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Instability in Plantations of Container-Grown Scots Pine and Consequences on Stem Form and Wood Properties

Göran Rune

Swedish University of Agricultural Sciences

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Abstract

This thesis summarizes and discusses results of four studies regarding the effects of growing Scots pine (*Pinus sylvestris* L.) in containers on root deformation, tree stability, basal sweep- and compression wood formation. The thesis is based on non-experimental surveys that include young (7- to 9-year-old) and older (19- to 24-year-old) Scots pine trees from naturally regenerated stands and from stands established with container-grown (Paperpot) seedlings. The thesis is also based on data obtained from 6- and 22-year-old trials with Scots pine seedlings reared from containers of different design. Results showed that root morphology, mechanical tree stability and stem straightness of container-grown Scots pine trees will improve over time and approach the state of naturally regenerated trees. However, inside the root system fibre disturbances as well as bark remains still occur. Root deformation caused by improper design of containers may lead to mechanical tree instability and leaning trees, which will cause compression wood formation. For 6-year-old Scots pine trees, the correlation between basal sweep and compression wood content was strong. No correlation between these variables was obtained for older trees that had become straighter over time. Therefore, the straightness of a stem is not *per se* a reliable measure of occurrence of compression wood within the stem. Because the formation of compression wood in the basal part is ongoing as long as trees are not completely straight, it is difficult to forecast the future quality of such logs. This thesis shows that container design affects root development, which can subsequently influence the formation of basal sweep. The stem form of Scots pine can be improved by the use of a container type that promotes a more natural root morphology, especially in fertile sites with dense soil types.

Keywords: *Pinus sylvestris* L., reforestation, root system, container types, mechanical tree stability, stem form, compression wood.

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Contents

Appendix

Papers I-IV

The present thesis is based on the following papers, which will be referred to by their Roman numerals: I - IV. It also includes some original data not published elsewhere.

I. Lindström, A. & Rune, G. 1999. Root deformation in plantations of container-grown Scots pine trees: effects on root growth, tree stability and stem straightness. *Plant and Soil 217*: 29-37.

II. Rune, G. 2003. Slits in container wall improves root structure and stem straightness of outplanted Scots pine seedlings. *Silva Fennica 37(3):* 333-342.

III. Rune, G. & Warensjö, M. 2002. Basal sweep and compression wood in young Scots pine trees. *Scandinavian Journal of Forest Research 17:* 529-537.

IV. Warensjö, M. & Rune, G. Stem straightness and compression wood in 22-year-old container-grown Scots pine trees. *Submitted manuscript.*

Papers I, II and III are reproduced with kind permission from the publisher.

In study I, Lindström was responsible for the design and measurements. Both authors were equally responsible for writing, literature search and for the data processing. In study III and IV, both authors were equally responsible for field measurements, data processing, writing and literature search.

"If you only learnt from success, you're not going to learn very much in life"

Bill Bowerman

Introduction

During the 1970s, there was a rapid and large-scale change from bare-root to container-grown seedlings for reforestation in Sweden. The changeover was evidently due to economic and technical considerations, not biological considerations (Lindström & Nyström, 1987). Of the total production in the beginning of 1970s, 90-95% was bare-rooted seedlings (Anon., 1971), but in 1975, more than 33% of the total production consisted of container-grown seedlings (Lindström, 1978). Current Swedish production is 236 million container-grown seedlings/year (Table 1). Over 95% of the commercial production is conifers, one-third Scots pine (*Pinus sylvestris* L.) and two-thirds Norway spruce (*Picea abies* (L.) Karst.). There is also a limited production of lodgepole pine (*Pinus contorta* Dougl.). Approximately 140 000 hectares, *i.e.*, 75 percent of the area reforested annually in Sweden, is planted with container-grown seedlings (Anon., 2002).

Table 1. *Millions of seedlings used in Sweden in 2001 divided into different species and method of production (%). (From Anon., 2002).*

	Species				
	Scots pine	Norway spruce	Other conifers	Broad-leaved trees	Total[1]
Millions of seedlings	124	172	12	3	311
Bare root	8%	34%	33%	74%	24%
Containerised	92%	66%	67%	26%	76%
Total	100%	100%	100%	100%	100%

[1]Also includes the hybrid between containerised and bare-root seedlings (Plug+ and T+)

The first types of containers for forestry plant production were solidwall containers with smooth inside walls and small bottom drainage holes, and softwall containers. Poor container design and insufficient growing regimes in the nurseries resulted in root deformations *e.g.* spiralling roots or compressed root systems. Deformed roots have been reported to be more common for container-grown pine seedlings compared to seedlings derived from either direct seeding (Rune & Mattsson, 1998) or naturally regeneration (Nicholls & Alm, 1983; Rebane, 2001). Root deformations as a result of a poor container design have been discussed in detail by *e.g.* Van Eerden & Kinghorn (1978), Scarratt *et al.* (1982), Hultén (1982) and Almqvist (1998).

One possible effect of root deformation is a weakly anchored root system in the soil resulting in instability. Studies of root systems from young container-grown Scots pine (Hultén & Jansson, 1978; Håkansson & Lindström, 1989) and lodgepole pine (Halter & Chanway, 1993) indicated that the trees had a root form that could cause instability. Besides juvenile mechanical tree instability, other reported negative effects from root deformation are reduced growth (Halter *et al.*, 1993; Lindström & Persson, 1996) and vitality due to root disease caused by fungal infections (Livingston, 1990). However, the ultimate negative consequences of root deformation are uprooting due to a weak root anchorage or root breakage caused by fibre disturbances within the stump. This has been suggested by observations in young plantations of pine trees and nursery cultivated in containers with inferior design (Lindström & Håkansson, 1995). Root growth in young seedlings is considerably higher for pine than for *e.g.* Norway spruce (Lindström & Hultén, 1978) and young pine seedlings may therefore develop more root deformation during nursery cultivation. In addition, pines do not have the ability to develop adventitious roots after planting as *e.g.* spruce and that makes pine more prone to instability (Coutts *et al.*, 1990; Rosvall, 1998).

The causes of root deformation and the subsequent mechanical tree instability are highly complex, with many factors interacting. Besides the container design, soil type, frost heaving, nutrient availability, water and oxygen status as well as soil compression and hereditary potentialities may affect root morphology and the mechanical tree instability (McMinn, 1978; Sutton, 1991; Goulet, 1995; Nielsen, 1998; Fischer & Binkley, 2000).

The seedling cultivation system in the nursery (growing density, growing time, light regime, fertilisation, root pruning *etc.*) may also affect the ability to develop an effective root system after outplanting in the field. For example, variations in stability of young Scots pine trees were best explained by the total root cross sectional area (Lindgren & Örlander, 1978; Lindström, 1990) and it is therefore also important to consider *e.g.* the root growth capacity (RGC) of the seedling before outplanting (Mattsson, 1986). Planting technique and soil scarification are examples of other factors that have been reported to affect root growth, root morphology and the future mechanical stability of the tree (Örlander *et al.*, 1990; Hallsby, 1994; Lindström & Håkansson, 1995; Örlander *et al.*, 1998).

