GIRTH}}} + \frac{\mathbf{7.502}}{\mathbf{HR^2}} + \mathbf{0.13}$$

$R^2 = 0.76$ S = 1,93 N = 414

b. Analysis of residues

The residues analysis points out a significant effect of the variable "*Country*" (F_{obs} = 15*** (DF = 2)) on the model. Table 27 gives the results of the variance analysis of residues.

Table 27. - *Variance analysis of residues for Douglas fir general non linear model.*

Mean residues (mm)	Number of observations N	Variable "*COUNTRY*"	Group
0.134	174	GERMANY	A
-0.085	240	ITALY	B

Compared with the general linear model for Douglas fir (table 17), the non linear model slightly improves the prediction of bark thickness considering the residues decrease. The distribution of residues presented in figure 30 shows that a bias is still remaining for the German trees when predicted bark thickness exceeds 5 mm.

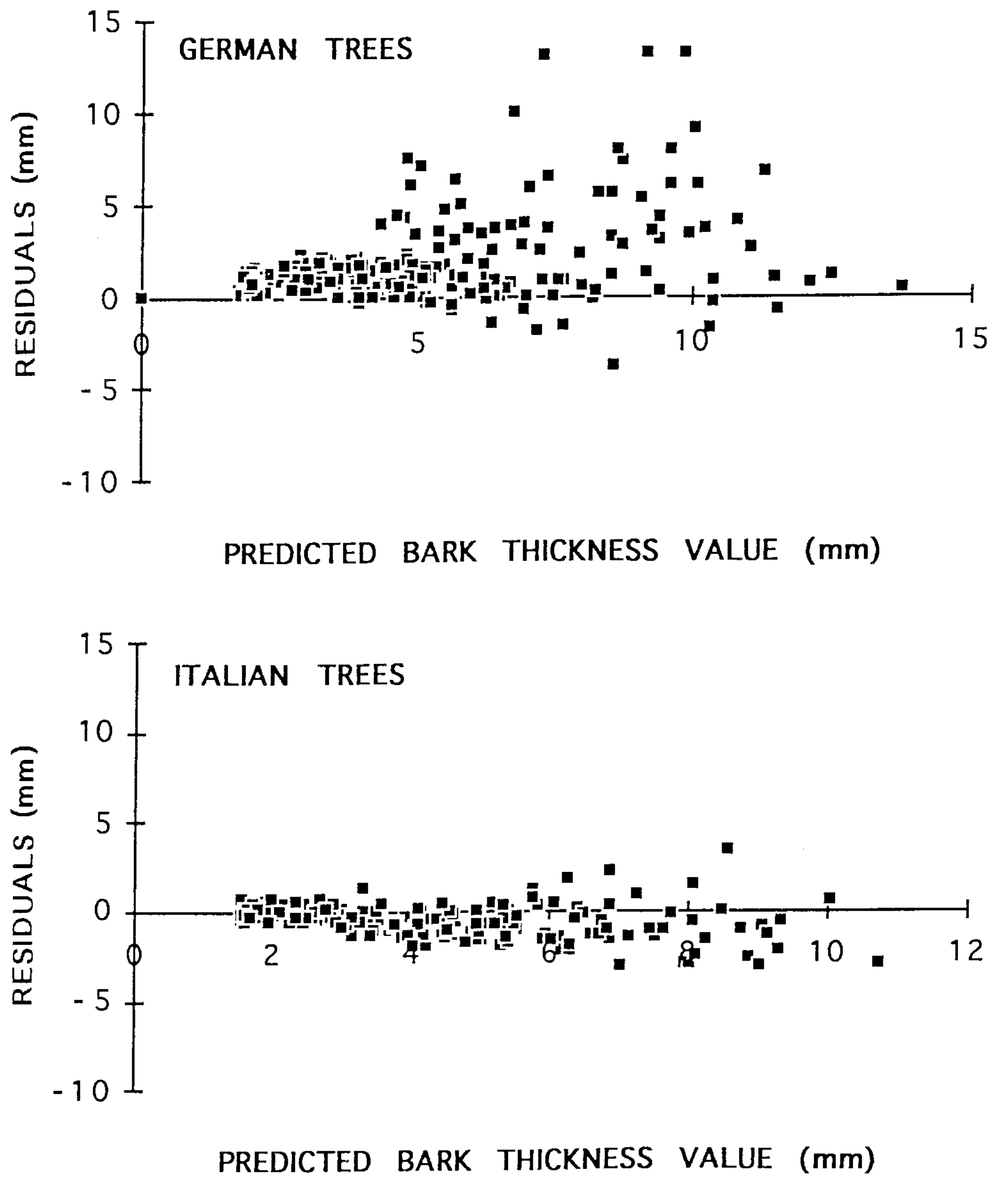


Figure 30. - *Distribution of bark thickness residuals for Douglas fir general non linear model.*

3.7.2 Common non linear model

The common non linear model build up for each country is given hereafter:

- in ***Germany***

$$\mathbf{THICK = (+ 3 * e^{- 4.023 * 0.990^{GIRTH}} + \frac{10.809}{HR^2} + 0.13)}$$

$R^2 = 0.78$ S = 1,86 N = 174

- in ***Italy***

$$\mathbf{THICK = (+ 3 * e^{- 5.685 * 0.988^{GIRTH}} + \frac{5.895}{HR^2} + 0.13)}$$

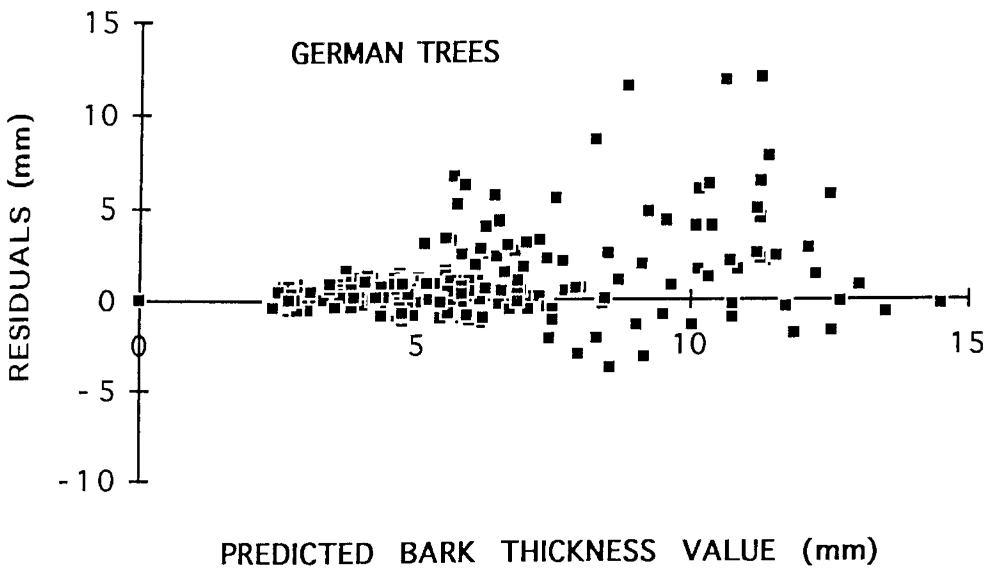
$R^2 = 0.84$ S = 1,13 N = 240

Referring to the common linear model (Chap.4 § 3.5.3), the common non linear model notably improves the prediction of bark thickness as well in Germany as in Italy. Compared with the general non linear model (Chap.4 § 3.7.1), the common non linear model is only perceptibly improving the prediction of bark thickness for Italian Douglas fir (figures 31).

3.7.3. Conclusion

As already observed from the German Douglas fir linear models, the non linear models let always appear a bias. The non linear models tend to under-estimate in Germany the bark thickness in the bottom part of the tree.

Nevertheless, the non linear models, and more particularly the common ones, are more accurate for predicting bark thickness of Douglas fir than the linear models.



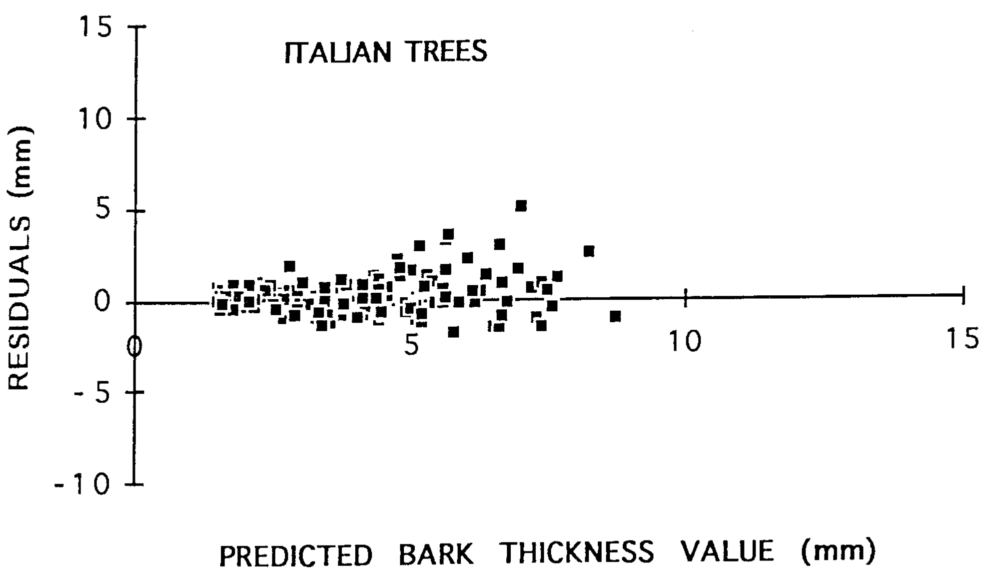


Figure 31. - *Distribution of residuals for Douglas fir non linear common model.*

4. Bark volume evolution

4.1. Effect of the Social position in the stand

Figure 32 presents the evolution of bark volume according to the Social position in the stand for each species and each country. Each stick represents the mean value of 8 trees.

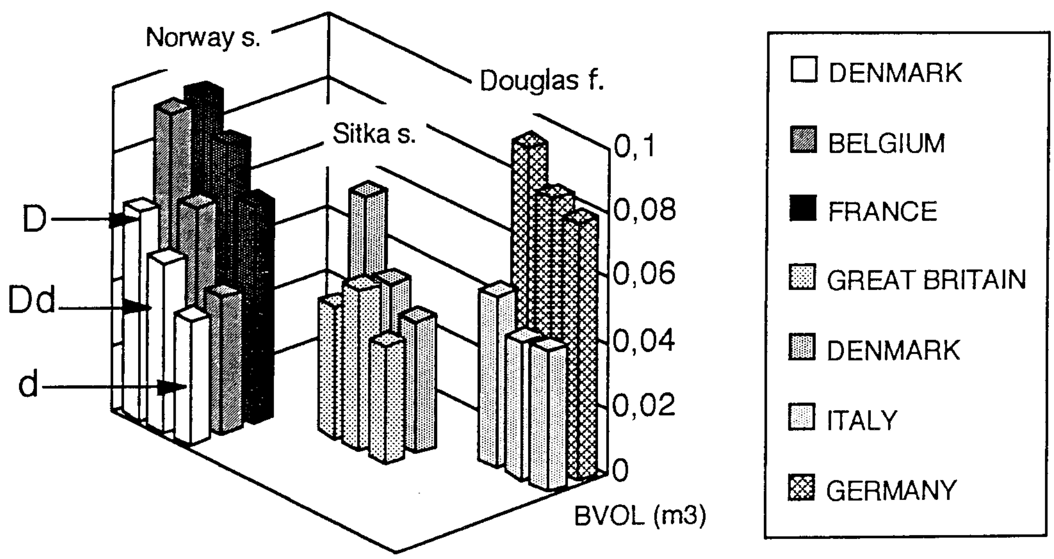


Figure 32. - *Bark volume by species, country and Social position.*

For the three species, bark volume is decreasing at least significantly from dominant trees to suppressed trees (Norway spruce: F_{obs} = 32,5*** (DF = 2); Sitka spruce: F_{obs} = 14,5 *** (DF = 2); Douglas fir: F_{obs} = 4,0 * (DF = 2)).

The relative bark volume "***RBTREE***" which gives an information about the production of bark compared to the total production of the stem (wood + bark) is illustrated per Social position for each species and each country in figure 33.

Broadly speaking, there is no significant effect of the Social position on the relative bark volume which means that the bark proportion seems to be independent of the Social position of the tree in the stand and thus of the tree girth, at least within the framework of the present sampling (dbh range: 30-35 cm).

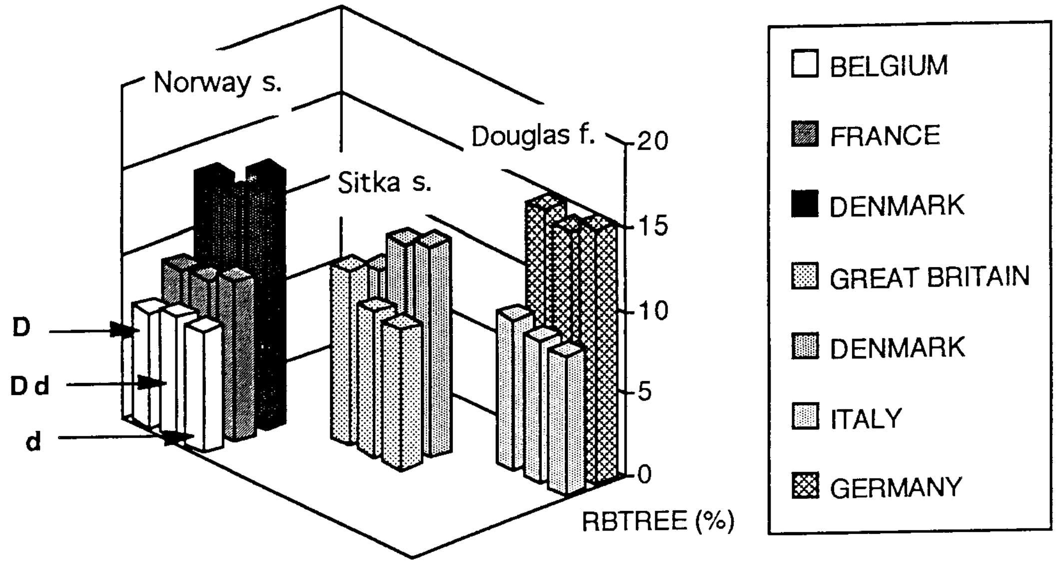


Figure 33.- *Relative bark volume by species, country and Social position.*

4.2 Effect of site productivity

Figure 34 illustrates the connection between bark volume and the site productivity for each species and each country. Each stick is corresponding to the mean value of 12 trees.

