New technical and alternative silvicultural approaches to pre-commercial thinning

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Abstract

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In the last decade relative pre-commercial thinning costs have increased, as a proportion of total silvicultural costs, and the annual area treated with pre-commercial thinning has decreased, partly because stands are denser and the development of tools has been slow compared to advances in tools for other forestry measures, calling for new methods and techniques to be developed. Reducing competition by topping secondary stems might be an attractive alternative to traditional pre-commercial thinning for biological, technical and financial reasons. However, the topped secondary stems must not overtop the main stems and should not present obstacles at the time of the first commercial thinning.

Topping, i.e. top-cutting or top-breaking of secondary stems, was tested in birch (*Betula sp*.) stands with the background that increased competition from topped secondary stems may promote higher quality in the main stems and that topped secondary stems might die and disappear by the time of the first commercial thinning as a result of treatment. Furthermore, growth of the topped birch stems was studied after treatment in different seasons. Motor-manual equipment for topping and a mechanised prototype were tested in an experimental rig and the mechanised prototype was also tested in a field experiment. All tools were compared with a conventional brush saw, regarding both time requirements and quality of work.

Results indicated that topping, especially at a higher level above ground leading to a smaller height lead for the main stems, gave a significant increase in main stem quality of birch, compared to traditional pre-commercial thinning. Secondary stems showed higher survival after topping compared to traditional pre-commercial thinning, but topping at a lower level above ground gave lower survival than topping at a higher level. No differences in growth or survival were detected between top-cut and top-broken stems over three years and survival and height growth was lower for stems treated in a growing condition compared to stems treated earlier in the year. Despite having a significantly less powerful engine, a motor-manual pole saw prototype designed to be used for topping was a competitive alternative to the brush saw in terms of both time consumption and damage to the residual stand. The mechanised prototype seemed to be a competitive alternative in high diameter and dense stands. Although the quality of work obtained with the mechanised prototype was equally high to the quality obtained with the brush saw, the results regarding time requirements for the mechanised prototype from the experimental study could not be verified in field experiments, resulting in a faster operation under field conditions with the brush saw irrespective of type of stand. It was also concluded that current standards for time requirements for brush saws might need to be revised, and that the height/diameter ratio might have an important influence on the time requirements for both motor-manual and mechanised pre-commercial thinning tools.

Topping seemed to be an attractive alternative to traditional pre-commercial thinning. However, further studies with varying initial and remaining stand density, stand height, species composition and tests of other possible advantages, e. g. reduced browsing pressure on main stems and reduced time requirements for mechanised tools when the cutting height can be raised above obstacles, should be performed. Tools for topping could be developed that would give equal or better results with respect to both quality and costs compared to the traditional brush saw. Mechanised equipment for pre-commercial thinning that can give acceptable results in terms of quality of work are available, but further development is needed in order to lower time requirements.

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Contents

Appendix

Papers I-IV

The thesis is based on the following papers, which will be referred to by the corresponding Roman numerals in the text:

I. Fällman, K., Ligné, D., Karlsson, A. & Albrektson, A. 2003. Stem Quality and Height Development in a *Betula*-Dominated Stand Seven Years After Precommercial Thinning at Different Stump Heights. Scandinavian Journal of Forest Research 18: 145-154.

II. Ligné, D., Karlsson, A. & Nordfjell, T. 2004. Height development of downy birch following pre-commercial thinning by breaking or cutting the treetops in different seasons. (Manuscript).

III. Ligné, D., Nordfjell, T. & Karlsson, A. 2004. New techniques for pre-commercial thinning – time consumption and tree damage parameters. (Accepted manuscript, International Journal of Forest Engineering).

IV. Ligné, D., Eliasson, L. & Nordfjell, T. 2004. Time consumption and damage to the residual stand in mechanised and motor manual pre-commercial thinning. (Manuscript).

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Introduction

Silviculture and applications

The first mention of a measure similar to pre-commercial thinning (PCT) in Swedish literature appears in a text by af Ström (1822), who described a silvicultural treatment that did not generate direct revenue and was designed to level out the tree crowns in height by cutting undesired stems at ground level. Recommendations concerning the desired number of remaining stems ha^{-1} and more direct advice on which stems to cut can be found in later papers by af Ström (1830, 1839, 1853). The Swedish term for PCT in its present form (röjning) is first found in Björkman (1877), who also gives recommendations concerning the numbers of stems ha^{-1} to leave and timing for the operation, depending on the species involved. Björkman (1877) was also the first to recommend the cutting of pioneer species, such as birch (*Betula sp.*) and aspen (*Populus tremula* L.), in mixed stands, primarily to favour conifers.