Poor stability may result in leaning stems and development of basal sweep because the shoot resumes growth in an upward direction and the tree gradually recovers a vertical orientation above the basal part of the leaning stem (Hurri, 1976; Burdett, 1979; Burdett *et al.*, 1986; Cremer, 1998). The resulting sweep always has a high content of compression wood (Timell, 1986). This type of wood is present in the lower side of a leaning tree in most conifer species when the tree is removed from its natural, equilibrium position in space (Timell, 1986). The chemical and physical properties of compression wood differ from those of normal wood. The properties of compression wood can cause problems in wood utilisation. The high longitudinal shrinkage may cause distortions such as bow and crook in sawn products (Warensjö & Lundgren, 1998) and the brittle fracture makes compression wood more difficult to use in structures. Additionally, the high level of hardness makes it hard to handle when sawing, drilling and nailing (Timell, 1986; Johansson, 2002). Its high lignin content and relatively low cellulose content also decrease the pulp yield (Timell, 1986). According to the Swedish grading system for sawlogs (Anon., 1999), compression wood is considered to be a severe defect that causes downgrading of logs.

Most parameters of commercial wood quality, such as number and diameter of branches, wood density, annual ring width and amount of juvenile wood, are correlated with growth rate and level of competition (Persson, 1976; 1977) and can to some extent be controlled by silvicultural regimes and genetic constitution of the reforestation material. The relation between external geometry of stems and the distribution of compression wood has been discussed by *e.g.* Low (1964), Barger & Ffolliott (1976) and Koch *et al.* (1990). Other studies have focused on the relation between external log geometry and quality features such as size and type of knots (see *e.g.* Lundgren, 2000; Jäppinen, 2000). According to Lundgren (2000) the external geometry of a trunk is a fairly good indicator of the log quality. Öhman (2001) found that external geometry features, such as the largest sweep and ovality in log ends, did not explain the variation of compression wood content. Warensjö *et al.* (2003) studied the compression wood distribution in boles of Norway spruce, and concluded that bow height and compression wood content in log ends are good measures of the internal compression wood distribution.

Today, about 36% of the productive forest area in Sweden consists of stands younger than 30 years (Anon., 2000). Forest established with seedlings reared from the early types of containers will from now on be a source of increasing importance for the forest industry. After the seedling has been planted, the mechanical tree stability, and subsequent stem sweep formation and development of compression wood are hard to control by silvicultural regimes. The economic consequences of instability of trees nursery cultivated in containers are difficult to predict because the extent of basal sweep and its impact on wood quality are not sufficiently investigated.

Research related to the production of container-grown seedlings has been carried out since the introduction of containers almost 30 years ago. This has been concerned mainly with improving root morphology, survival and growth performance of outplanted seedlings through planting experiments (for references, see Van Eerden & Kinghorn, 1978; Lindström, 1998) and studies relating to cultural regime (for references, see Hannerz, 1996; Stattin, 1999; Bigras & Colombo, 2001). This research has resulted in development of new container designs, *e.g.* slitwall containers with vertical slits in the sidewalls, and improved cultivation methods in the nursery. Today many nurseries use containers of modern design that allow fairly undisturbed root growth. To date, no artificial method for plant production has been designed that has been able to entirely eliminate problems with deformed roots. In fact, many billions of seedlings grown in early generation of containers that promote root deformation have been planted in Sweden (Nyström, 1989). However, the development of containers has been fast during the last three decades. The field tests of container types take several years, and new containers or growing techniques are in general developed before scientific results from older container systems are ready. Consequently, few scientific papers have been published concerning the effects of container design on root structure and planting performance.

Objectives

The objectives of this thesis were to study the effect of container design on root development, tree stability, basal sweep formation and compression wood content and distribution in younger and older Scots pine trees. This was achieved by conducting the studies included in this thesis (I-IV) (Fig. 1). The main objectives in the studies were as follows:

(i) To investigate trees cultivated in softwall containers (Paperpot) and naturally regenerated trees 7 to 9 and 19 to 24 years after establishment. Special emphasis was put on stability, root morphology and stem straightness.

(ii) To examine the structure of root systems derived from two different container types, solidwall containers with vertical ribs on the inside walls and slitwall containers, and their impact on the formation of basal sweep in young Scots pine trees grown at two sites with different fertility.

(iii) To determine whether young trees with basal sweep become straighter over time and whether this process is associated with compression wood formation.

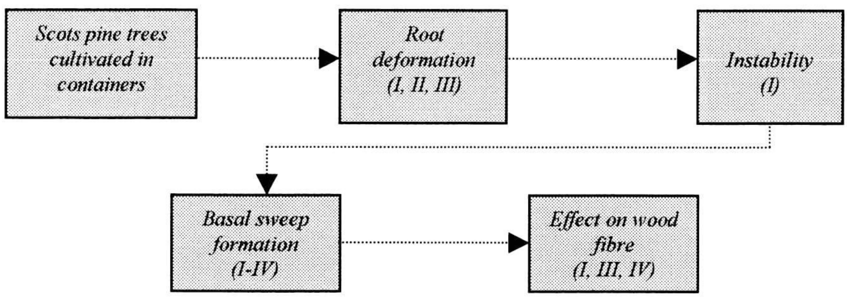

Fig. 1. Diagram showing the different subjects considered in this study (I-IV). (Orig.).

Overall, this thesis aims to provide information that can be used to improve reforestation techniques and pursue more efficient utilization of wood resources from Scots pine plantations in Sweden.

Materials and methods

The materials and methods are described in detail in the papers I-IV. Only a short outline is given in this section. An overview of the material are shown in Table 2.

Table 2. *Type of study site, age, regeneration method, number of sites, trees, root systems, wood discs and logs used in the four studies. (Orig.).*

Study	Type of study site	Age, year	Regeneration method	Number of sites	trees	root systems	wood discs	logs
I	survey	7-9	natural., softwall	11	198	66	-	-
		19-24	natural., softwall	12	120	60	-	-
II	field trial	6	hardwall, slitwall	2	826	99	-	-
III	field trial	6	different containers	2	2210	152	257	-
IV	field trial	22	different containers	1	440	-	-	-
					resp. 72	-	176	15

The term seedling applies to a young tree, grown from seed with a diameter at breast height of no more than 1 cm and a height of no more than 1.5 m. A seedling reared in a container and with roots that are still in their growing medium at the time of outplanting is termed container-grown or containerised seedling.

Study locations

Study I is based on non-experimental surveys in central Sweden and includes young, 7- to 9-year-old, and older, 19- to 24-year-old, Scots pine trees from naturally regenerated stands and from stands established with container-grown seedlings. Study II, III and IV are based on field experiments established with container-grown Scots pine seedlings. Study II and III are based on the same field experiments, located on two sites differing in fertility, soil type and method of soil scarification. All field trials were located in a radius of 40 km from Högskolan Dalarna's research station in Garpenberg (lat. 60°15′N, long. 16°15′E, alt. 140 m), 200 km NW Stockholm, Sweden. The trees were 6 years old in study II and III and 22 years old in study IV.

Container types

The container types used in the studies represent the most frequently used container designs in the past (softwall and solidwall) and today (solidwall and slitwall). Softwall containers (Paperpot 408™) was used in study I. In study II solidwall containers (Hiko V50™, V93™) and slitwall containers (Planta 80™, 90™) were used (Fig. 2). In study III and IV container types were not taken into consideration.