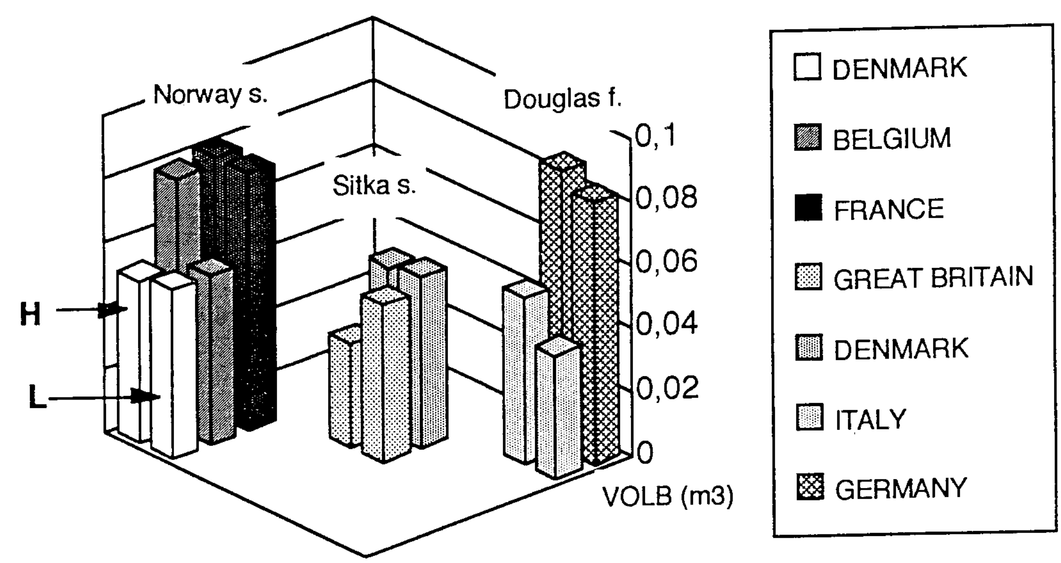


Figure 34.- *Bark volume by species, country and productivity.*

The site productivity class only influences significantly the bark volume of Norway spruce (F_{obs} = 5,3 * (DF = 1)) and Sitka spruce (F_{obs} = 6,3 * (DF = 1)). However, it must be noted that the significant effect observed for Norway spruce is due to the weight of Belgian trees in the statistical analysis. As the trends are not the same for both species, it may be concluded that the bark volume of the three species is relatively independent of the site productivity class.

Figure 35 shows the evolution of the relative bark volume according to the site productivity class for each species and each country.

The statistical analysis reveals at least a significant effect of the site productivity class on the relative bark volume of Norway spruce ((F_{obs} = 16,7 *** (DF = 1)) and Douglas fir (F_{obs} = 5,6 * (DF = 1)). Nevertheless, the proportion of bark compared to the total tree volume does not seem to be strongly linked with the site productivity.

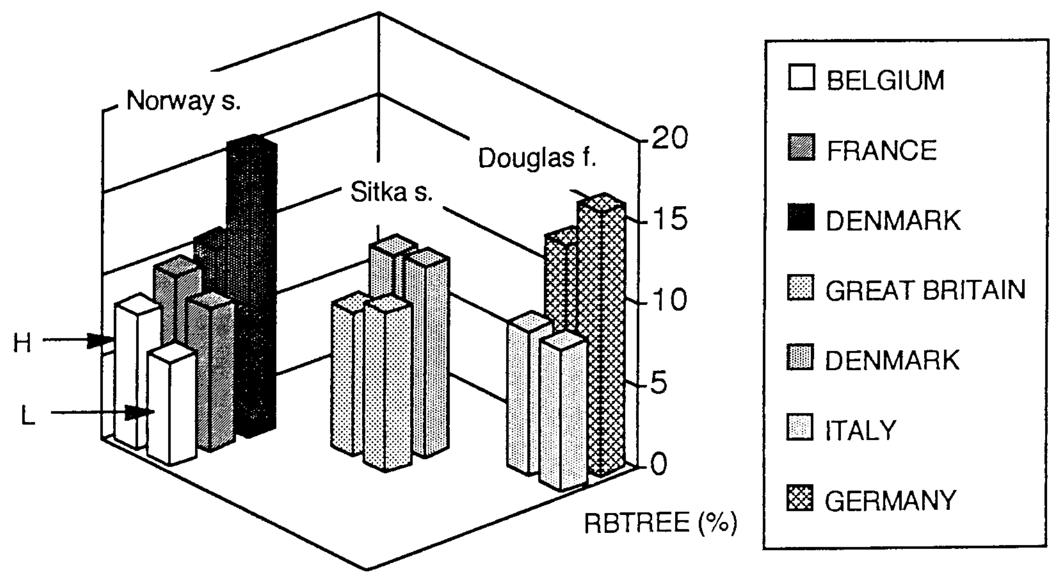


Figure 35.- *Relative bark volume by species, country and productivity.*

4.3. Effect of thinning intensity

Figure 36 shows the distribution of bark volume according to the thinning intensity for each species and each country. Each stick represents the mean value of 12 trees.

The statistical analysis points out at least a significant effect of thinning intensity on bark volume for the three species (Norway spruce: F_{obs} = 6,6 * (DF = 1); Sitka spruce : F_{obs} = 26,2 *** (DF = 1); Douglas fir: F_{obs} = 21,5 *** (DF = 1)). The bark volume of the three species becomes bigger when the thinning intensity is increasing.

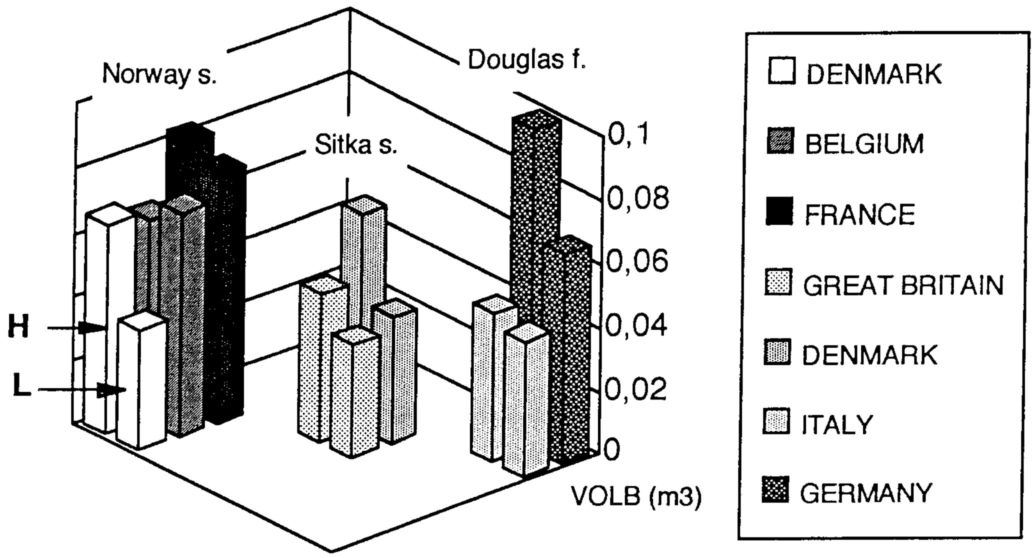


Figure 36. - *Bark volume by species, country and thinning intensity.*

In addition, the bark proportion (figure 37) is only significantly higher for Norway spruce (F_{obs} = 16,6 *** (DF = 1)) and Sitka spruce (F_{obs} = 12,4 ** (DF = 1) when the thinning intensity is lowering.

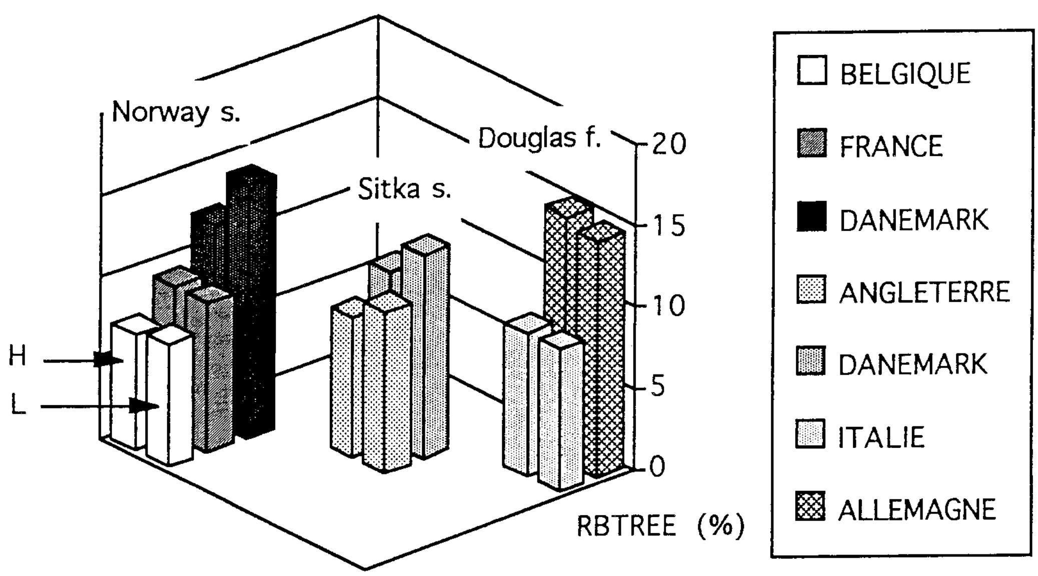


Figure 37.- *Relative bark volume by species, country and thinning intensity.*

4.4. Effect of the country

For the three species, the *"country"* influences significantly as well the bark volume (Norway spruce: F_{obs} = 24,6 *** (DF = 2); Sitka spruce: F_{obs} = 8,9 ** (DF = 1); Douglas fir: F_{obs} = 86,5 *** (DF = 1)) as the bark proportion (Norway spruce: F_{obs} = 165,4 *** (DF = 2), Sitka spruce: F_{obs} = 23,5 *** (DF = 1); Douglas fir: F_{obs} = 83,5 *** (DF = 1)).

For Norway spruce, the bark volume is lower in the Danish trees (Table 11) than in the Belgian trees and above all in the French trees, but the proportion of bark is the highest in Denmark, being two times bigger than in Belgium (Table 14), due to tree age.

For Sitka spruce, the bark volume and the proportion of bark are slightly higher in Denmark than in Great Britain.

For Douglas fir, the bark volume and the proportion of bark are almost two times higher in Germany than in Italy, due to large age differences between trees.

4.5. Conclusion

If the bark volume of the three species is varying in different ways according to the growing conditions (stable with the site productivity, increasing with high thinning intensity, lowering from dominant to suppressed trees), the proportion of bark is always increasing when the growing conditions become worse.

5. Bark volume modelling

The procedure followed for modelling bark volume is the same as that used for bark thickness (Chap.4 § 3.1). Only general models have been investigated according to the level of accuracy achieved.

5.1. Main variables taken into account for bark volume modelling

Two different dependent variables are used for the definition of bark volume:

- The net bark volume	**BVOL**
- The relative bark volume	**RBTREE**

For both dependent variables, the following independent variables were used:

- Total height of the tree	**HT**
- Girth at breast height	**GIRTH13**
- Living crown base level	**CBL**
- Girth at the living crown base level	**GIRTHCB**
- Total age of the tree	**AGE**
- Square total height of the tree	**HT2**
- Girth at breast height times total height	**GIRTHT**

5.2. General models

The general models are separated by species for each dependent variable. According to the limited number of observations, the models have been voluntarily restricted to two variables.

5.2.1. Norway spruce

The following models were selected:

BVOL = - 0,030 + 0,0003 AGE + 0,00003 GIRTHT

R2 = 0,78 S = 0,01 N = 72

RBTREE = + 12,227 - 0,089 GIRTH13 + 0,098 AGE

R2 = 0,69 S = 2,18 N = 72

5.2.2. Sitka spruce

BVOL = - 0,023 + 0,0003 AGE + 0,00003 GIRTH T

R2 = 0.90 S= 0,01 N = 48

RBTREE = + 14,166 - 0,088 GIRTH13 + 0,068 AGE

R2 = 0.53 S= 1,63 N = 48

5.2.3. Douglas fir

BVOL = - 0,135 + 0,001 GIRTH13 + 0,002 AGE

R2 = 0.87 S= 0,01 N = 66

RBTREE = + 1,044 + 0,484 AGE - 0,009 HT2

R2 = 0.62 S= 2,57 N = 66

5.2.4. Conclusion

The prediction gained by the general model is far better for bark volume than for the proportion of bark. In this last case, investigations on models by country could provide higher predictive values. Anyway, it is interesting to observe the great similarity between the bark volume models achieved for Norway spruce and Sitka spruce. The bark volume models selected make use of independent variables easily measurable on the field.

CONCLUSIONS

The study of bark thickness evolution made on 186 trees belonging to three different softwood species (Norway spruce, Sitka spruce and Douglas fir) collected through six European countries (Belgium, Denmark, France, Germany, Great Britain and Italy) has first shown that, at a given height level in a tree, bark thickness is relatively constant according to the orientation.

On an other hand, all along the stem, bark thickness is evolving according to a particular profile characterized by a steep decrease from the bottom up to a given height variable from species to species, due to a bottom effect, then being relatively constant up to the living crown base level and finally decreasing slightly in the living crown part. The most important bottom effect has been observed on Douglas fir for which a non linear model will be required.

A variance components analysis has shown that bark thickness variability is mainly due to the tree itself and the stand factor which globalized the cumulated effect of thinning intensity and site productivity. However, it appears that the trees selected by couple for each Social position in each stand are similar whatever the species could be, and may be considered, in fact, as true replicates.

For each species, the Social position of the tree in the stand influences in the same way bark thickness. In all cases, dominant trees have indeed the thickest bark, whilst suppressed trees are always characterized by the thinnest bark and co-dominant trees range to this respect in an intermediate position.

Broadly speaking, the effect of site productivity is not clear through this sampling, due to interferences of different factors, mainly the differences in tree age which let appear a significant effect of the country. Nevertheless, when tree age is almost the same in different countries, the general trends are going in the direction of a decrease of bark thickness when the site productivity becomes lower.

The same general trends are observed in connection with the thinning intensity because bark thickness generally decreases when thinnings are less intense.

In fact, bark thickness is far to be constant according to the stand selection criteria (site productivity, thinning intensity) but is noticeably affected by the tree selection criteria (Social position).

The search for a general model for bark thickness was revealed to be useless according to the accuracy gained. This is mainly due to a large effect of the country. Therefore, the common linear models appeared to be the best effective for a good description of bark thickness evolution, excepted for Douglas fir which is described in a better manner by using a common non linear model.

When selecting an one variable model, it is interesting to point out that always girth is the best explicative factor, clearly indicating that bark thickness is above all linked with tree growing in diameter.

Concerning bark volume, this parameter is significantly affected by the Social position of the tree in the stand, whatever the species could be, seing that bark volume is decreasing from dominant trees to suppressed trees. If bark volume is clearly linked with the Social position, the percentage of bark with regards to timber volume is independent of the Social position, in the case of the present sampling.

Site productivity does not seem to influence bark volume of the three species, but the percentage of bark compared to timber volume becomes higher on low productivity sites.

On an other hand, bark volume is increasing when thinnings are more intense and these trends observed for the three species are quite opposite regarding the proportion of bark. This last parameter is always increasing when the growing conditions become worse.

The prediction of bark volume gained by general models is far better than for the proportion of bark. In this last case, it would have been more interesting for improving the prediction to consider probably models established country by country.

In this context, it seems important to note that the models gained for bark thickness and bark volume are valid for the present sampling. It would be careless to generalize the species models without any further extension of the present sampling in view of a better control of some parameters through the different countries involved in this research.