By the beginning of the 20th century knowledge about PCT and its consequences were quite well developed, and processes like self-pruning and different species` requirements from the surrounding environment were understood almost as well as they are today. The economic rationale for PCT had also been well described and different recommendations on how to perform the measure, depending on the specific intentions and interest demands were available (cf. Obbarius 1857a, 1857b, Brynte 2002). The current Swedish definition of PCT, loosely translated from Swedish, "a tending removal of trees, without extraction of merchantable timber" (Anon. 2000a) is almost identical to the one given by Wahlgren (1914). Wahlgren (1914) also developed different programs for tending different species and thoroughly described how to achieve high quality for the different species with species-specific timing and types of PCT.

Thoughts and recommendations concerning PCT for nature conservation and aesthetic considerations were developed early in the 20th century by Wahlgren (1914) and Amilon (1923). These authors advocated the use of broad-leaved species along roads and rivers, and recommended using a general mixture of species wherever possible, to spread risks and favour wildlife. In addition, ideas on how to encourage wildlife, especially hare (*Lepus timidus*) and moose (*Alces alces*) by conserving wildlife zones in suitable parts of the stand were well developed (cf. Wahlgren 1914, Amilon 1923).

The idea of adapting the PCT to different conditions prevailing in different parts of the stand (site adaptation) and adapting the treatment program to the regeneration measures are developed by Juhlin Dannfelt (1947) and Sundin *et al.* (1955). In order to maximise the future outcome from the stand the choice of regeneration methods and subsequent PCT programs should be considered jointly to minimise their costs. The first reference to PCT in the Swedish Forestry Acts is found in the Act of 1948, where the measure is considered part of the regeneration process (Ekelund & Hamilton 2001).

Af Zellén (1904) suggested rationalising methods for PCT through breaking or cutting the undesired stems at a higher level above ground (0.5-1.5 m) than previously recommended (*c.* 0-0.2 m) and girdling thicker stems. These ideas were developed further by Beer & Sjöholm (1914), who discussed the effects of cutting birch trees at different heights in order to eliminate them in favour of Scots pine (*Pinus sylvestris* L.). The idea of cutting or breaking secondary stems at a higher level above ground has also been described in other parts of the world. In Germany the method has been described for Scots pine (Wagenknecht & Henkel 1962), and in Great Britain the method has been used in Sitka spruce (*Picea sitchensis* (Bong) Carrière) plantations (Harris 1986). Raulo (1987) suggested topping as an attractive alternative for birch in Finland and the method can also be seen in practical use in the Baltic States and eastern Europe (D. Ligné pers. obs. 2002). Furthermore, the method has been used in steep areas to give main stems support from secondary stems in order to protect them from stresses such as snow pressure (cf. Loycke 1965, Mayer 1984).

Ebeling (1955) focused on the northern parts of Sweden, and gave many recommendations on how to tend a stand in order to avoid calamities such as snow-breakage and fungus attacks. In the same publication, Ebeling also developed the idea of forming a crown surface that was as even as possible in order to maximise the growth and quality of the stand. In contrast, Hagner (2004) suggests an uneven crown surface should be created in young stands, either naturally or with PCT, to maximise the quality of the stand. Bergman (1955) investigated the potential importance of the time of year in which PCT is carried out; giving recommendations that were primarily designed to avoid leaving suitable nesting material for insects (cf. Andersson 1961). Nordström (1961) was the first author to adapt the timing of PCT to large numbers of moose, suggesting that the measure should be delayed until the average stand height has reached 3.5 m in situations where there are likely to be large numbers of browsing moose.

In the early 1950´s research concerning the production of young forests and factors limiting growth were investigated on a more scientific basis (Vestjordet 1959). Pettersson (1951a, 1951b) developed yield tables for young forests and made financial calculations based on the results. Holmgren (1954) also considered stem quality aspects and the effects of different spacings; testing different regeneration methods and types of PCT. However, much of today's knowledge is based on the findings of Andersson (1952, 1963). There was not much difference between his results and earlier recommendations, but Andersson verified them scientifically. His work was continued by Eriksson (1977, 1981) and Pettersson (1992), who further monitored the development of Norway spruce (*Picea abies* (L.) Karst.) and Scots pine following PCT at different spacings, and developed growth and stem quality models for young stands.