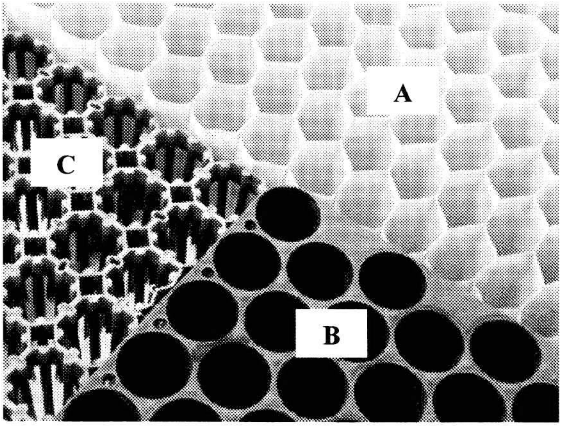

Fig. 2. Container system used for nursery cultivation of seedlings in study I (A) and II (B and C). Paperpot FH 408™ (A), Hiko V50™, V93™ (B) and Planta 80™, 90™ (C). (Orig.).

The growing medium in the softwall container (Paperpot 408™) is surrounded by a thin wall of paper and plastic fibres, which is usually planted with the seedling. Ideally the wall decomposes in soil, which may improve root exit after planting. Solidwall containers (Hiko V50™, V93™) are made of hard plastic with vertical ribs on the inside wall, whereas slitwall containers (Planta 80™, 90™) have vertical slits in the sidewalls. Lateral root growth in slitwall containers used in this study was controlled by air pruning during nursery growth and mechanically at lifting.

Root morphology

Root measurements were conducted in study I, II and III to reveal root morphology (total root cross sectional area, lateral and bottom root cross sectional area, number of spiralling roots and evenness of root distribution in four quadrants *i.e.* a root area index, RAI) for naturally regenerated seedlings (I) and seedlings cultivated in containers (I, II and III). In study IV no root measurements were made.

Stability test and measurement of basal sweep

In study I, planted and naturally regenerated trees were tested for stability using a method described by Hultén & Jansson (1978). Trees were pulled to an angle of 10° from their vertical position by a wire attached to a winch. The pulling force was then registered by a dynamometer and the bending moment was calculated.

Degree of basal sweep was measured in all studies (I-IV) using a digital protractor (Lucas Anglestar, model DP 45, USA). The angle was registered at the point were the greatest angle was found within 50 cm above ground for the older trees (I and IV) and 30 cm above ground for the younger trees (I, II and III). In study IV the angle of basal sweep was divided into four categories according to Hultén & Jansson (1978) in 1986: straight (0-5°), slightly crooked (6-30°), crooked (31-45°) and very crooked (>46°) stem bases. Measurements of basal sweep were repeated in 1997 and 2001 by using a digital protractor. All trees in study IV were then divided into four categories according to their history of basal curvature in 1986 and 1997 as follows: 1, trees with straight stem base in 1986 and straight stem base in 1997; 2, trees with straight stem base in 1986 and basal sweep in 1997; 3, trees with basal sweep in 1986 and basal sweep in 1997; and 4, trees with basal sweep in 1986 and straight stem base in 1997.

Measurements and analyses of external stem and log geometry and virtual simulated cross cutting

Because the trees in study III were small, stem straightness for 36 sampled container-grown trees was manually measured in three dimensions in a frame. Each stem was positioned with the maximum bow upward. Horizontal and vertical distances from the measuring frame to the centre of the stem were measured. In study IV, larger trees were used, which made it possible to use a Rema Log 3D scanner (RemaControl, Västerås, Sweden) to determine the external stem geometry for 16 sampled container-grown trees, 4 trees per category according to their history of basal curvature.

The software VIRTUAL MILL 1.0 (Dianthus, Boden, Sweden) was used for the analysis of external stem geometry data obtained from the 3D scanner and simulation of cross-cutting (IV). The software makes it possible to visualise and combine 3D log data sets into whole tree data sets as well as virtually simulate crosscuts. In study IV, 30 log sections (length 240 cm and 420 cm) with known external geometry were simulated.

Analyses of wood quality in roots and compression wood content and distribution in trees

For the 19- to 24-year-old container-grown and naturally regenerated trees in study I, tensile strength and strain of wood samples during loading were used as measures of the effects of fibre disturbances in roots. Wood samples were taken from the root collar, the central and the peripheral part of the stump (see Fig. 3). The samples were tested for tension in a machine (Hounsfield 5000, England). When breakage of the wood fibres occurred, force and tensile strain were registered.

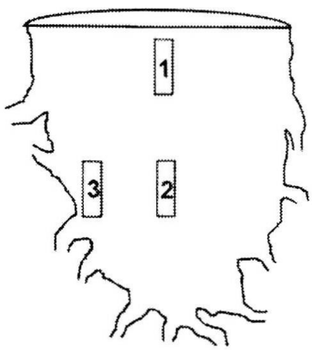

Fig. 3. Position of wood samples selected for tensile strength test. Samples were taken in 1) root collar, 2) central and 3) peripheral part of the stump. Wood samples were taken from 19- to 24-year-old, container-grown and naturally regenerated trees. (From study I).

Bark remains inside the stumps of the older trees may indicate that the roots are affected by deformations that have been concealed over time due to secondary growth. Randomly selected stumps from young and older container-grown and naturally regenerated Scots pine trees (I) were vertically split through the pith. The surface was then visually evaluated with regard to remains of bark (% of total cross section area) using pictures from digital image analyses.

Compression wood (CW) will be formed in the new growth rings as long as the stem or stem section is displaced from the vertical (Timell, 1986). It is also well known that wind is a major factor in compression wood formation in trees (Westing, 1965, Timell, 1986). Because of the high stand density in study III and IV, wind is not expected to be a major factor stimulating compression wood. Therefore, compression wood content and distribution was used as a wood characteristic and tested for correlations with basal sweep, pith eccentricity, out-of- roundness and bow-height (III and IV). Pith eccentricity expressed the deviation of the pith from the geometric centre of the cross section. Out-of-roundness expressed the deviation from a perfect circular cross section. It is well known that pine trees always contain branch-induced compression wood (Timell, 1986). In this study this type of compression wood was excluded in all analyses

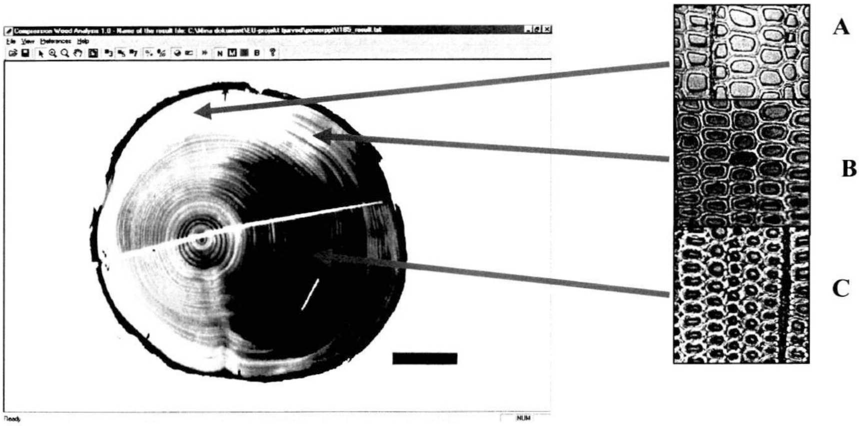

Fig. 4. Wood disc viewed in transmitted light for CW analyses (left) and images from light microscope (right) showing normal wood (A), mild CW (B) and severe CW (C). (From www.sh.slu.se/compwood).