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LIST OF ABBREVIATIONS

B	Belgium
CBL	Height of the crown base level
d	Suppressed tree
D	Dominant
dbh	Diameter at breast height
Dd	Codominant
DF	Douglas fir
DIAM/I/B	Diameter inside bark
DIAM/O/B	Diameter outside bark
DK	Denmark
DF	Degrees of freedom
F	France
F_{obs}	Observed variable F of Snedecor
G	Germany
GB	Great Britain
GIRTH13	Girth at 1.3 m
GIRTH2	Girth square
GIRTHCB	Girth at the crown base level
GIRTHR	Girth at 1.3 m x relative height
H	High
HEIGHT2	Height square
HT	Total height of the tree
HT2	Total height square
HR	Relative height
I	Italy
L	Low
M	Meter
M^3	Cubic meter
min	Minimun

max	Maximun
mm	Millimeter
N	Number of observations
NLIN	Non linear
n^r	Number
NS	Norway spruce
OBS	Observation number
π	Pi value
Pr	F Snedecor variable probability
PRODUCT	Productivity
R	Radius
R^2	Correlation coefficient
RBTREE	Relative bark volume (in proportion of the tree volume)
RBWOOD	Relative bark volume (in proportion of the wood volume)
S	Standard deviation
SAS	Software System for data Analysis
SS	Sitka spruce
SURF/I/B	Surface inside bark
SURF/O/B	Surface outside bark
THICK	Bark thickness
THIN	Thinning
VOLB	Bark volume
VOL/I/B	Volume inside bark
VOL/O/B	Volume outside bark
^	Exponent

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ANNEX 1

Stand and tree data

Table 28 - *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	56

Table 29. - *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

Table 30. - *Stand description of Norway spruce sampled in France.*

STAND	1	2	3	4
Site index (m)				
Productivity	high	high	low	low
Basal area(m^2/ha)	36.3	54.3	41.4	45.5
Number of trees (/ha)	435	1105	410	480
Thinning	high	low	high	low
Mean dbh of the biggest 300 trees / ha (cm)	34.7	32.4	40.1	39.1
Age	53	53	63	63

Table 31. - *Tree description of Norway spruce sampled in France.*

STAND	TREE	SOCIAL POSITION	AGE (year)	GIRTH13 (cm)	GIRTHCB (cm)	HT (m)	CBL (m)
1	17	D	53	119.4	69.9	27.25	15.3
1	30	D	53	119.4	76.7	28.24	13.5
1	39	Dd	53	99.0	59.7	26.67	15.3
1	53	Dd	53	106.8	61.0	27.70	16.7
1	57	d	53	83.2	49.3	26.06	14.8
1	78	d	53	86.4	58.0	25.48	13.8
2	72	Dd	53	97.4	56.0	29.13	18.6
2	88	d	53	89.5	41.9	28.79	21.1
2	94	Dd	53	94.3	46.1	29.10	20.3
2	124	D	53	106.8	56.0	28.56	18.3
2	170	d	53	83.3	41.4	28.20	18.4
2	201	D	53	103.7	57.4	28.84	18.1
3	65	d	63	94.3	68.3	25.05	10.0
3	209	D	63	142.9	75.7	25.24	11.3
3	400	d	63	102.1	53.8	25.30	16.2
3	407	Dd	63	110.0	61.0	24.74	14.2
3	459	D	63	136.7	66.4	27.80	16.7
3	798	Dd	63	119.4	65.1	27.30	16.4
4	128	Dd	63	103.7	52.4	23.70	13.7
4	232	d	63	100.5	57.7	26.26	15.2
4	472	Dd	63	108.4	61.3	27.07	17.0
4	602	D	63	119.4	64.0	26.05	14.0
4	654	d	63	99.0	61.0	25.93	14.6
4	716	D	63	119.4	68.8	26.07	14.9

Table 32. - *Stand description of Norway spruce sampled in Denmark.*

STAND	GL	IS	KM	RU
Site index (m)				
Productivity	low	low	high	high
Basal area(m^2/ha)				
Number of trees (/ha)				
Thinning	low	high	high	low
Mean dbh of the biggest 300 trees / ha (cm)				
Age	102	99	50	55

Table 33. - *Tree description of Norway spruce sampled in Denmark.*

STAND	TREE	SOCIAL POSITION	AGE (year)	GIRTH13 (cm)	GIRTHCB (cm)	HT (m)	CBL (m)
GL	1	d	102	41.2	278	15.1	10
GL	2	D	102	46.3	28.3	17.9	12
GL	3	D	102	60.1	49.0	17.3	9
GL	4	Dd	102	58.8	36.8	16.7	11
GL	5	Dd	102	47.9	35.5	16.9	11
GL	6	d	102	38.9	23.9	15.2	12
IS	1	D	99	97.4	78.9	24.4	11
IS	2	Dd	99	87.9	70.4	22.1	11
IS	3	d	99	85.8	60.3	20.1	12
IS	4	d	99	78.2	49.6	20.2	13
IS	5	D	99	97.6	80.4	22.1	11
IS	6	Dd	99	80.9	58.1	21.2	12
KM	1	D	50	90.1	62.8	23.7	14
KM	2	Dd	50	101.6	69.1	22.8	11
KM	3	Dd	50	78.2	62.8	23.5	11
KM	4	Dd	50	92.1	66.0	22.9	12
KM	5	D	50	75.2	59.7	23.6	13
KM	6	d	50	72.4	53.4	21.3	12
RU	1	d	55	72.3	45.6	23.5	16
RU	2	Dd	55	60.3	27.0	23.7	20
RU	3	d	55	46.3	12.6	22.5	21
RU	4	D	55	91.3	61.6	28.4	17
RU	5	Dd	55	81.6	39.9	24.3	18
RU	6	D	55	84.3	53.4	25.4	16

Table 34. - *Stand description of Sitka spruce sampled in Great Britain.*

STAND	G1	G	H	H1
Site index (m)				
Productivity	high	high	low	low
Basal area(m^2/ha)	34.1	34.1	51.5	57.8
Number of trees (/ha)	710	612	700	1738
Thinning	low	high	high	low
Mean dbh of the biggest 300 trees / ha (cm)	29	31	36	29
Age	28	28	58	58

Table 35. - *Tree description of Sitka spruce sampled in Great Britain.*

STAND	TREE	SOCIAL POSITION	AGE (year)	GIRTH13 (cm)	GIRTHCB (cm)	HT (m)	CBL (m)
G1	A	d	28	84.8	56.5	18.40	9.58
G1	B	D	28	62.8	44.0	17.42	7.60
G1	C	D	28	69.1	53.4	18.11	8.00
G1	D	Dd	28	94.2	62.8	18.80	8.83
G1	E	d	28	75.4	44.0	17.79	11.00
G1	F	Dd	28	94.2	62.8	19.10	9.10
G	G	Dd	28	88.0	47.1	20.47	11.29
G	H	Dd	28	75.4	50.3	20.76	11.63
G	I	d	28	69.2	44.0	20.60	11.88
G	J	D	28	106.8	66.0	20.10	9.28
G	K	d	28	78.5	44.0	19.40	11.60
G	L	D	28	78.5	69.1	20.25	10.35
H	M	Dd	58	91.1	62.8	22.27	12.40
H	N	Dd	58	131.9	84.8	23.21	12.99
H	O	D	58	94.2	62.8	20.84	10.74
H	P	d	58	78.5	44.0	19.46	12.97
H	Q	D	58	84.8	53.4	21.61	11.01
H	R	d	58	110.0	59.7	23.00	14.63
H1	S	d	58	94.2	53.4	19.27	13.3
H1	T	D	58	78.5	53.4	19.2	10.63
h1	U	D	58	69.1	47.1	15.71	9.00
H1	V	d	58	78.5	37.7	19.00	12.65
H1	W	Dd	58	70.5	50.3	17.82	11.29
H1	X	Dd	58	78.7	44.0	20.58	12.95

Table 36. - *Stand description of Sitka spruce sampled in Denmark.*

STAND	FE	FR	LH	UG
Site index (m)				
Productivity	low	high	high	low
Basal area(m^2/ha)				
Number of trees (/ha)				
Thinning	low	high	low	high
Mean dbh of the biggest 300 trees / ha (cm)				
Age	61	58	34	64

Table 37. - *Tree description of Sitka spruce sampled in Denmark.*

STAND	TREE	SOCIAL POSITION	AGE (year)	GIRTH13 (cm)	GIRTHCB (cm)	HT (m)	CBL (m)
FE	1	d	61	71.6	48.1	19.6	12
FE	2	d	61	61.8	46.8	18.4	11
FE	3	D	61	90.3	62.2	23.0	13
FE	4	D	61	96.1	71.3	21.5	11
FE	5	Dd	61	59.7	45.8	19.8	12
FE	6	Dd	61	71.3	42.4	20.5	14
FR	1	D	58	97.5	57.2	31.2	21
FR	2	Ddd	58	80.3	44.0	27.2	19
FR	3	d	58	89.3	36.4	23.5	17
FR	4	Dd	58	107.0	81.7	27.5	13
FR	5	D	58	99.9	54.7	28.7	19
FR	6	d	58	72.1	41.5	25.5	17
LH	1	Dd	34	52.7	35.2	20.8	13
LH	2	D	34	66.6	50.3	22.4	13
LH	3	D	34	70.7	57.2	23.0	12
LH	4	Dd	34	50.7	44.9	21.8	13
LH	5	d	34	41.6	29.8	19.8	12
LH	6	Dd	34	43.7	32.7	21.5	14
UG	1	D	64	106.3	66.6	26.1	17
UG	2	D	64	114.9	80.7	25.5	15
UG	3	Dd	64	77.2	50.0	23.5	15
UG	4	Dd	64	79.9	42.7	24.2	18
UG	5	d	64	59.5	43.0	22.2	16
UG	6	d	64	59.6	33.9	21.3	15

Table 38. - *Stand description of Douglas fir sampled in Italy.*

STAND	1	2	3	4
Site index (m)	29.6	30.45	34.52	36.2
Productivity	low	low	high	high
Basal area(m^2/ha)	53.75	53.9	51.79	65.97
Number of trees (/ha)	1130	1417	792	1566
Thinning	high	low	high	low
Mean dbh of the biggest 300 trees / ha (cm)	29.6	29	33.3	31.2
Age	25	25	28	28

Table 39. - *Tree description of Douglas fir sampled in Italy.*

STAND	TREE	SOCIAL POSITION	AGE (year)	GIRTH13 (cm)	GIRTHCB (cm)	HT (m)	CBL (m)
1	1	D	25	88.9	57.5	22.0	9.2
1	2	Dd	25	82.0	51.0	21.5	11.0
1	3	d	25	81.1	39.4	18.0	12.0
1	4	Dd	25	81.7	52.0	21.0	10.4
1	5	d	25	85.7	57.2	21.2	11.0
1	6	D	25	82.0	53.1	23.5	11.5
2	1	d	25	79.2	43.1	21.5	12.8
2	2	D	25	88.0	48.9	22.3	11.2
2	3	Dd	25	92.0	42.4	21.5	12.0
2	4	Dd	25	80.1	47.4	19.7	8.7
2	5	D	25	88.9	47.8	22.6	11.5
2	6	d	25	75.1	43.0	20.3	11.5
3	1	D	28	92.0	47.7	27.0	15.6
3	2	D	28	109.0	49.6	27.5	15.6
3	3	d	28	93.9	46.2	25.5	15.0
3	4	Dd	28	99.9	52.9	25.0	14.9
3	5	Dd	28	92.0	46.0	24.0	13.15
3	6	d	28	93.0	48.1	24.0	13.2
4	1	Dd	28	81.1	45.4	25.5	14.8
4	2	D	28	101.8	46.2	24.8	13.6
4	3	d	28	88.9	48.4	24.8	15.6
4	4	Dd	28	92.0	44.1	25.0	15.2
4	5	d	28	76.0	39.1	23.2	14.6
4	6	D	28	88.9	48.0	27.3	16.5

Table 40. - *Stand description of Douglas fir sampled in Germany.*

STAND	A = Westerhof	B = Erdmannshausen	C = Lüß 93 a 2	D = Lüß 93 a 1
Site index (m)				
Productivity	high	high	low	low
Basal area(m^2/ha)	25	23.5	31.1	35.4
Number of trees (/ha)	628	365	588	770
Thinning	low	high	close spacing weakly thinned	wide spacing very weakly thinned
Mean dbh of the biggest 300 trees / ha (cm)	31	30.2	30.6	30.4
Age	33	42	41	41

Table 41. - *Tree description of Douglas fir sampled in Germany.*

STAND	TREE	SOCIAL POSITION	AGE (year)	GIRTH13 (cm)	GIRTHCB (cm)	HT (m)	CBL (m)
B	1	d	42	97.4	48.2	24.95	13.4
B	2	D	42	106.8	46.4	24.6	14.5
B	3	d	42	110.0	67.5	25.2	11.9
B	4	Dd	42	94.2	54.2	24.0	11.3
B	5	Dd	42	110.0	74.1	25.7	11.1
B	6	D	42	110.0	52.3	25.5	13.1
B	7	D	42	128.8	102.4	26.2	7.8
B	8	D	42	113.1	78.6	27.8	10.5
B	9	Dd	42	100.5	74.2	24.6	11.1
B	10	Dd	42	113.1	78.6	24.7	12.0
B	11	d	42	94.2	65.3	24.3	11.4
B	12	d	42	100.5	50.1	24.5	13.3
A	1	D	32	128.8	70.9	22.85	11.2
A	2	D	32	91.1	50.4	21.9	8.7
A	3	d	32	84.8	42.4	19.8	9.3
A	4	Dd	32	97.4	47.0	21.2	10.7
A	5	Dd	32	84.8	43.8	22.2	10.4
A	6	d	32	75.4	43.9	21.1	11.5

Table 41.(continued) - *Tree description of Douglas fir sampled in Germany.*

STAND	TREE	SOCIAL POSITION	AGE (year)	GIRTH13 (cm)	GIRTHCB (cm)	HT (m)	CBL (m)
C	1	D	40	106.8		24.0	10.2
C	2	Dd	40	100.5		23.7	12.4
C	3	d	40	103.6		23.9	9.5
C	4	Dd	40	94.2		26.1	10.6
C	5	D	40	116.2		25.6	12.6
C	6	d	40	91.1		24.4	12.7
C	7	D	40	97.3		23.1	12.0
C	8	Dd	40	100.5		22.6	11.4
C	9	d	40	94.2		25.8	11.0
C	10	D	40	110.0		22.9	9.0
C	11	d	40	100.5		24.5	13.6
C	12	Dd	40	94.2		26.7	11.3
D	1	D	40	84.8		23.5	11.0
D	2	d	40	84.8		20.8	10.0
D	3	D	40	106.8		26.0	13.4
D	4	D	40	88.0		22.0	12.6
D	5	Dd	40	94.2		23.8	11.7
D	6	Dd	40	88;0		24.1	11.2
D	7	Dd	40	94.2		24.0	10.5
D	8	Dd	40	91.1		22.5	12.9
D	9	d	40	97.4		24.95	12.7
D	10	d	40	81.6		21.5	11.0
D	11	D	40	97.4		25.0	8.8
D	12	d	40	84.8		24.4	11.6

ANNEX 2

Douglas fir non linear model

FINAL REPORT FOR SUBTASK 6.1: DOUGLAS FIR
"MODELLING BARK THICKNESS IN THE TREE"
by TEAM 4

Prof.Dr. G.Becker & Dipl.-Forstw. J.Wobst

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Göttingen, 07.05.1993

Prof.Dr. G.Becker

Dipl.-Forstw. J.Wobst

1. Introduction

This report is the Douglas-fir-part of the Final Task Report for Task 6 "Modelling bark thickness in the tree in relation to silvicultural treatment", based on bark thickness data of Douglas fir from Team 4 (Germany) and Team 11 (Italy).