At the same time as Andersson in Sweden, Vestjordet undertook similar experiments, and came to similar conclusions, in Norway (Vestjordet 1971, 1977, 1979). The same type of research took place in Finland, according to a literature review by Fryk (1984). The development of PCT in other parts of the world is not easy to describe, since the measure, species and definitions differ significantly, depending on where it was performed and/or described (cf. Ryans 1988). Current definitions abroad, however, are similar to the one used in Swedish forestry; e. g. *removal of trees not for immediate financial return but to reduce stocking to concentrate growth on the more desirable trees* (Helms 1998), and *cutting in an immature crop or stand to improve crop spacing and to accelerate the diameter increment of favoured trees and/or form the trees that remain* (Anon. 2000c).

The transformation of Swedish forestry after the second world war, from a selection system to a clear cutting system also led to larger areas requiring PCT on a more rational basis (Bäckström 1984). Consequently, a lot of ideas and new tools were tested to find more rational and cost-effective ways to tend the young stands (Bäckström 1984). However, the PCT method has been relatively constant over time with respect to parameters such as the numbers of remaining main stems ha^{-1} (Fig. 1) and cutting height, the standard approach being to cut secondary stems just above the ground. The only exception being a period during the 1970´s when assumptions of poor economic conditions for Swedish forestry led to initiatives by the forest companies Iggesunds Bruk AB and SCA AB to reduce significantly the number of main stems left after PCT to enhance growth and reduce the number of commercial thinnings (Anon. 1969, Andersson 1973, Fryk 1984) (Fig. 1).

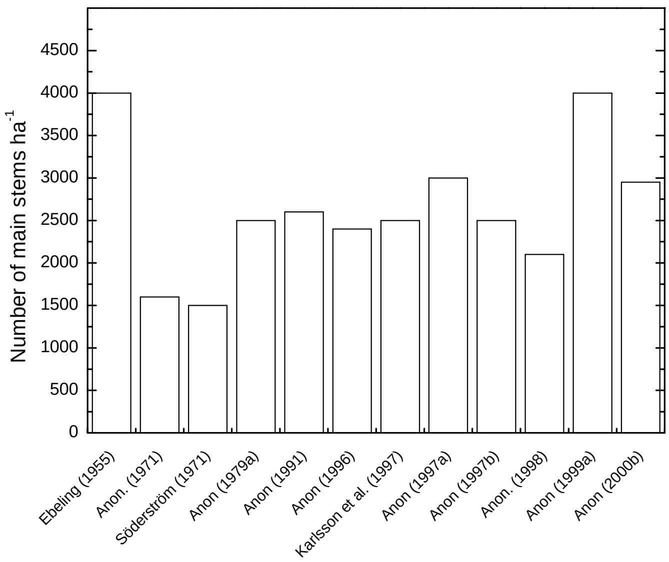

Figure 1. Number of main stems ha^{-1} to leave after pre-commercial thinning in young stands of Scots pine (*Pinus sylvestris*), as recommended by various authors in the period 1955-2000, site index T24 (cf. Hägglund & Lundmark 1987).

Finnish scientists started early to investigate the potential of birch as main stems (Saramäki 1973, Raulo 1987). In the early 1980´s a lot of Swedish research was also concentrated on the importance of broad-leaved species, especially birch, in young forests (Elfving & Nyström 1984, Andersson & Björkdahl 1984, Bärring 1984). As a result of technical developments in soil scarification and a more liberal attitude towards broad-leaved species the number of stems ha^{-1} started to rise significantly during the early 1980´s, which increased the importance and costs of PCT (cf. Johansson 1984, Anon. 1988, Fryk 1989) (Fig. 2). Stump sprouts from previously cut secondary stems also posed problems, and their growth was thoroughly investigated in order to optimise the PCT timing to minimise the number of pre-commercial thinnings (Andersson & Björkdahl 1984, Johansson 1986, 1987, 1992a, b).

In the 1990´s a new phase, in which PCT activity steadily decreased in young forests occured (Fig. 3). The obligation to carry out PCT in stands that fulfilled certain density criteria, which was introduced in the Forestry Act of 1979, was removed from the Forestry Act of 1994 (Ekelund & Hamilton 2001). Furthermore, it was difficult to attract personnel, especially in northern Sweden where PCT was only performed on a seasonal basis due to snow conditions, to do this type of work (Ekelund & Hamilton 2001). The fact that PCT activity has decreased has been reported to be one of the largest problems in Swedish forestry currently, and the government has expressed concerns regarding this development (Anon. 2002).