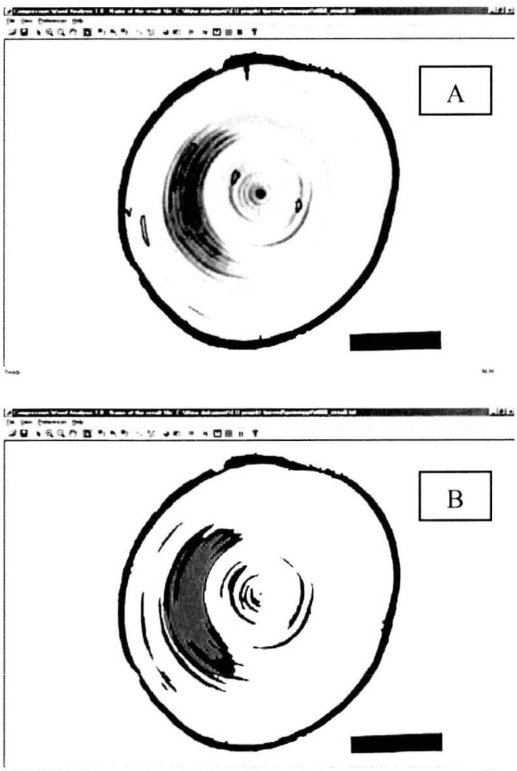

Fig. 5. Manual classification of colours corresponding to normal wood (yellow), mild CW (blue) and severe CW (red), (A) giving prerequisites for the image analyse software (B) to calculate areas of normal wood and CW. (From www.sh.slu.se/compwood).

because the aim was to consider only compression wood developed due to the stem deviation from the vertical position.

In study III, 36 sampled, container-grown trees were sawn into a total of 257 discs. In study IV, 16 sampled, container-grown trees, *i.e.*, 4 trees per category according to their history of basal curvature, were sawn into 176 discs. The discs were used for the analyses of pith eccentricity, out-of-roundness and compression wood content and distribution. For the compression wood analyses, wood discs were placed on a light box in order to view the discs in transmitted light and to visualise compression wood. Images were registered with a digital camera (JVC 3-CCD KY-F55) and were used to quantify compression wood.

Characteristics of the wood tracheid make it possible to distinguish between normal wood, mild compression wood and severe compression wood (Fig. 4). In general, a rounded outline and thick cell wall of the wood tracheid and the small intercellular spaces between the wood tracheids are typical features of compression wood in cross sections. The procedure is based on observations that compression wood is opaque to transmitted light whereas normal wood is translucent (Pillow, 1941). According to Andersson and Walter (1995) mild compression wood appears light orange to red in colour, and severe compression wood appears dark brown in transmitted light.

COMPRESSION WOOD ANALYSIS 1.0 (Dianthus, Boden, Sweden) was used to assess the compression wood content and its position in each disc. The steps during analysis were to subjectively designate typical areas for the different types of wood (normal wood, mild, and severe compression wood) on the image (see Fig. 5A). The computer software uses supervised multivariate classification for dividing the discs into normal wood, mild and severe compression wood, illustrated by different colours in Figure 5A and 5B. The computer software automatically extracted shape parameters that could be used for calculation of pith eccentricity, out-of-roundness and diameter.

After the compression wood analysis, each disc was determined for pith eccentricity and out-of-roundness. In study IV, discs from sampled logs were used for growth ring analyses using the WINDENDRO software (Instruments Régent Inc., Québec, Canada).

Statistical analyses

Differences in morphological characters between trees (I) and differences between sites (II, III) for the variables root spiralling and basal sweep were analysed using χ^2 test (df=1). Differences in bark remains and tensile strength and strain of wood samples in stumps were evaluated using analyses of variance (I). One-way analysis of variance was used for testing the equality of population means between tree height, diameter and root area (III) and to reveal differences in compression wood distributions between categories according to the history of basal curvature of the trees (IV). Analyses of variance with repeated measures were used to observe differences in development of pith eccentricity over time (IV).

Student's *t*-tests were used to observe differences in population mean values between lateral and bottom roots and for differences in root distribution in four quadrants (root area index, RAI) (I, II and III). The relationship between stump diameter and total root area for excavated root systems (I, II and III) was described by the function: $R=e^{a}\times D_{20}^{b}$ where R=total root transversal area (mm^2), D=cross-calipered stump diameter at 20-cm height (mm), and 'a' and 'b' are constants.

In study III and IV, Spearman rank correlation coefficients were used to measure and calculate the association between the variables compression wood content, out-of-roundness, pith eccentricity and maximum bow height (Bluman, 1997).
All statistical analyses were carried out by Minitab, Release 12 (Anon., 1998) except for analyses of variance with repeated measures for which SAS statistical package version 6.12 (SAS Institute, 1990) was used.

Results and discussion

This study is based on one survey study (I) and three field experiments (II, III, IV). In a survey study, where data on sites and trees may vary considerably it can be difficult to draw adequate conclusions about tree level. However, practical plantations are often the only available material for investigations. In this survey study, the sampling of sites was done randomly from a catalogue with available objects for comparisons. Even though the sites were selected as comparable in terms of tree age and site conditions, variations between sites may have affected the results. Despite this, this survey study contributes knowledge concerning the extent of stability problems in commercial plantations and natural regenerated stands of pine. In addition, another limitation of the survey study is that conclusions about the development of root deformation, tree stability and stem straightness over time are based on two different materials. However, the conclusions are based on trees grown in the same container type and at sites with comparable site conditions.

Study II and III are based on same field experiments located at two sites differing in fertility, soil type and method of soil scarification. However, each site can be interpreted as a case study and results are therefore presented separately for each site.

The aim of study IV investigation was to study the relationship between stem straightness and compression wood formation. This was done through comparisons of trees whose basal stem curvature differed. For this purpose trees were divided into four categories from which trees were randomly selected independently of their location on the experimental plot. This has limited the possibility of utilizing the randomized block design in statistical calculations.

Root morphology

Young Paperpot-grown Scots pine trees had a smaller root cross-sectional area than naturally regenerated trees at comparable diameter (Fig. 6A) (I). The average numbers of roots per root system were similar between planted and naturally regenerated young trees. This indicated thicker roots for naturally regenerated trees, which is favourable for the support of the tree because bending moment resistance correlate linearly with total cross sectional area of all roots (Coutts, 1983) and the stiffness of a single root correlate with root diameter in the fourth power.

Cultivation of Scots pine seedlings in containers with slits in the wall improved root morphology (II). Seedlings cultivated in containers with slits had less root spiraling compared to trees cultivated in solidwall containers. At the high fertility site they also had a larger root area in proportion to stem diameter, compared to seedlings grown in solidwall containers. At the low fertility site, this relationship was not as evident (Fig. 7A, B). Alternative ways to prune lateral roots are box pruning (Burdett, 1982) and chemical pruning (Landis *et al.*, 1990; Struve, 1993; Watt & Smith, 1998).