During our last common meeting in Florence (end of March 1993) we put together the experience and results of all the teams made during their work up to this time. There we agreed, that modelling bark thickness of Norway Spruce and Sitka Spruce had made good progress and the results of multiple linear or binomial functions fit quite well to all the data, with differences between stands from different countries. The attempt to adapt this kind of model also for Douglas fir failed. The conclusion was, that a different model for Douglas fir had to be established by using non-linear functions.

The German Team took the part of establishing a fitting model for the German as well as for the Italian data. Because the Italian data have not been available before April 13th 1993 for the general model, Team 4 started the more detailed analysis only on its own data (see chapter 3). The general model (see chapter 4) is slightly different from the model only built up for German trees, because of differences in the data base from the different countries.

In the following you will find in chapter 2 only the detailed description of German stands and methodology, the corresponding information from Italy shall be added as a separate paper requested by the Task Leader.

2. Sample collection and methodology

In each country four stands have been selected, from each Italian stand six trees were cut, in Germany from the first stand six trees, from the following ones twelve trees. One third of the trees per stand belonged to different sociological positions, ranging from pre-dominating, dominating to co-dominating (soccl=1,2,3; according to the Kraft'sche Baumklassen). The sampling methodology for the disks per tree for bark thickness measurements has been different, the Italian data come from disks at breast height and at every 10% of the total tree height (10 disks per tree), the German data come from disks at breast height and at every 15% of the total tree height, up to 75% (7 disks per tree). This was the result from the problem, that different height levels were prescribed for Task 2 (ring width analysis, => 10%) and Task 6 (bark thickness => 15%). The German data contain also the age of each single disk, these data is missing in the Italian data. The disks have been kept in fresh conditions, measurements of bark thickness have been taken on the disks in four main directions (north, south, east, west) with a caliper square with an accuracy of 1/100 mm. Mean bark thickness values per disk were used for modelling as well as the means of the four radii per disk.

2.1. Stand information

Detailed stand information for the four stands selected in Germany

Stand	A=Westerhof 177b	B=Erdmannshausen 659a1	C=Lüß 93b2	D=Lüß 93b1
site class	high	high	low	low
spacing	1,5 *1,5	2,0 * 2,0	1,5 * 1,5	3,0 * 3,0
thinnings (Year/m³/N)	1978/?/? 1981/25/1000 1988/55/400 1991/55/170	1968/?/? ? ? 1983/?/? ?	1972/13/1350 1975/38/800 1979/30/600 1981/37,5/260 1987/62/320 1991/70/190	1967/?/?
area (ha)	2,8	2,0	2,3	10,4
age from seed when felled (y)	33	42	41	41
dom.height(m)	22,04	25,83	23,52	24,44
estimated dom.height (50)	31,5	29,6	27,4	28,6
mean dbh	26,3	27,3	25,2	23,1
mean dbh (h300)	31,0	30,2	30,6	30,4
basal area(m²/ha)	25,0	23,5	31,1	35,4
n/ha	628	365	588	770
exposition (dir/degree)	N / 5	- / -	- / -	- / -
drainage	good	good	good	good
rock nature	sandstone	glacial	glacial	glacial
soil	sandy loam	loamy sand	(loamy) sand	(loamy) sand
Altitude	250-300m	0-50m	100-150m	100-150m
next City	Northeim	Diepholz	Uelzen	Uelzen
N of selected trees	6	12	12	12
coordinates	O 10'15" N 51'45"	O 8'30" N 52'42"	O 10'20" N 52'45"	O 10'20" N 52'45"
genetic origin	Baker D71	unknown	Oerrel D22	Oerrel D22

See above the detailed stand information for the four selected German stands. Stand 'A' is just conventional managed, with initial spacing of 1,5m² and lower thinning intensity in first 30 years, stand 'B' has been planted in 2m² and heavily thinned. Trees from the poorer site class have been growing in the same forest district in northern

Germany (C&D) with very different silvicultural management (Stand 'D' with initial spacing of 3-4m² and only very weak thinning, stand 'C' with initial spacing of 1,5m² and conventional management).

3. Modelling bark thickness for German trees

As mentioned before we first tried to build up multiple linear models for bark thickness of Douglas fir. The most important variables were fixed by testing single variables as independent variables in the model. As most important independent variables we found out the 'age of the disk', followed by 'girth of the disk' and 'relative height'. The variables with a significant correlation were then put into a multiple linear model. This lead to a general model with an $R^2 = 0.68$ (for all German Douglas fir). Stand by stand models for German stands could improve the model up to $R^2 = 0.70$ to 0.79 with 'relative height', 'radius' and 'age of the disk' as independent variables.

A look at the residues showed clearly, that the model did not fit to the data well enough. Plots of the relation from bark thickness to any variable showed a non-linear shape (see fig.1 to 3), beginning at a certain age or diameter. Physiologically this is the point, where the smooth surface of the young Douglas fir bark turns to the rough rind. Because of the low age of the German stands (33 to 42 years) it was not possible to decide, if there were two models necessary - one for the smooth bark of young Douglas fir and the other for the rough rind of older trees - or if the bark growth can be described by only one non-linear function.

Finally one non-linear function has been selected, which would describe this non-linear relation in that way, that an extrapolation of the model could be plausible. The function used for the variable 'diskage' was the GOMPERTZ-function, which is oftenly used for the description of natural growth processes.

$$y = b * e^{-c * a^{n}}$$

To improve the model we completed it by adding a linear function for the variable 'girth of the disk', to integrate the dimension of the disk to the model and a square function for the 'relative height' in order to integrate height and footing effect to the model.

Because of the increasing variability with increasing values of bark thickness the function has been weighted by the factor 1/bark.

3.1. General model for German trees

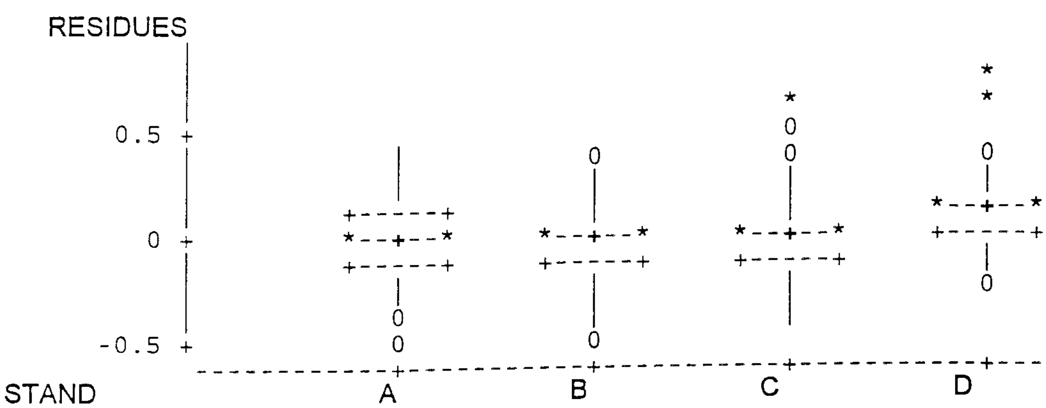
The best general model for bark thickness of German Douglas fir follows the function

$$bark = 3 * e^{-11,66 * 0,952^{n}} + 0,005 * girth + \frac{7,568}{rh^2} + 0,13$$

with bark = bark thickness [cm]
n = age of the disk (years)
girth = girth of the disk (cm)
rh^2 = square of the relative height value $(rh[\%]*100)^2$

This model has an R^2 = 0,82. The residues (bark_res) against the predicted values (bark_pre) are shown stand by stand in fig.4. It can be seen, that at least one stand -'flaeche B'- seems to have a different distribution of the residues, they are mostly negative. A common model for the three stands A, C and D gives an improvement of R^2 to 0,85. This result shows, that an influence of the stands on bark thickness can be observed. It is tested with a T-test, if the difference is significant. The following figure shows the box plots and the mean values for the weighted residues for each stand.

Comparison of the distribution of residues stand by stand



STAND	A	B	C	D
MEAN	- 0,018	- 0,059	+ 0,012	+ 0,102

The result of a T-Test between the residues of the stands was, that there is a significant difference between the mean values of the residues between stand D and all other stands and between stand B and C, the variances are in all cases homogeneous (see following table).

		VARIANCE			
	STAND	A	B	C	D
MEANS	A	-	hom.	hom	hom
	B	equal	-	hom	hom
	C	equal	not equal	-	hom
	D	not equal	not equal	not equal	-

Results of T-test of residues between stands

The T-test for stand differences between mean values of the residues shows, that there is a significant difference between the growth of the bark in different stands. The reasons for the differences can not be clarified totaly. Only the comparison of stand C with D, which shows significant differences, allows the conclusion, that the silvicultural control has an influence on bark thickness, because these stands only differ in the silvicultural management (see ch. 2). Following that, not only genetics have an effect on the growth of the bark.

Because material from only four stands has been investigated no further trends could be detected.

3.2. Models for German trees stand by stand

In order to eliminate the overlaying variation of bark thickness between stands the influence of other parameters, like 'sociological position' of the tree in the stand was investigated in stand by stand models, using the same function, but computing separate values for the parameters in the function.

Stand by stand models for German Douglas fir

$$bark_A = 3 * e^{-616*0.791^n} + 0,005*girth - \frac{3,314}{rh^2} + 0,13 \qquad R^2 = 0.81$$

$$bark_B = 3 * e^{-3,45*0,981^n} + 0,001*girth + \frac{12,593}{rh^2} + 0,13 \qquad R^2 = 0.86$$

$$bark_C = 3 * e^{-14,41*0,936^n} + 0,004*girth + \frac{3,405}{rh^2} + 0,13 \qquad R^2 = 0.84$$

$$bark_D = 3 * e^{-18,99*0,931^n} + 0,005*girth + \frac{7,095}{rh^2} + 0,13 \qquad R^2 = 0.88$$

All the weighted residues are normal distributed, what shows, that the models fit well to the data. The improvement of the R^2 compared with the general model does not seem to be very high, especially for stand 'A'. The reason for that could be found in the lower age of these trees, as shown in fig.5. The variability of bark thickness increases at the age of about 20 to 25 years corresponding to a girth of about 75 cm (see fig.1 and 2). The very high first value of the function, which changed from 11,66 (general model) up to 616,67, shows, that this model normally needs data from older trees than these ones are, because the non-linear part of the distribution is missing in this case. Therefore the function for stand A should be regarded carefully. The difference between the values of the other stands show that, for each stand, the independent variables get a different weight and/or different values.

The graphical plots of the residues as well as the plots of measured versus predicted bark thickness values show that neither in the common nor in the stand by stand plots a *general* effect of the sociological position of the tree can be observed (see fig. 6 to 10). The stand by stand plots show that a higher thinning intensity seems to reduce differences between trees of different sociological position, the plots for stands of lower thinning intensity show a trend only for the third sociological class, but in opposite directions for two stands. No test for differences between trees out of different sociological classes was made because of the too small number of samples.

4. General model for German and Italian Douglas fir trees

Because of the fact, that for the Italian data no 'diskage' was available for Team 4, we simplified the model and replaced the 'diskage' variable by 'girth' and left the additional girth function out of the formula. The parameter for the general model for the Italian as well as the German Douglas fir was computed.

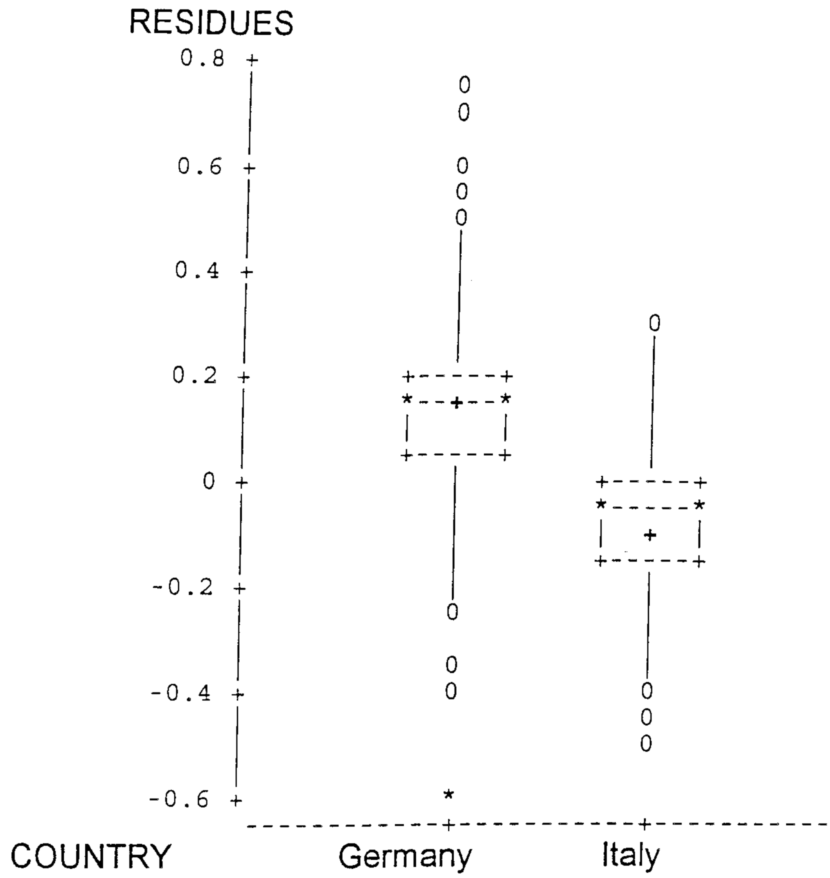
4.1. General model for trees from both countries

Resulting from that, we got the following function:

general model: $$bark_{GI} = 3 * e^{-5,447*0,987^{girth}} + \frac{7,502}{rh^2} + 0,13; \quad \text{with } R^2=0.76$$

The plot of the residues in comparison of the countries (see fig. 11), (keep in mind: representing only four stands per country) as well as the box plots (see following page) show, that there is a difference between bark thickness of German and Italian Douglas fir. Again the T-test - now between bark thickness of Douglas fir out of different countries - confirms the significant difference (T=15, Prob>T=0,0001). The variances are not homogeneous, what might be caused by the different age of the trees (Italy:25-28 years, Germany 33-42 years).

Comparison of the distribution of residues country by country



Mean of residues	Mean of residues
+ 0,134	- 0,085

4.2. General model for each country using the same function

What we wanted to test with this, is - although the variances are not homogeneous - to see, if the clouds of residues are then melting together to one cloud, or if for Douglas fir in different countries different types of functions will have to be used. Computing the parameters country by country we got the following two functions:

Models for each country using the same function

Italian model:	$bark_I = 3 * e^{-5{,}685*0{,}988^{girth}} + \frac{5{,}895}{rh^2} + 0{,}13;$	with R^2=0.84
German model:	$bark_G = 3 * e^{-4{,}023*0{,}990^{girth}} + \frac{10{,}809}{rh^2} + 0{,}13;$	with R^2=0.78

The T-test for the mean values confirms the thesis, that there is no significant difference between the mean values any more, but the variances are still not homogeneous. The higher R^2-value for the Italian data corresponds with the unhomogeneous variances, when we keep in mind the age of the trees. The optical impression of the two subcollectives in fig. 12 ,which are no more beneath each other but showing the same distribution in the lower range, allows the conclusion, that this type of model fits to Douglas fir from Italy as well as from Germany. The same trends can be observed, only a significant lower level on trees from Italy can be ascertained.