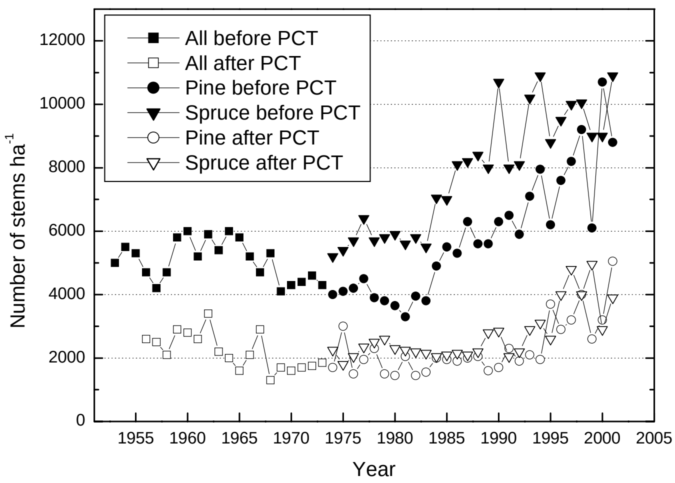

Figure 2. Total number of stems ha^{-1} in young pine- and spruce-dominated stands before and after pre-commercial thinning is Sweden, 1952-2001 (Nilsson 2003).

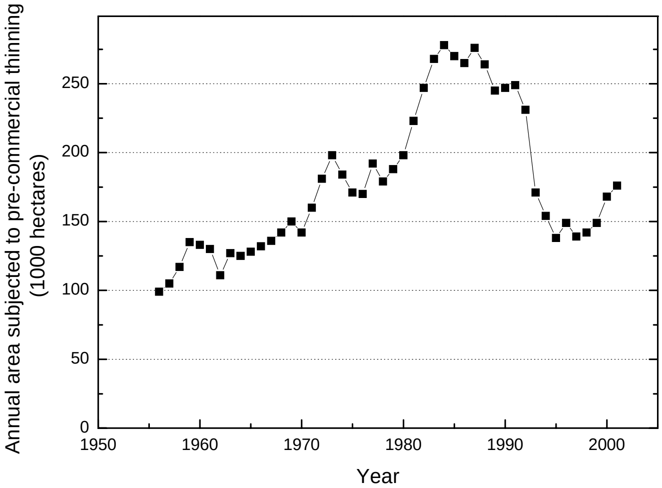

Figure 3. Annual area subjected to pre-commercial thinning in Sweden 1956-2001. (Anon. 2004a).

Technique and applications

The main tools recommended by Wahlgren (1914) for PCT were a brash hook and a specialised type of shears. For birch, breaking treetops by hand is recommended and birches shorter than 1 m are best removed by simply pulling the whole trees up (Anon. 1914). Bulley *et al.* (1997) investigated the productivity of breaking the tops of secondary jack pine (*Pinus banksiana* Lamb) stems by hand, in comparison with conventional PCT with a brush saw. It was concluded that with densities between 8000-24000 stems ha^{-1} the breaking treetops at waist height was preferable from a productivity perspective. In the lower part of this density interval breaking was twice as fast as using a conventional brush saw, but the difference decreased with increasing number of stems ha^{-1} (Bulley *et al.* 1997). Callin (1950, 1954) tested productivity for a number of manual tools and also developed productivity norms for use in cost calculations. It was concluded that in stands higher than 1.5-2 metres the Sandvik cleaning axe was to be preferred (Callin 1954). Kährä (2002) studied similar tools in stands similar to those tested by Callin (1954), with a stump diameter of 2-3 cm, and concluded that the productivity obtained with the best manual tools was about 30-35% of corresponding figures for the brush saw which is the mainly used tool for PCT today.