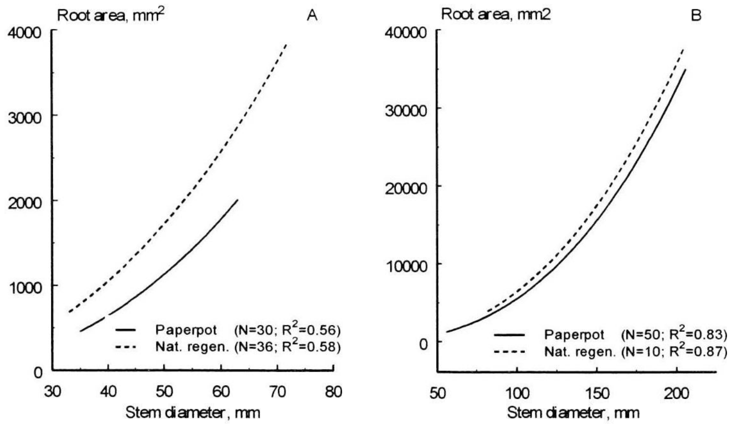

Fig. 6. Relationship between stem diameter at 20 cm height and total root area for young. 7- to 9-year-old, (A) and older, 19- to 24-year-old, (B) planted and naturally regenerated Scots pine trees. (From study I).

Pruning of lateral roots mechanically or chemically is known to improve the root system morphology (see *e.g.* Van Eerden, 1982). As seedlings normally suffer from water stress after planting (Örlander, 1986) pruning of roots just before outplanting may be detrimental for water uptake (Parviainen, 1979). The mechanical pruning of roots of seedlings reared in the slitwall containers in study II resulted in a low root:shoot ratio at planting. The low root:shoot ratio may have negatively affected early shoot growth of slitwall grown trees because they tend to be somewhat smaller six year after planting. Therefore, to avoid water stress the way root pruning is performed is probably of great importance.

Growth on the low fertility site resulted in a relatively larger share of bottom roots than growth on the high fertility site representing a dense soil type for young container-grown trees (II and III). A weak development of bottom roots for trees grown in dense soils are reported by Lähde & Mutka (1975). The small share of bottom roots on high fertility sites with a dense soil type may be due to deficiency of oxygen and high moisture content (Köstler *et al.*, 1968).

Young naturally regenerated trees had a more even root distribution in the four defined quadrants compared to young planted trees, expressed as RAI (I). Young naturally regenerated trees also had a lower frequency of spiralled roots compared to young planted trees. No differences were obtained for the RAI between seedlings reared in containers with slitwall and solidwall respectively, or across the poor and rich site (II). The morphological studies of root systems indicate better root development for natural regenerated seedlings compared to planted seedlings. Root studies (II) also indicate that it is possible to improve the formation of root morphology by using a container system that allows lateral root growth. Although the use of slitwall containers in the nursery improved the root system morphology 6 years after planting (II), there is no evidence that it is optimal for future tree stability.

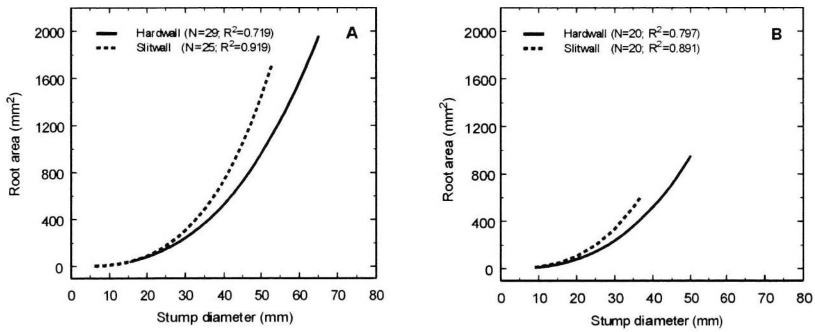

Fig. 7. Relationship between stem diameter at 20-cm height and total root area for 6-year-old Scots pine trees nursery cultivated in solidwall and slitwall containers in a high fertility (A) and in a low fertility site (B). (From study II).

Knowledge of the long-term development of a root system that is deformed during the juvenile stage is limited and only a few studies have shed some light on this. Both Gillgren (1971) and Van Eerden & Kinghorn (1978) mention that juvenile root deformation such as spiralling roots would be concealed by secondary growth and will approach the state of root systems of naturally regenerated trees when they grow older.

Root studies of Douglas fir trees by Newton & Cole (1991) and by Scagel & Evans (1992) show that nursery-produced root deformities might be overcome 5 to 10 years after planting, whereas Halter & Chanway (1993) and Halter *et al.* (1993) suggest this is not always the case. It is thought that susceptibility to mechanical instability for lodgepole pine trees is no longer a concern once the trees reach two or three metres in height (Van Eerden, 1982). It has also been suggested that if the supposedly inferior root structure of a pine tree persists throughout its life, it will be more susceptible to windthrow as it approaches rotation age (Burdett, 1979).

However, the first root study (I) does not confirm this. According to study I, root systems of Scots pine trees cultivated in containers improve over time and resemble those of a naturally regenerated tree. Root area (Fig. 6B), frequency of spiralling roots and RAI become more similar over time between the regeneration methods. However, inside the root, problems such as abnormal fibre direction and inferior root strength may remain, due to fibre disturbances as a result of spiralled roots. Improved root distribution over time has also been reported by Nielsen (1998).

Mechanical tree stability

Bending moments calculated from the mechanical tree stability test (I) provide comparisons of anchorage strength between method of regeneration (container reared versus naturally regenerated) and tree age (7- to 9-year-old versus 19- to 24-year-old). Unlike naturally regenerated trees, planted Scots pine trees reared in containers require a number of years to achieve a firm anchorage in the soil. In the stability test in which trees were pulled to an angle of 10° from its vertical position, the young naturally regenerated trees were considerably more stable than the young planted trees (Fig. 8A). Also Lindgren & Örlander (1978) and Burdett (1979) found that naturally regenerated pines were more stable than planted. However, for older trees the difference in bending moment was less pronounced (Fig. 8B) which demonstrates the improvement of the root systems ability to anchor the tree to the soil with increasing age.

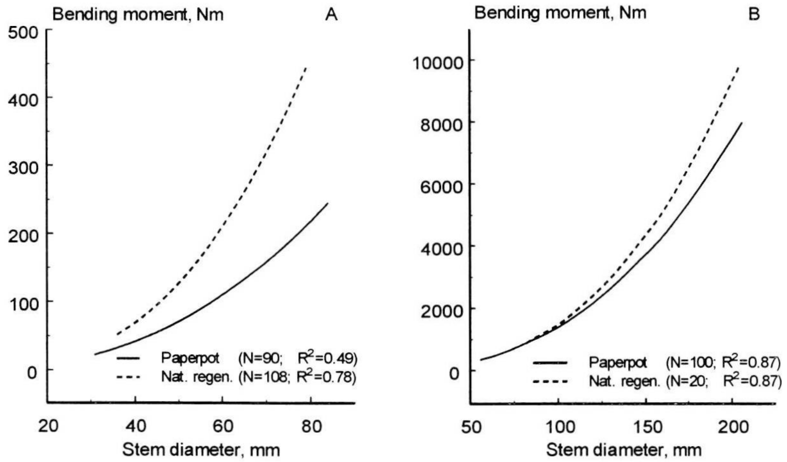

Fig. 8. Relationship between stem diameter and bending moment when pulling the tree to a 10° angle from its vertical position for A) 7- to 9-year-old and B) 19- to 24-year-old naturally regenerated and planted Scots pine. (From study I).