May be the model could be improved by using the 'disk age' instead of or additionally to 'girth' or 'diameter'.

5. Summary

The aim of this Task was, to establish a model for bark thickness in trees of Douglas fir, regarding silvicultural control and site class.

Because in contrast with Norway Spruce and Sitka Spruce modelling was not successful when using only linear and multiple linear models for Douglas fir, team 4 established a non-linear model for the German data with the most correlating variables

1. disk age
2. girth of the disk
3. relative height in the stem

which take into account the effect of age (non-linear GOMPERTZ-function) and dimension (linear function) of the disk as well as the relative height (square function => footing effect).

A general model for German Douglas fir was built with an R^2 of 0.82, a test for differences of bark thickness between stands showed that there are significant differences between some of the stands. There is a significant difference between bark thickness of trees from different silvicultural management (stand C is different from D), what results from same other factors (same provenance, soil, climate, age,...).

Neither in this general model nor in stand by stand models a general effect of sociological position could be observed. The stand by stand plots show that a higher thinning intensity seems to reduce differences between trees of different sociological position, the plots for stands of lower thinning intensity show a trend only for the third sociological class, but in opposite directions for the two stands. No test was made because of a too small number of samples.

A general model was built for Douglas fir from Germany and Italy using 'girth' and relative height, giving a value of R^2 = 0.76. The T-test showed significant differences between the residues of the common model for bark thickness of German and Italian Douglas fir. The model could be improved by computing separate parameters for the function, resulting in R^2 for Italy = 0.84 and for Germany R^2 = 0.78.

The lower R^2 for the German trees can be explained by the higher age of the trees, which leads to increasing values and - corresponding to that - to increasing variance. The distribution of the residues of the trees from two countries fits very well together, so that the use of a general model with different parameters for each country can be agreed upon.

This model uses the GOMPERTZ-function to come to plausible values when the model is extrapolated. If it really fits to bigger and older trees can not be predicted, a verification with a data base of older trees should be made.

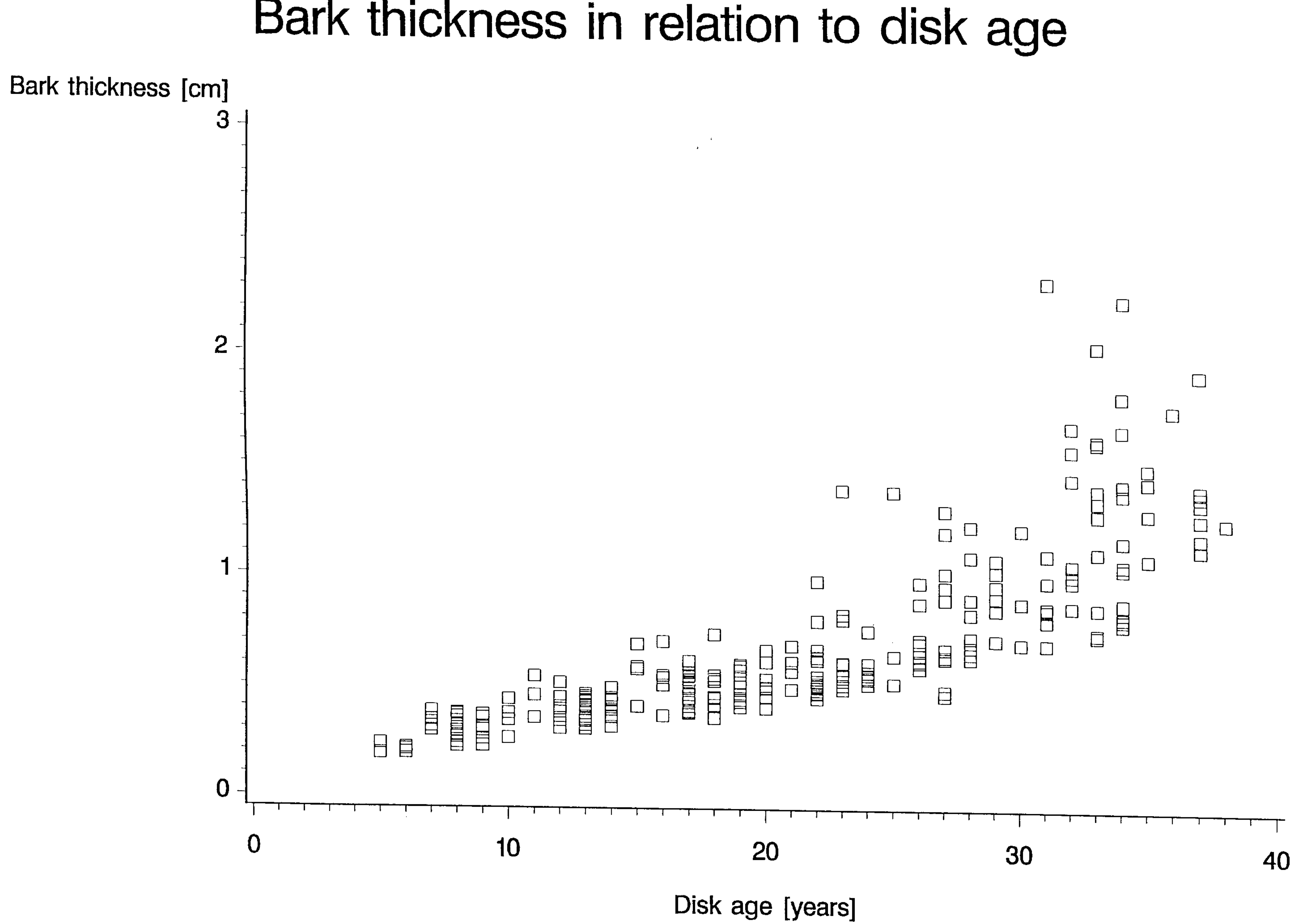

Bark thickness in relation to disk age
Bark thickness [cm]
3
2
1
0
0
10
20
30
40
Disk age [years]