Deep roots are reported to increase mechanical tree stability (Coutts, 1983). Also the total root area (Lindgren & Örlander, 1978), the distribution of root area in bottom and lateral roots (Coutts *et al.*, 1990), and the distribution of roots in the four defined quadrants (see Langerud *et al.*, 1988; Nielsen & Sønnichsen, 2002) as well as root spiralling (Persson, 1978; Balisky *et al.*, 1995; Lindström, 1998) are factors known to be of importance for the capacity of a root system to anchor the tree. This study indicates that root morphology is important for the mechanical tree stability and that a young unstable tree becomes more stable over time. The speed with which this occurs is probably due to site factors determining root growth.

Seedlings reared in solidwall containers lack laterally directed root tips at lifting and during a period after outplanting (Fig. 9). Root growth is therefore restricted to the bottom drainage hole the first season after outplanting, whereas roots of naturally regenerated trees are free to colonize the soil at any depth (Balisky *et al.*, 1995). If the containers have slits in the wall, roots have the possibility to explore the soil at any depth in a similar manner as naturally regenerated trees, which favours tree stability (see Fig. 9).

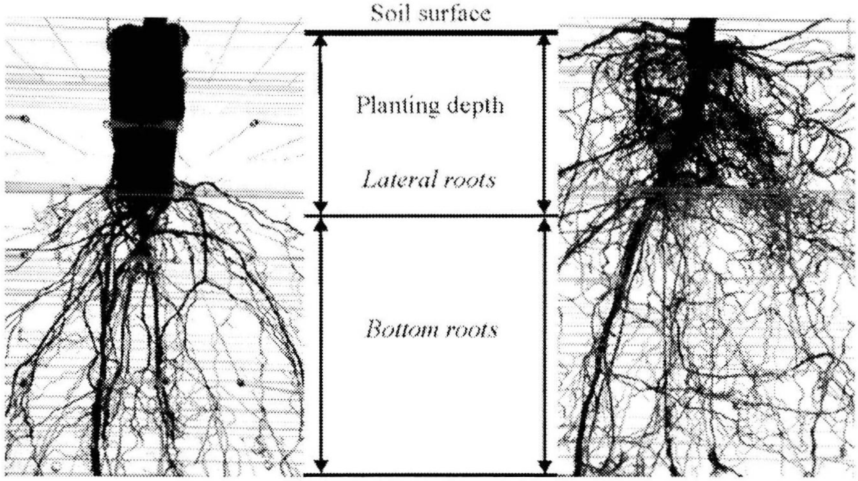

Fig. 9. Root systems from seedlings reared in a solidwall container with inside ribs for root guidance (left) and seedlings reared in a slitwall container system (right) after one growing season in a root study box according to a method described by Lindström (1982). (Orig.).

The pattern when a tree loses root anchorage in the soil is probably different for juvenile and mature trees. A juvenile tree has a flexible stem. Frost heaving may therefore at that stage be more serious than external forces such as wind and snow-loading. Later, when stems become stiffer, the tree may suffer more from wind and snow-loading, resulting in breakage of lateral roots or losses of the root-soil plate (Coutts, 1983).

Stem straightness and basal sweep

Naturally regenerated trees had straighter stems compared to planted trees (I). The absence of basal sweep for naturally regenerated trees can be attributed to the natural root structure anchoring the tree firmly in the soil. In the younger stands it was found that naturally regenerated Scots pine trees had straighter stem bases than container-grown trees (I). Also older naturally regenerated trees had straighter stem bases than planted trees, but the difference was smaller. This indicates that young trees affected by juvenile basal sweep are straighter over time. Straighter stems of naturally regenerated Scots pine trees compared to planted have been reported by Kärkkäinen & Uusvaara (1982), Burdett *et al.* (1986), Strand *et al.* (1997) and Agestam *et al.* (1998). The single-sided development of compression wood within the inner growth rings (III and IV) and the high frequency of basal sweep among young planted trees (I, II and III) indicate that mechanical tree instability has occurred during an early period of their growth.

Scots pine trees cultivated in slitwall container system and grown at the high fertility site had straighter stem bases than trees cultivated in a nursery in solidwall containers (II). At the poor site no significant difference concerning stem straightness and proportion of basal sweep were found between the container systems. Lines (1980), Auburlinder (1982) and Anon. (1987) also found that high soil fertility negatively affects juvenile pine stability. To achieve straighter stem bases, especially on fertile sites with a dense soil type, these observations emphasise the importance of a non-deformed root system. In general, trees cultivated in a nursery in containers that contribute to poor root morphology are more sensitive to external forces such as wind, snow loading and frost heaving, resulting in higher frequencies of basal sweep than trees grown in container systems that promote a natural root development (II).

Study I shows that young trees with basal sweep will be straighter over time and forms a normal appearing bole, hiding the fact that the trees may contain a large amount of compression wood. In study IV the degree of basal sweep in the basal 50 cm of the stem was measured on the same planted trees in 1986, 1997 and 2001. After 7 growing seasons (1986), 60% of the 440 Scots pine trees had straight stem bases and by 1997, this had increased to almost 89%. Studies have earlier emphasised the ability of a tree to straighten over time (Burdett *et al.*, 1986). However, measurement on the same trees during 22 years of growth showing that a tree with juvenile basal sweep will straighten over time has, to my knowledge, never been reported before.

Poor root morphology due to *e.g.* an inappropriate container design or dense and fertile soil type are only two factors that influence mechanical tree stability and subsequent basal sweep formation. Root system morphology is also influenced by environmental conditions. Therefore it is difficult to determine the influence of initial root system morphology on anchorage (Coutts, 1983). Wright & Boldwin (1957) showed that growth rate positively correlated with stem deformation in a Scots pine provenance test. Studies on lodgepole pine have confirmed this (O'Driscoll, 1980; Rosvall, 1994). Study II and III showed that Scots pine grown on a fertile site and a dense soil type were higher and had a higher frequency of basal sweep than trees grown at a poor site. According to Nambiar & Sands (1993), the reason for stability problems on fertile sites is the abundant supply of nutrient in the soil, which may decrease the stability as a result of changed allocation of growth and the increased growth itself. This results in a low root:shoot ratio. Despite an increase in root growth as a result of increased soil fertility, root growth is less compared to above ground growth. Root deformation in terms of, *e.g.*, number of spiralled roots and unevenness of roots in the four defined quadrants (RAI) seems to be of minor importance for the ability of the root to supply the plant with water and nutrition (Cabrera & Woods, 1975). A positive correlation between degree of root deformation and a large increment rate of above ground part of the tree was found by Wibeck (1923) and more recently by Grene (1978). One reason for this can be that trees with a superior growth potential develop a large root system, causing high risks for root deformation in nursery and field (Jansson, 1971). On the other hand Halter *et al.* (1993) and Lindström & Persson (1996) reported decreased growth for trees with root deformation.

A leaning tree develops basal sweep as the shoot resumes growth in an upward direction with the aid of compression wood formation on the lower side of the sweep or the leaning stem (Fig. 10). The stem recovery pattern shown in Figure 10 was initiated at the top and proceeds slowly downward to the stem base, which is an observation in accordance with Yoshizawa *et al.* (1986).