fig.1

Bark thickness in relation to girth

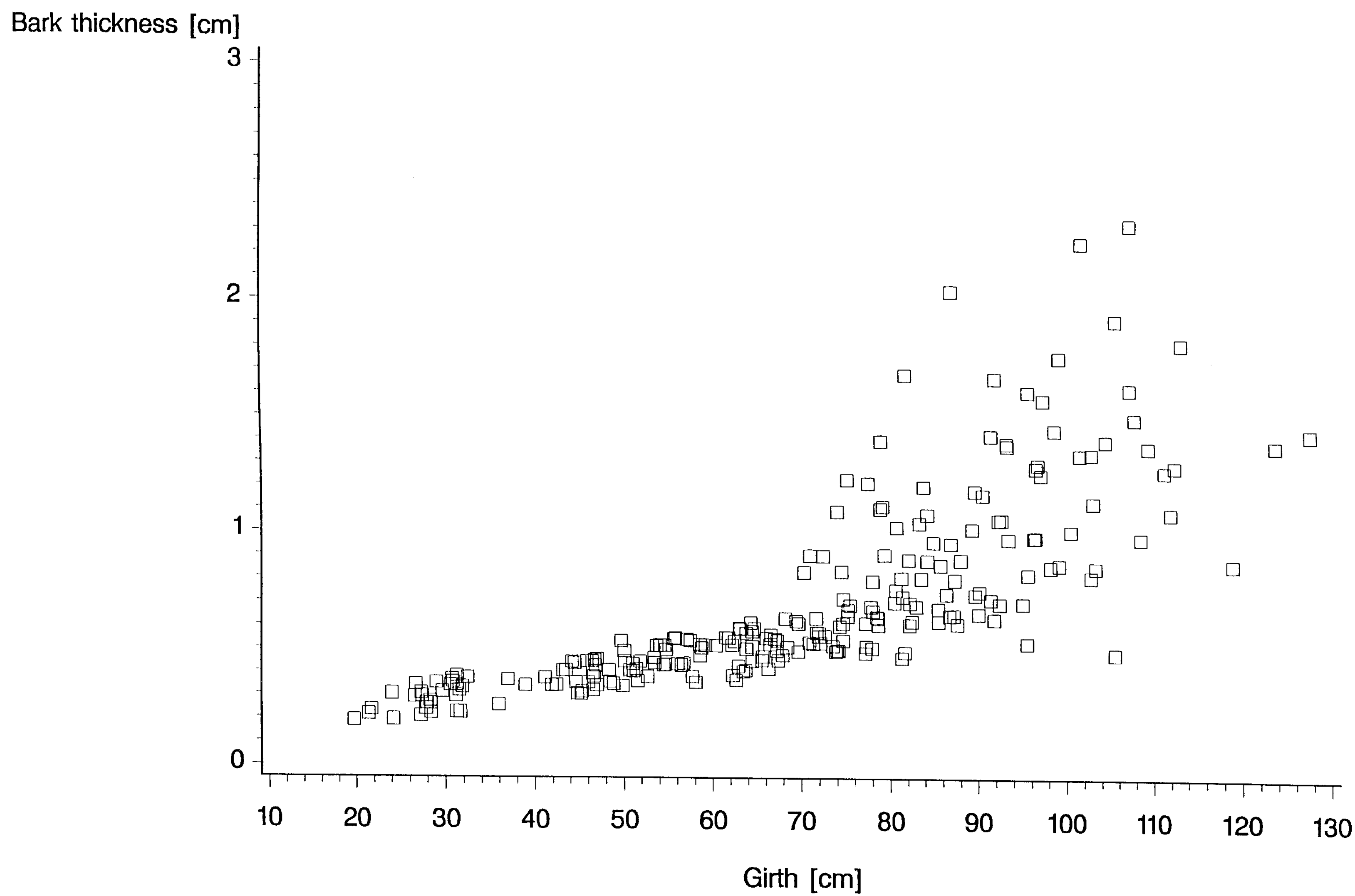


fig.2

Bark thickness in relation to relative height

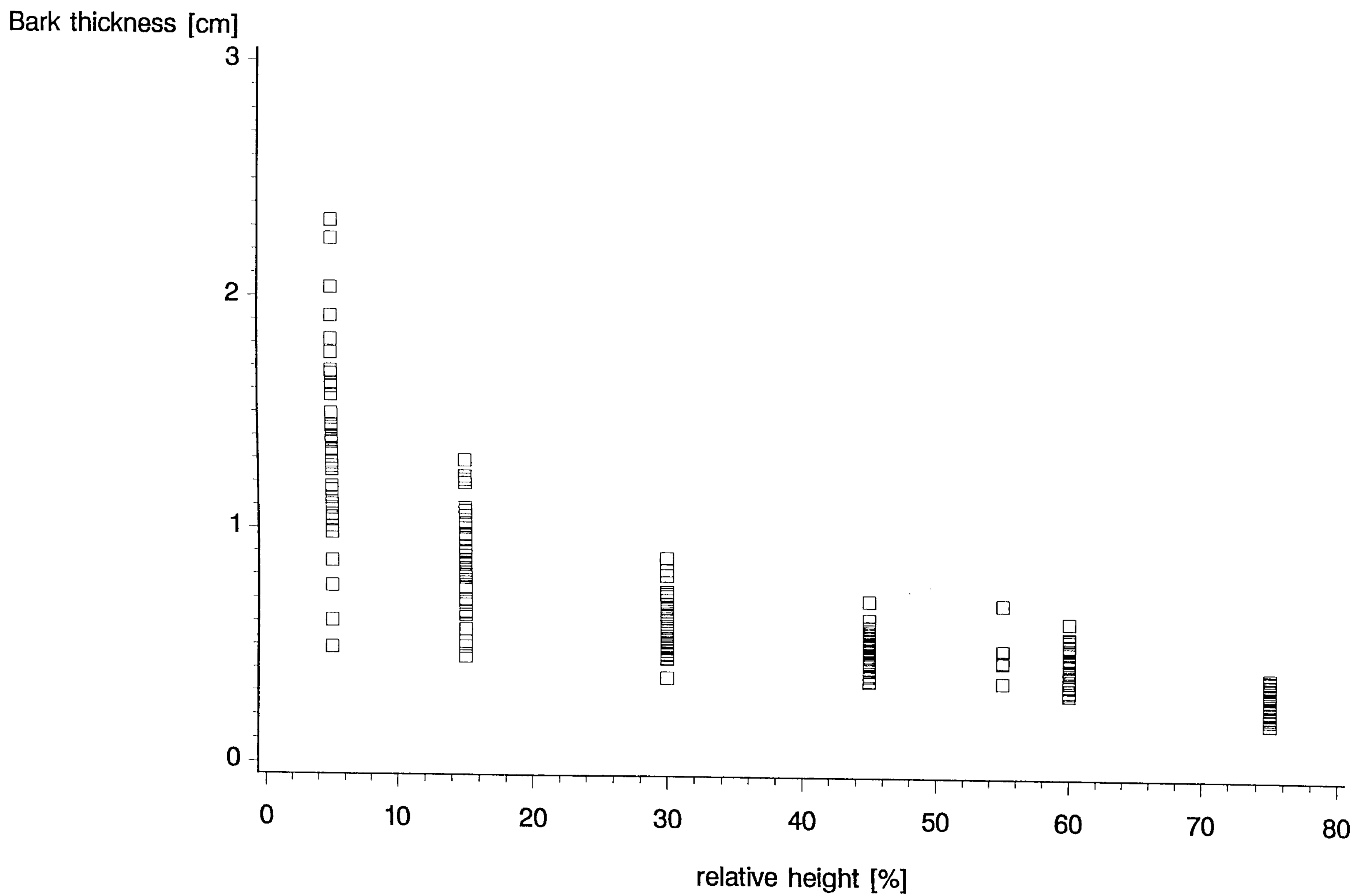


fig.3

Distribution of weighted residues

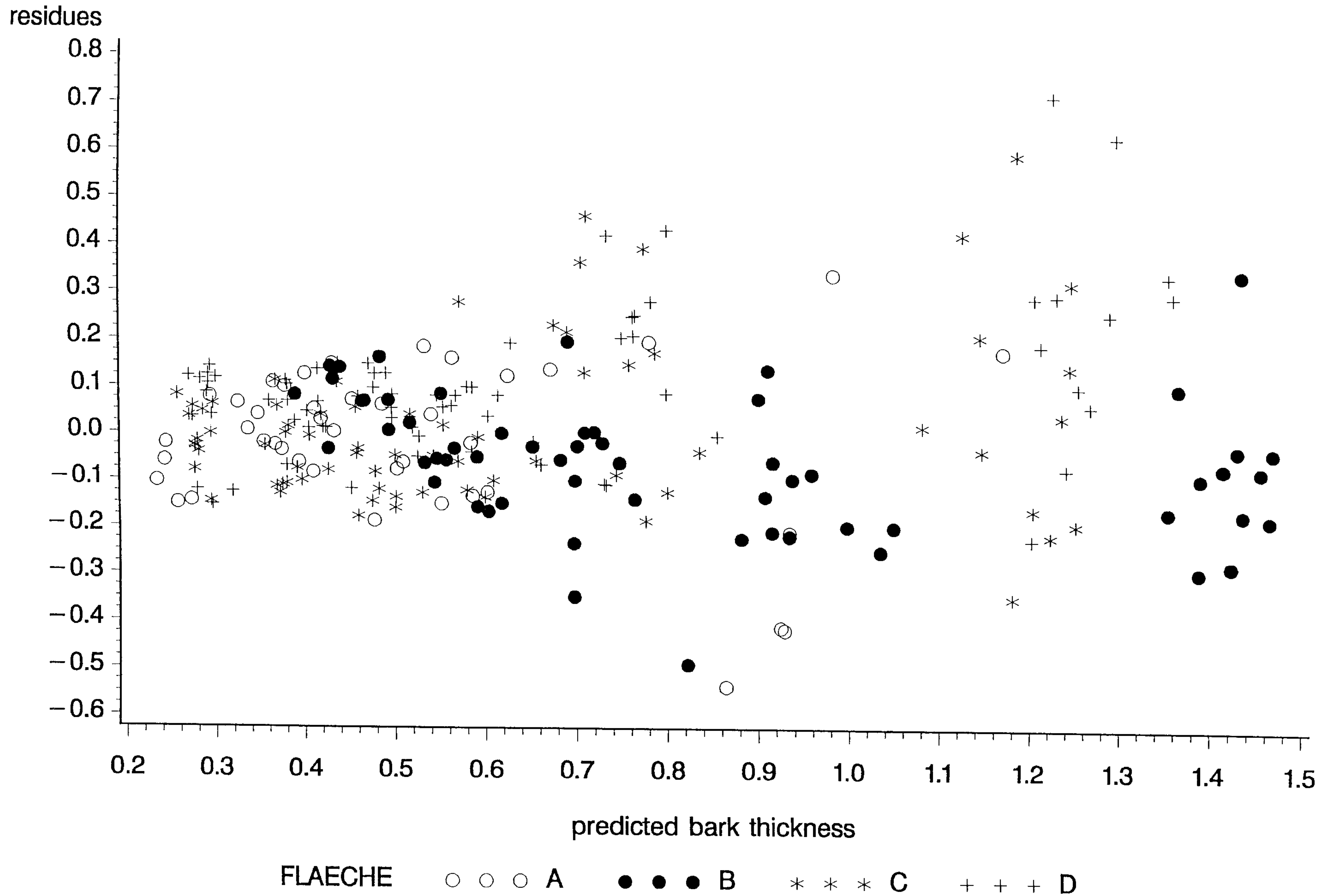


fig.4

Bark thickness in relation to disk age, Stand A

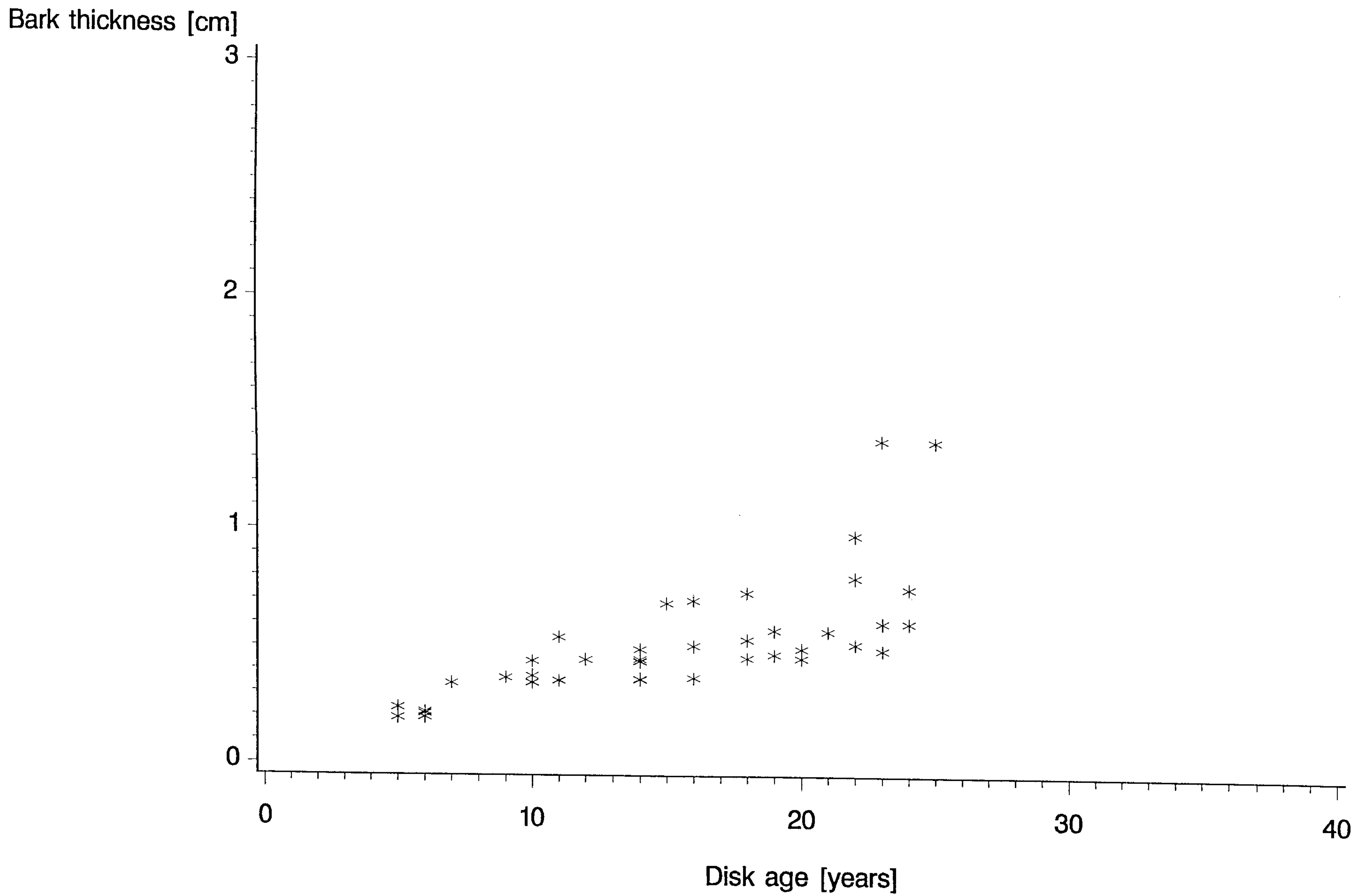


fig.5

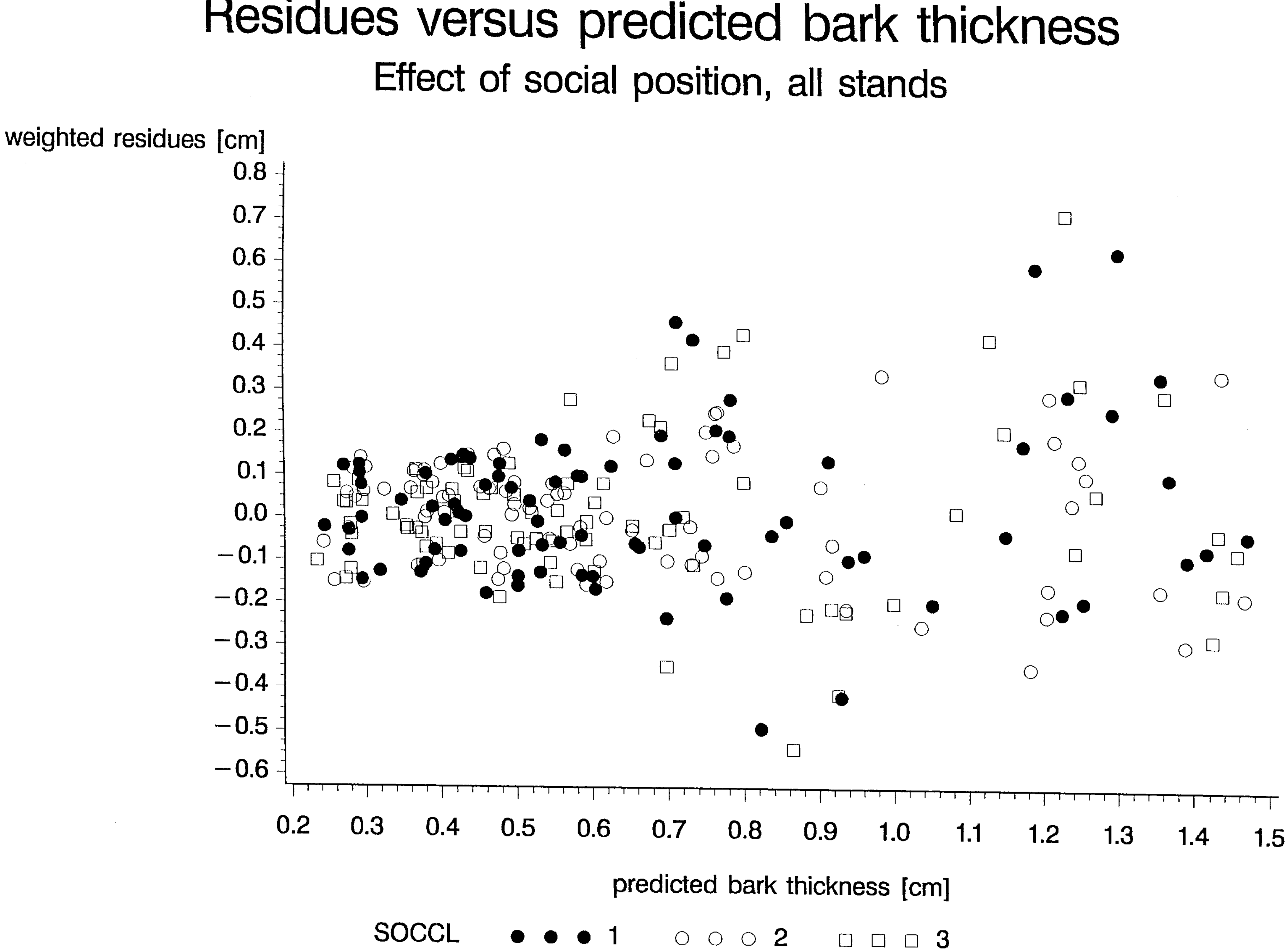

Residues versus predicted bark thickness
Effect of social position, all stands
weighted residues [cm]
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
−0.1
−0.2
−0.3
−0.4
−0.5
−0.6
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4
1.5
predicted bark thickness [cm]
SOCCL
1
2
3

fig.6

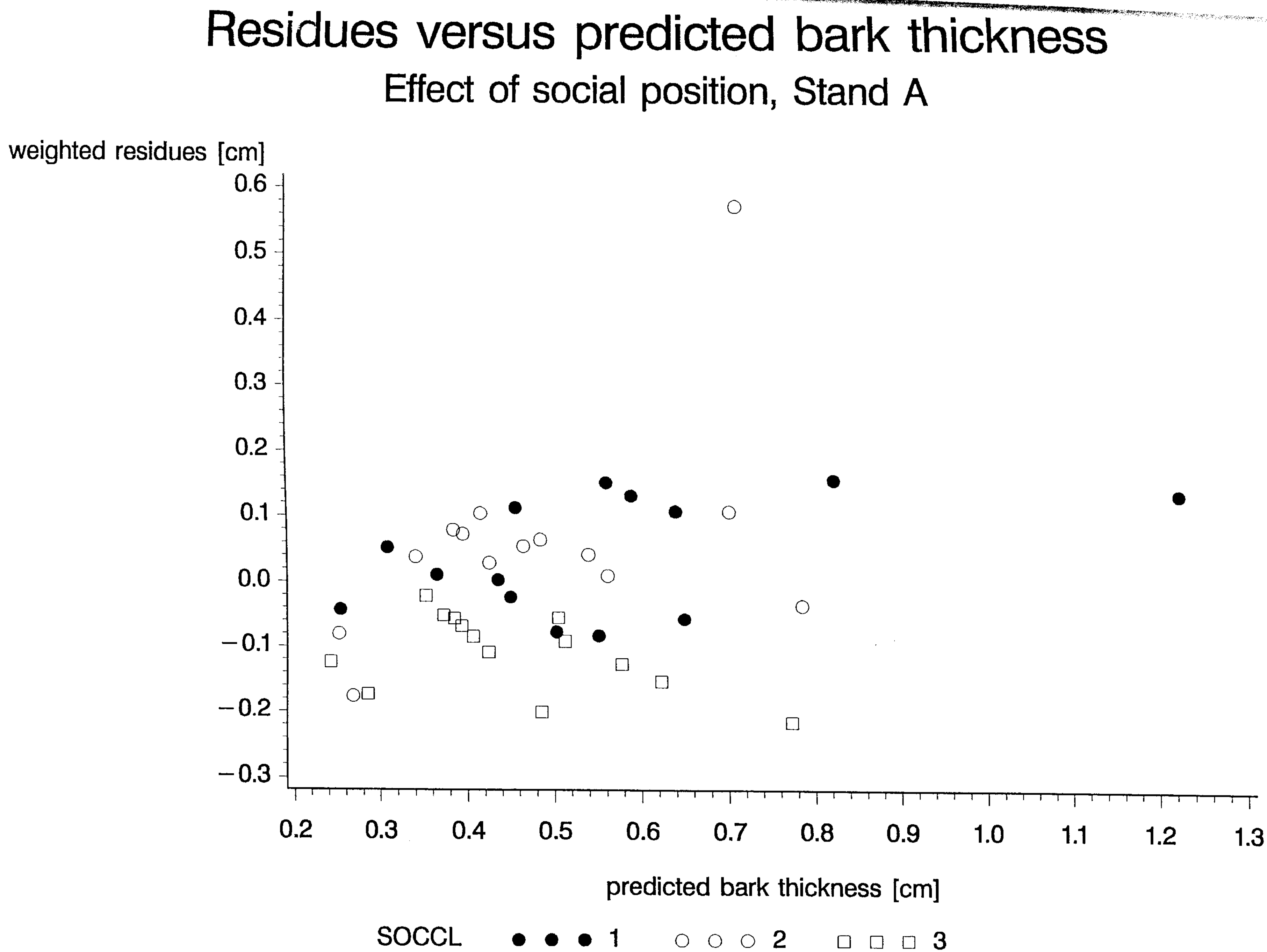

Residues versus predicted bark thickness
Effect of social position, Stand A
weighted residues [cm]
0.6
0.5
0.4
0.3
0.2
0.1
0.0
−0.1
−0.2
−0.3
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
predicted bark thickness [cm]
SOCCL
1
2
3

fig.7

Residues versus predicted bark thickness

Effect of social position, Stand B

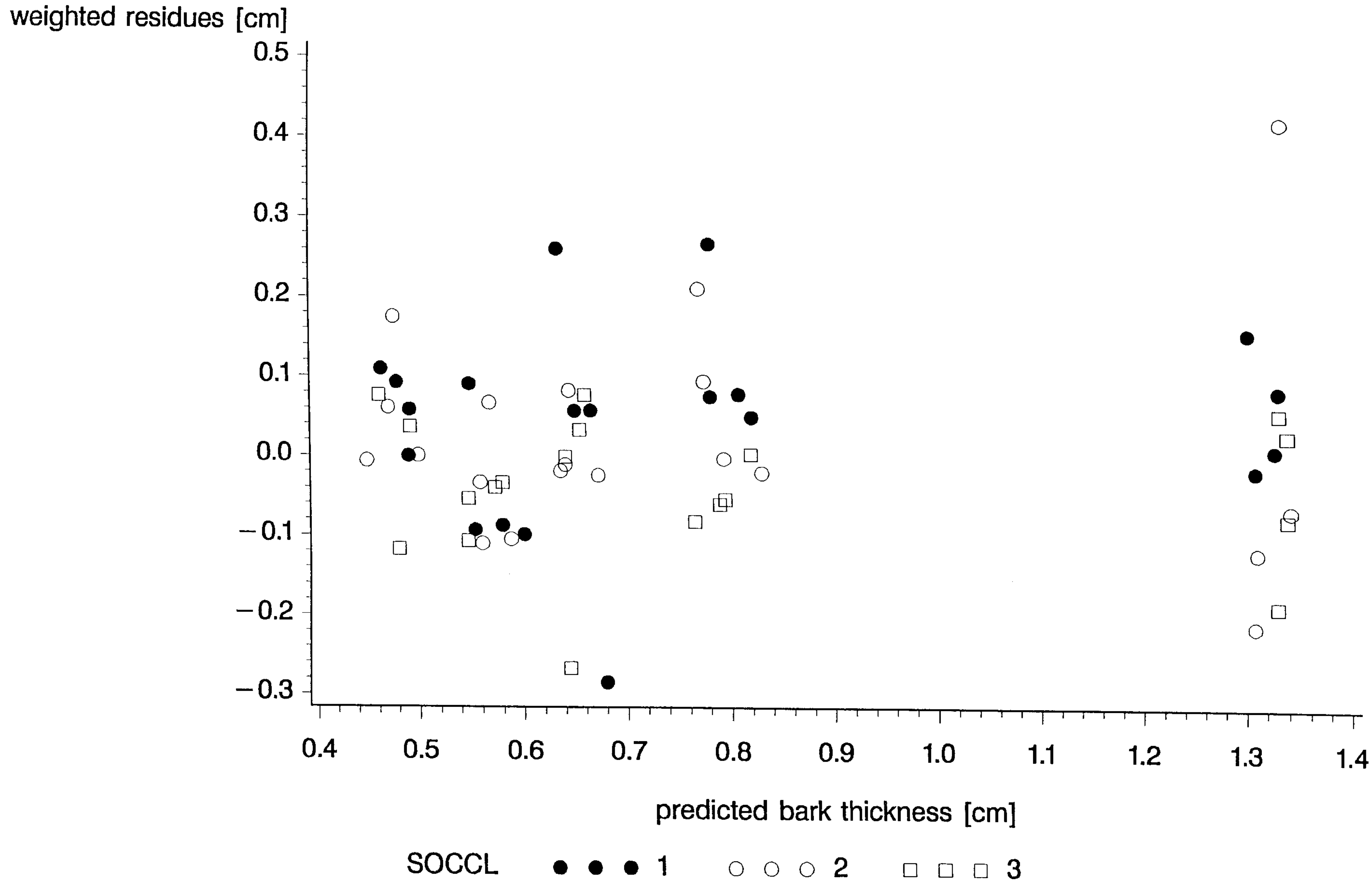


fig.8

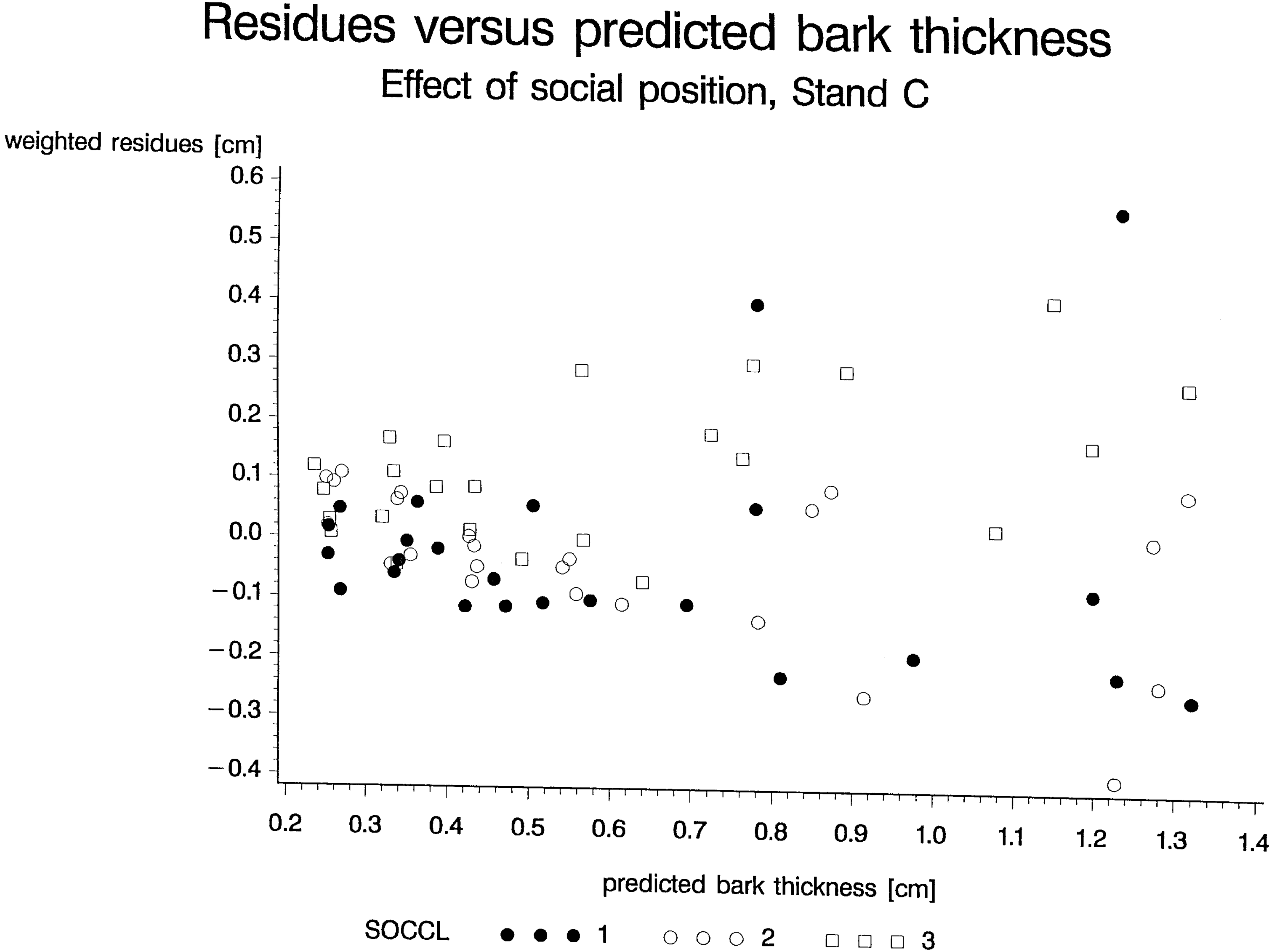

Residues versus predicted bark thickness
Effect of social position, Stand C
weighted residues [cm]
0.6
0.5
0.4
0.3
0.2
0.1
0.0
−0.1
−0.2
−0.3
−0.4
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4
predicted bark thickness [cm]
SOCCL 1 2 3

fig.9

Residues versus predicted bark thickness

Effect of social position Stand D

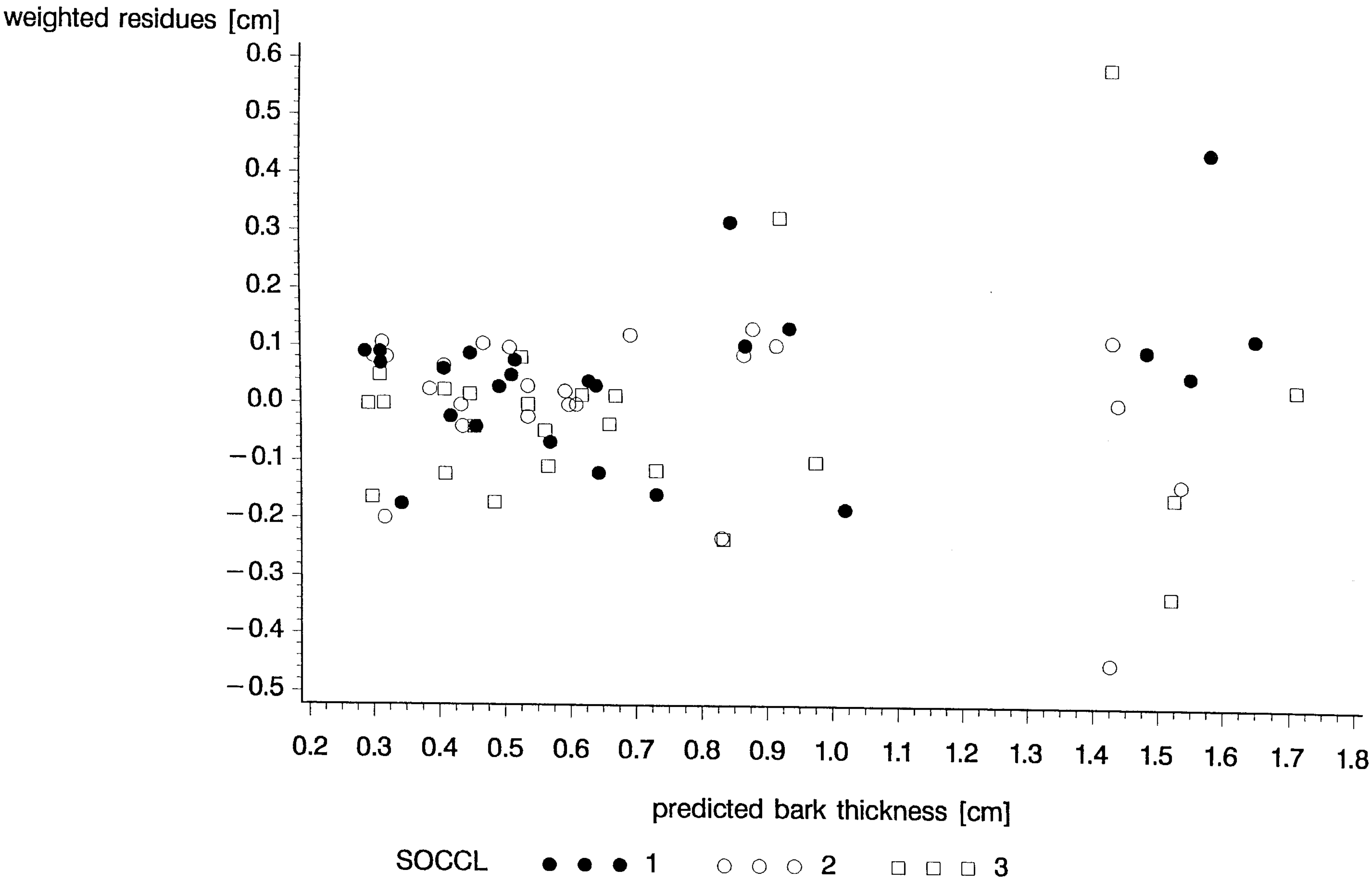


fig.10

Predicted values versus measured values
with common parameters for German and Italian trees