The forces leading to the righting of the inclined stem are generated in compression wood formation. Cremer (1998) mentions that trees up to the height of 2 m readily grew upright again, even after severe tilting, and usually straightened satisfactorily, except at the very base. According to Mason (1985), a young established pine tree that is leaning 15 degrees will probably retain the defect. As a consequence a relatively limited basal sweep can be expected. For a larger tree the process will take longer, leading to a relatively large basal sweep and more compression wood formation. Mason (1985) also stated that a young tree leaning more than 45 degrees would never be able to conceal the basal sweep. Neither oblique notch planting nor the seedling leaning from the vertical as a result of a negligent planting is a problem if the root system is able to immediately colonize the soil to any depth (see Fig. 9). If the root system of a leaning seedling is fixed in the soil, the stem recovery pattern is rather quick and compression wood will be formed close to the pith (Fig. 10).

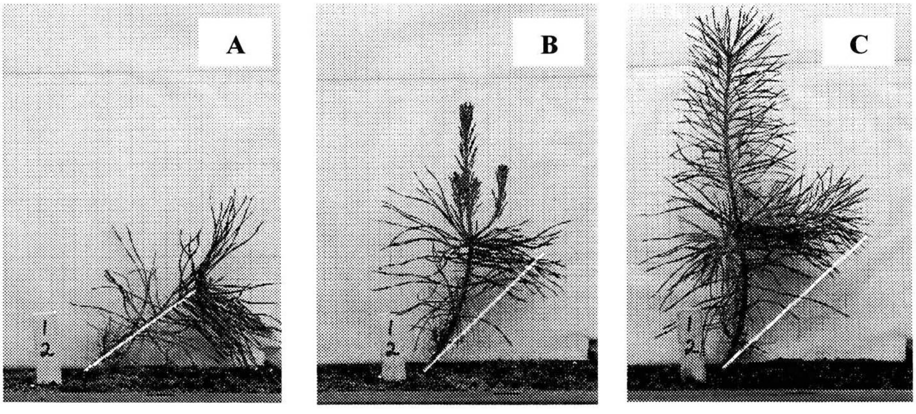

Fig. 10. Development of basal sweep. The seedling was planted in a box at an angle of 45° from the vertical and was grown for 30 days in a greenhouse. Image A=day 0, B=day 15 and C=30 days after planting. (Orig.).

Compression wood content and distribution, pith eccentricity and out-of-roundness

Compression wood content and distribution, pith eccentricity and out-of-roundness were measured on planted trees. Compression wood was found in all examined stems (III, IV). In general, compression wood content increased with increased degree of basal sweep for 6-year-old Scots pine trees (III) but not for the 22-year-old Scots pine trees (IV) (Fig. 11).

Basal sweep among the young trees in study III had not yet been concealed by eccentric growth and therefore the correlation between compression wood and the size of basal sweep is significant. In study IV, trees with juvenile basal sweep had been concealed over time by eccentric stem growth.

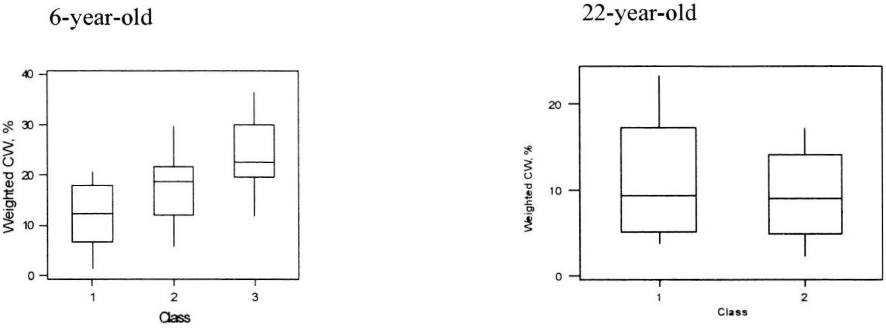

Fig. 11. Box plots of the weighted compression wood content in the basal 30 cm part of 6-year-old Scots pine trees in study III (from study III) and in the basal 60 cm part of 22-year-old Scots pine trees in study IV (orig.) for the basal sweep classes: 1: <4°, 2: 5-15°; and 3: >15°. Weighted CW = severe CW + 0.5 × mild CW.

Today these stem bases appear straight, which hides the fact that they contain large amounts of compression wood. Cross-section of these stems showed an obvious pith eccentricity, *i.e.* deviation of the pith from the geometric centre, indicating eccentric stem growth. At an early stage, in 1985, after seven growing seasons, no significant differences in pith eccentricity were found for the basal 1.2 m part of the stems irrespective of the stem form (Fig. 12).

In 2000, 21 years after planting, significant differences were obtained for pith eccentricity between different trees depending on their development of basal sweep (IV). Trees that had basal sweep in 1997 are still increasing their pith eccentricity, whereas trees with straight stem bases 1997 show a constant centric pith position. This indicates that concealment of the sweep by eccentric growth was completed for those trees appearing straight in 1997. Concealment of the sweep resulted in a straighter stem form and a reduction of compression wood formation. For straight stems no compression wood could be found in the outer growth rings. This is supported by Miller (1974) who studied radial growth in sinuous stems of radiata pine and found no compression wood in the extra wood that was formed since the stem segment was straight. Results from study IV indicate that the share of compression wood as well as pith eccentricity will be reduced when the basal part of the stems appear straight.

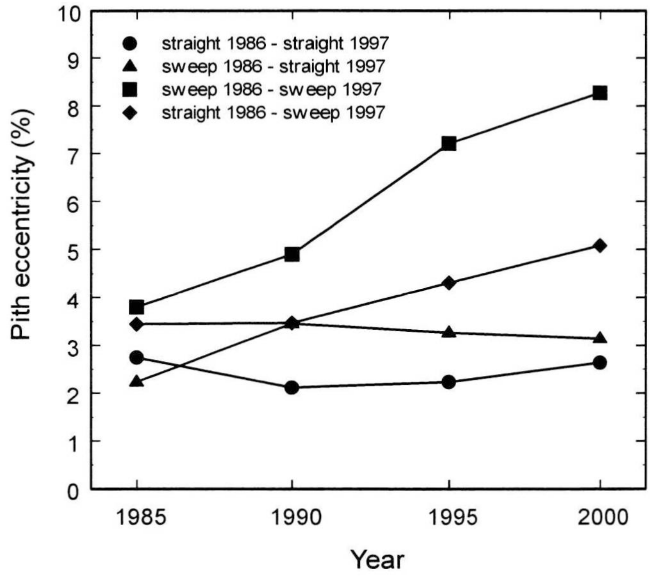

Fig. 12. Pith eccentricity (%) expressed as mean values for wood discs taken from 0, 0.6 and 1.2 m height representing growth intervals: 1982-1985, 1982-1990, 1982-1995 and 1982-2000, for Scots pine trees with straight stem base in both 1986 and 1997, straight stem base 1986 and basal sweep 1997, basal sweep both 1986 and 1997 respective basal sweep 1986 and straight stem base 1997. (From study IV).

Severe compression wood was found in all stems, but the stem height with registered compression wood varied among the four categories. Moreover, the extension of severe compression wood in the stem varied (Table 3).