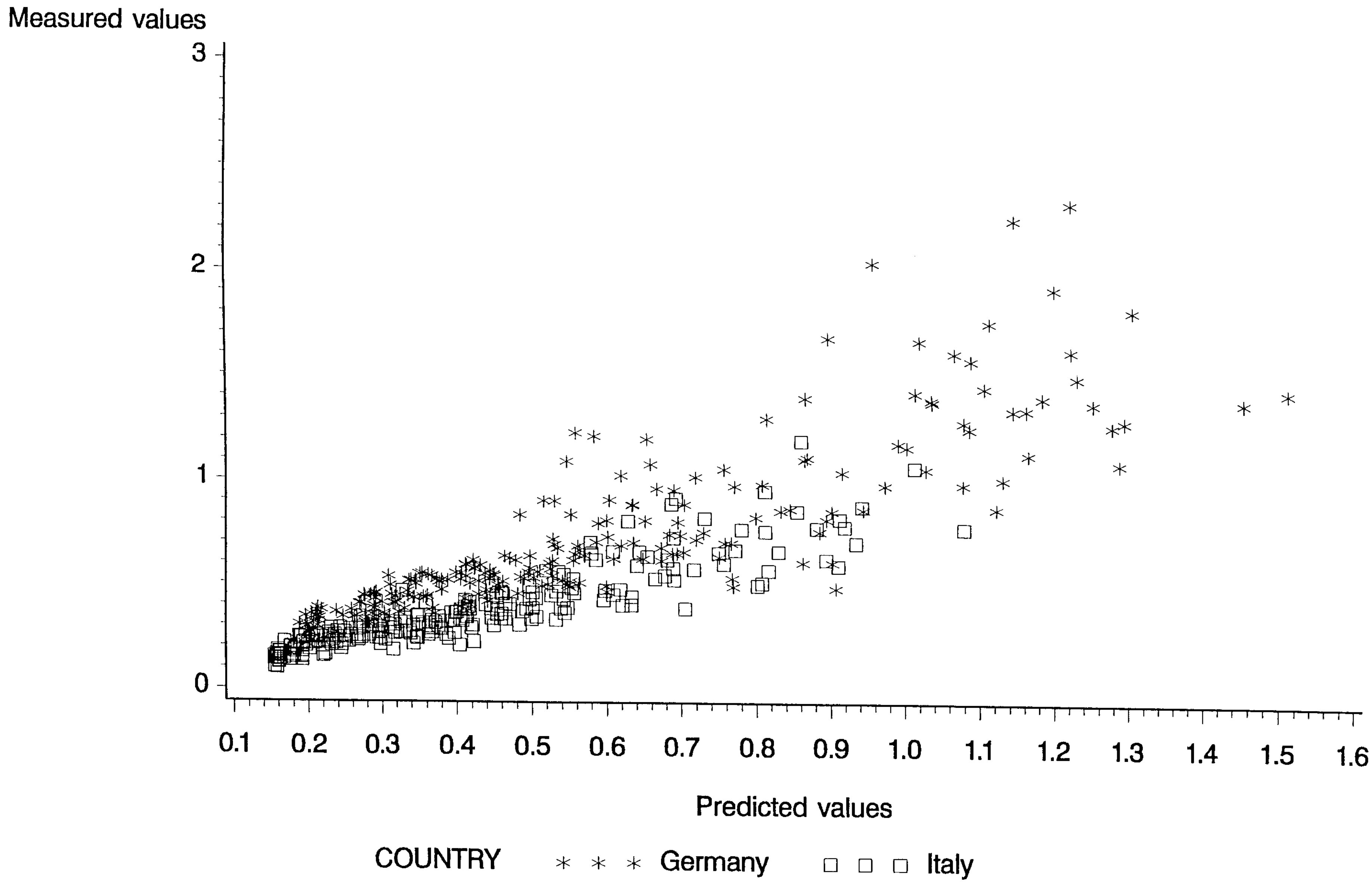


fig.11a

Residues versus predicted values

with common parameters for German and Italian trees

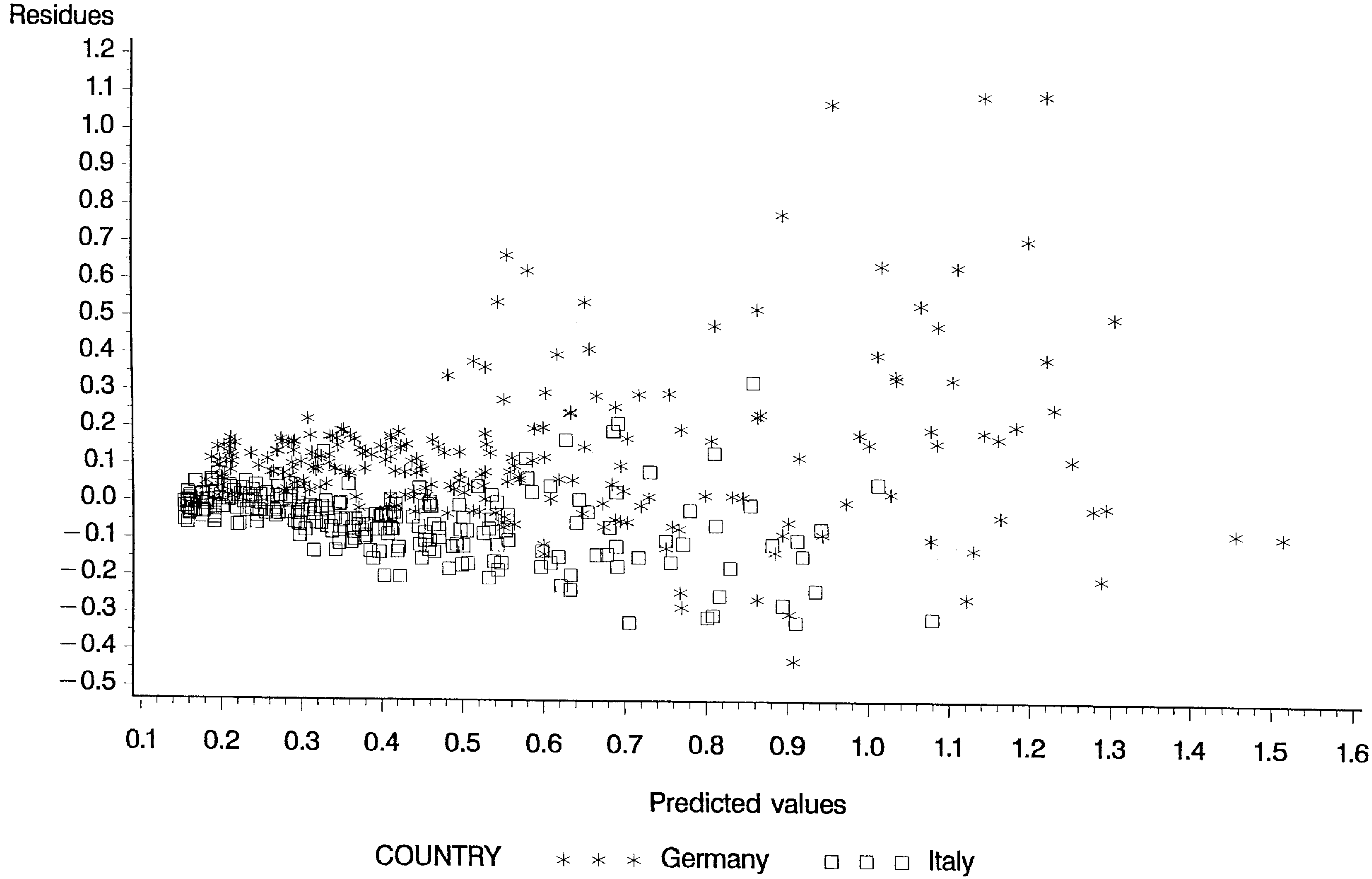
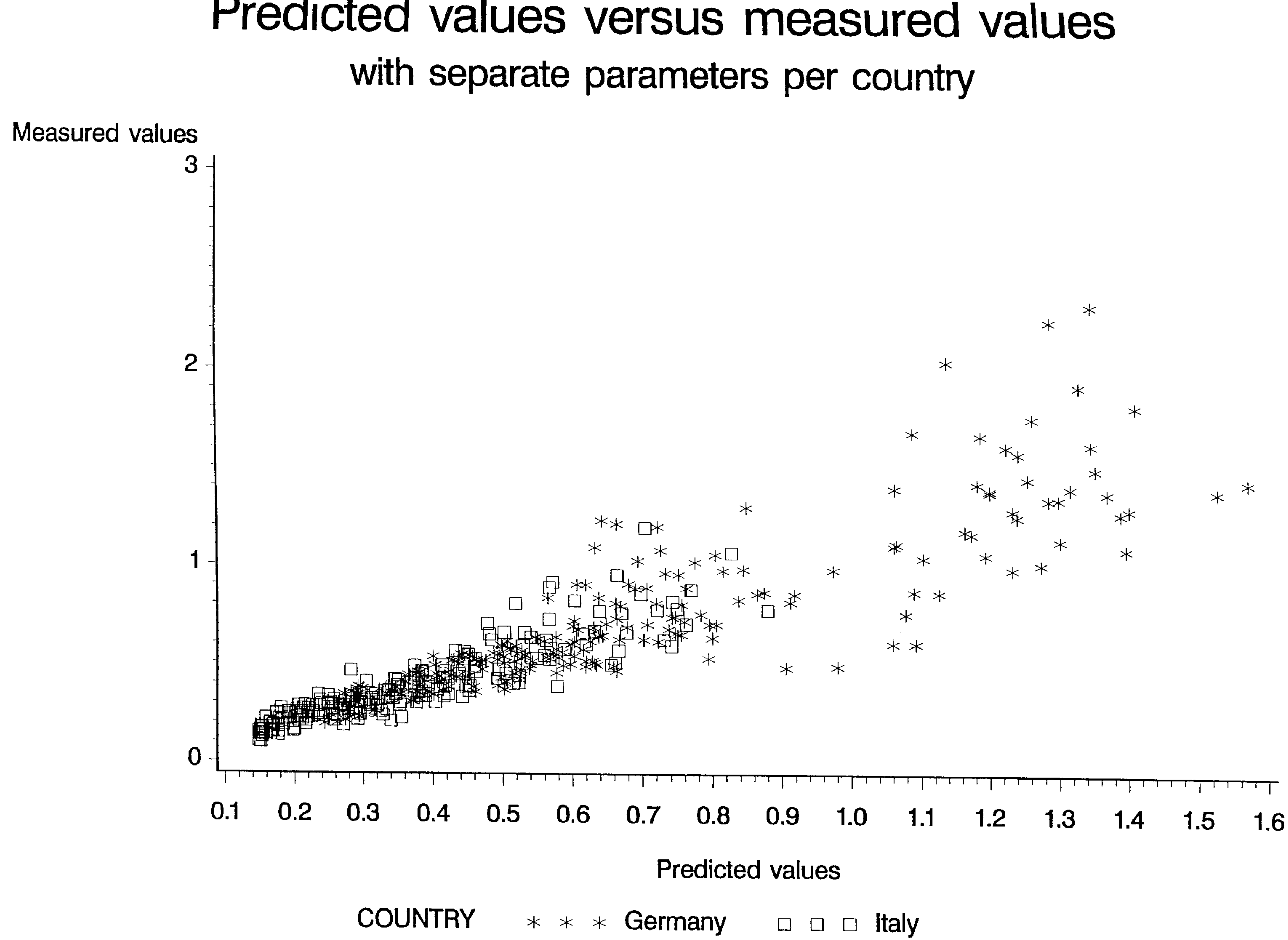
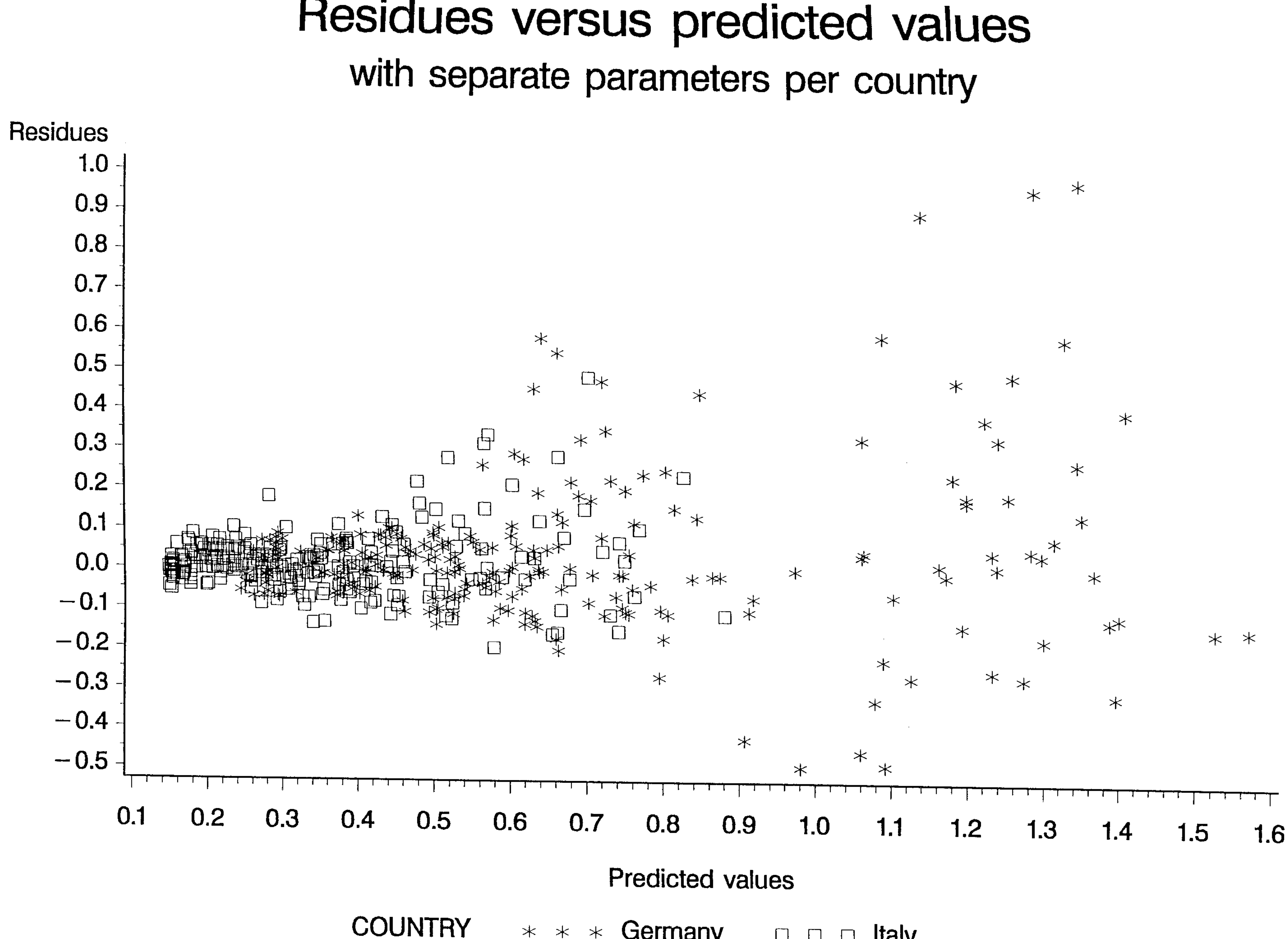


fig.11b



Predicted values versus measured values
with separate parameters per country
Measured values
3
2
1
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4
1.5
1.6
Predicted values
COUNTRY
Germany
Italy

fig.12a



Residues versus predicted values
with separate parameters per country
Residues
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
−0.1
−0.2
−0.3
−0.4
−0.5
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4
1.5
1.6
Predicted values
COUNTRY
Germany
Italy

fig.12b

ANNEX 3

Choice of bark thickness common models

Table 42. - *Residuals variance of 5 best common models by country for the three species..*

SPECIES : **NORWAY SPRUCE**						
	MODELS		Belgium residual variance	France residual variance	Denmark residual variance	Mean residual variance
GIRTH	AGE	HT2	0.309	0.320	0.489	0.372
GIRTH	**AGE**	**HEIGHT2**	0.309	0.300	0.486	**0.365**
GIRTH	HT	AGE	0.313	0.319	0.479	0.371
GIRTH	CBL	HT2	0.318	0.323	0.958	0.533
GIRTH	HT	HT2	0.319	0.314	1.008	0.547
GIRTH	GIRTH13	HT2	0.320	0.323	0.913	0.519
HEIGHT	GIRTH	AGE	0.323	0.307	0.478	0.369
GIRTH	GIRTH13	HEIGHT2	0.428	0.308	1.130	0.622
GIRTH	AGE	HR	0.340	0.310	0.521	0.390
GIRTH	CBL	HEIGHT2	0.393	0.312	0.989	0.565
GIRTH	AGE	GIRTHR	0.322	0.312	0.470	0.368
GIRTH	AGE	GIRTHé	0.380	0.319	0.435	0.378
GIRTH	GIRTH13	AGE	0.330	0.323	0.485	0.379
SPECIES : **SITKA SPRUCE**						
	MODELS		Denmark residual variance	Great Britain residual variance		Mean residual variance
GIRTH	AGE	GIRTH2	0.555	0.491		0.523
GIRTH	AGE	CROWNR	0.578	0.411		0.494
GIRTH13	AGE	HEIGHT2	0.578	0.471		0.524
GIRTH	**CBL**	**AGE**	0.578	0.400		**0.489**
GIRTH	AGE	HEIGHT2	0.580	0.482		0.531
GIRTH	AGE	HT2	0.580	0.472		0.526
CBL	AGE	GIRTH2	0.661	0.406		0.534
HEIGHT	GIRTHCB	AGE	0.651	0.407		0.529
AGE	HR	CROWNR	0.643	0.409		0.526
GIRTHCB	AGE	HR	0.630	0.418		0.524
SPECIES : **DOUGLAS FIR**						
	MODELS		Germany residual variance	Italy residual variance		Mean residual variance
AGE	HR	GIRTHR	5.758	1.148		3.453
HEIGHT2	HR	GIRTHR	5.764	1.047		3.405
HEIGHT	GIRTH13	AGE	5.792	1.059		3.426
HEIGHT	AGE	GIRTH2	5.817	1.198		3.507
AGE	HT2	HR	5.835	1.152		3.493
HEIGHT	**HEIGHT2**	**HT2**	5.870	0.899		**3.385**
GIRTH13	AGE	HR	5.871	1.070		3.471
HEIGHT	GIRTH2	HEIGHT2	6.698	0.746		3.722
GIRTH	GIRTH2	CROWNR	7.096	0.778		3.937
GIRTH	GIRTH2	HR	6.489	0.779		3.634
GIRTH	GIRTHCB	GIRTH2	7.087	0.782		3.934
GIRTH	CBL	GIRTH2	7.236	0.783		4.010
HEIGHT	GIRTH	GIRTH2	6.365	0.783		3.574

Remark: The best combinations of variables are presented in bold