Table 3. *Average (±standard error of the mean) and max. stem height with registered severe compression wood for stems in category 1 to 4. (n=15). (From study IV).*

Category[1]	Average stem height (cm)	Max. stem height (cm)
1	120±0	120
2	165±38	240
3	195±51	300
4	150±71	300

[1]Category 1: trees with straight stem base in 1986 and 1997, category 2: straight stem base 1986 and basal sweep 1997, category 3: basal sweep 1986 and 1997, category 4: basal sweep 1986 and straight stem base 1997.

Compression wood will be formed in the new growth rings as long as the stem or stem section is displaced from the vertical (Timell, 1986). Therefore, the location and appearance of compression wood in stem discs can be used to reveal the time for start or end of tree leaning. Among trees with basal sweep in 1986, single-sided compression wood was observed in growth rings five to eight from the pith in the butt end discs. This indicates that trees were inclined from 1983 to 1986. This is also in accordance with the observations of the temporal pith eccentricity showing that all trees had similar pith eccentricity in 1985. In study III it was observed that cross sections from the 6-year-old trees were almost circular even though they had an eccentric pith position. As a consequence, investigations of the relationship between compression wood content in basal part of stems and the size of stem sweep have to be conducted before the sweep is concealed. This is important because the basal part of the stem from older trees contain compression wood although they appear straight. Eccentric growth in coniferous stems without formation or only a weak formation of compression wood is not unknown (Burdon, 1975; Barger & Ffolliott, 1976). In this study (III, IV) compression wood formation and eccentric stem growth are significantly correlated. However, from this study it is impossible to estimate any limits for tree size or size of basal sweep that can be concealed by eccentric growth.

A spiral compression wood pattern was found in the basal disc in some of the trees (III and IV). This indicates that the lean direction of these trees has changed over time. The large amounts of single-sided severe compression wood found in some of the basal discs of the trees (IV) indicate a large basal sweep formation in only one direction. The absence of spiral compression wood in the basal discs of these trees indicated that the anchorage of the root in the soil had improved over time or that a large size of the lean makes it impossible for the tree to lean in the opposite direction. This is supported by study I, showing that mechanical stability of young containerised trees would be improved over time.

In conclusion, this thesis shows that the risk for root deformation is larger for Scots pine seedlings grown in solidwall containers with inside ribs than in slitwall containers with slits in the sidewall. This thesis also shows that root deformation cause mechanical tree instability and subsequent basal sweep formation, especially at high fertility sites with a dense soil type. The formation of basal sweep is always associated with compression wood formation. Compression wood will only have a limited influence on wood value if the tree at an early stage overcomes the instability resulting in a straight and upward growth direction. On the other hand, if the instability remains for a longer period the compression wood formation will continue resulting in lower value of the log.

Practical implications and further research

The effect of the container design on subsequent field establishment depends to a large extent on soil type and site fertility. In this study, basal sweep formations were more common for trees grown at the high fertility site representing a dense soil type. Under these conditions, trees grown in hardwall containers had an increased incidence of basal sweep compared to trees grown in containers with slitwalls. This study indicates that stem form of Scots pine can be improved by the use of a container type that promotes more natural root morphology. This can best be achieved by growth in slitwall containers and pruning of lateral roots.

Repeated mechanical root pruning during growth in the nursery could result in a better balance between the root and shoot part at outplanting. Further investigations are needed to study the impact of different pruning methods on the water uptake of seedlings. Besides the risk of severe water stress after outplanting of mechanically pruned seedlings problems with nursery growth of seedlings in slitwall container systems are desiccation of the peat and difficulties to use other substrates than peat as a growing medium. For example, a coarser growing medium than peat, *e.g.* decomposed bark, may not be reinforced sufficiently by roots, resulting in disintegration of the substrate when lifting the seedling from the container at outplanting. This may limit the use of slitwall containers.

Planting with seedlings cultivated in containers imply a risk of future mechanical instability, especially if seedlings are cultivated in a container of unsuitable design. Root morphology and mechanical tree stability can be improved by methods that minimize effects of nursery growth and planting on root form. One approach is to plant small seedlings, which retain the capacity to initiate first order lateral roots. After planting, such seedlings establish a system of primary laterals that is unaffected by nursery factors or planting. Generally when using hardwall containers a shorter growing time in the nursery reduces risks of instability problem caused by root deformation.

According to the Swedish Timber Measurement Council (Anon., 1999), there are five quality classes for pine logs: A class 1 to 3 log must be a butt log or middle log and be almost completely straight, *i.e.* its bow height should be no more than 1% of the log length. Class 5 logs expected to yield sawn timber have low quality requirements. All the examined trees would today pass the quality grading requirements for class 1 to 5. Whether they will be able to pass the quality grading requirements when they are older is uncertain because compression wood formation still is ongoing in several of the trees (IV).

From this thesis it is evident that young Scots pine trees with basal sweeps will be straighter over time. Eccentric stem growth and compression wood formation play a major role in this process. As a result, the logs that have become straight contain large amounts of compression wood. As a consequence, log straightness is not a reliable measure of the internal log quality regarding compression wood content. The correlation between amount of compression wood in log ends and deformations on sawn wood needs to be further investigated.

This thesis indicates that chance of selecting trees containing compression wood as a consequence of basal sweep formation is little at the time of first commercial thinning as most trees then were straight. However, it is possible to identify trees with a potential to develop compression wood at the time of precommercial thinning. Therefore the precommercial thinning shall be focused at trees with basal sweep.

Due to the long period of time between nursery growth of seedlings and the time of commercial thinning, which in Sweden is between 20 and 40 years, the work with this thesis has raised a number of questions. For example, the economic significance of mechanical tree instability is difficult to predict, but since mechanical instability usually results in basal sweep, it would be expected that lumber recovery and value would be reduced. Therefore an assessment of the area affected by instability and stem deformation would be desirable. Such input data could be used for modelling tree and stand level quantification of potential losses in wood volume, wood quality and product value in economic terms for commercial species in Sweden. This could be achieved by:

- Identification of stands affected with instability and basal sweep formation.
- Identify the locations of existing containerised seedlings and soil preparation trials for further measurements.
- Examine the relationship between stem deformations and various wood and fibre properties.
- Create recommendations for commercial thinning strategies in stands with a high incidence of unstable trees and provide information on the impact of stand age on tree stability.
- Extrapolate information on the incidence of unstable stands in relation to silviculture and soil properties to model the potential effects of instability on wood supply on a forest management unit and on regional basis.

Further research is also needed to improve nursery practices and container systems and to determine the effects of containerised seedlings on quality of sawn woods for different species. Probably the container effect on stem straightness is larger for pine than for spruce because pines do not form adventious roots (Selby & Seaby, 1982) after planting that may compensate for malformed roots. As a consequence, pine probably suffers more from growth in solidwall containers than spruce and is more sensitive to external forces such as wind, snow loading and frost heaving. However, to my knowledge little is known about how field establishment *e.g.* stability and stem straightness of Norway spruce is affected by container growth in the nursery. In addition, the newest commercial seedling assortment in Sweden,, hybrids between containerised and bare root seedlings, termed Plug+ and T+, which mainly were created to produce spruce, has never been satisfactory evaluated despite over 15 years production.

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