The first Swedish trials of another approach, killing unwanted broad-leaved trees (mainly birch) with chemicals, were carried out in 1944 (Rennerfelt 1948). Subsequently there were rapid developments in chemical methods and the area treated expanded (Rennerfelt & Fransson 1949, Ebeling 1950, Fransson 1952). In the 1950´s various chemical methods were tested and the practical use of chemicals became widespread (Häggström 1955, 1956a, b, Bärring 1956, 1958a, b). The use of herbicides steadily increased in Sweden until 1969, when 92000 ha were treated (Ekelund & Hamilton 2001). The use of herbicides in Swedish forestry became a major issue in the late 1970´s for Swedish society as a whole, and the use of chemical substances for PCT was prohibited in 1979, starting the first major crisis of confidence for forestry and the methods used (cf. Andrée *et al.* 1979, Ersson 1981, Olsson 1985, Löf 1993). Investigations (Anon. 1971b, 1974,

1980) and adverse public opinion eventually led to a permanent prohibition in 1983 of the use of herbicides in Swedish forestry, apart from certain exemptions that required special permits (Bäckström 1984). The use of similar substances remained widespread in other parts of the world (Jakkila & Pohtila 1978, Söderström 1980), and they were still used in some countries in the 1990´s (Ryans & Cormier 1994).

In the 1950´s, some years after the first chemical treatments were developed, the motor-manual brush saw was introduced to Sweden (Anon. 1988). Callin (1957) was the first to study its productivity and concluded that PCT with a 12.0-16.5 kg brush saw was *c.* 40 % faster than with the Sandvik cleaning axe. When comparing these early brush saws with the models described later and today's saws it is obvious that the weight and ergonomic qualities (especially with regard to vibrations) of the saws have improved (Callin 1957, Hägglund & Petterson 1974, Åkerman & Österlöf 1976, Ryans 1988). Today's brush saws weigh only about half as much as the first types and there have also been improvements in both harnesses and blades (cf. Anon. 2004b). In addition, advances in work organisation, rationalisation of the working teams, better planning instruments and saw reliability have all enhanced productivity over the years (cf. Pettersson 1973a, b, Ryans 1988).

At about the same time as the brush saw was introduced in the United States, in the late 1940´s, the process of mechanising PCT also started (Ryans 1988). Until the 1980´s, mainly schematic-geometric tools and methods were tested in the United States and Canada (Ryans 1988, Ryans & Cormier 1994). In Sweden in the early 1970´s it was difficult to recruit people for silvicultural work and it was therefore necessary to develop equipment that required low manpower inputs (Bäckström 1971). Hägglund (1974) estimated that more than 200 PCT machines would be needed in Sweden by 1979. Hägglund divided the machines into two types, geometric and geometric-selective, and concluded that the latter would be the ones required in the largest numbers in Swedish forestry.

Theoretical studies on the mechanisation of PCT in Sweden started in the early 1970`s (cf. Berg *et al.* 1973), and the first practical experiments were performed with modified harvesters, working selectively, in 1978 (Arvidsson & Knutell 1976, 1978). By the early 1980´s the shortage of trained personnel, combined with an increased area in need of PCT and the ban on the use of herbicides, had created a PCT backlog (Mellström & Thorsén 1981, Bäckström 1984). Work on mechanisation began at a practical level and by the mid-1980´s three machines were in practical use, all modified 11-ton forwarders (Mellström & Thorsén 1981, Lindman 1985). Studies concluded that the final prototype could compete economically with motor-manual PCT in deleaved stands with initial densities of ≥10000 stems ha^{-1}. However, 8-10% of the remaining main stems were damaged by the machine (Petré 1983, Fries *et al.* 1985, Lindman 1987).

In the late 1980´s, testing of new base machines for mechanised PCT began, since the previous machines had low ground clearance and thus were only suitable for early operations to avoid damaging the main stems they straddled. A specialised PCT machine with high ground clearance, called Lillebror 504R, was therefore developed from a 6-ton single-grip harvester. It was competitive with motor-manual PCT at densities over 13000 stems ha^{-1} and damaged 3-6% of the remaining main stems (Lindman 1988, Lindman & Nillson 1989). A number of other small-to-medium sized single-grip harvesters were also tested as base machines for mechanised PCT (Eickhoff & Lindman 1987, Andersson & Karlsson

1991, Freij & Tosterud 1991, Nordmark 1993). There were also efforts to build highly specialised machines for PCT, but none of them were successful (Nordberg & Rudén 1988, Myhrman 1990). However, conditions changed, the anticipated shortage of labour failed to materialise and there was no problem to find labour on a seasonal basis (Freij 1989). This development, together with the poor cost effectiveness of mechanised PCT, led to a decrease in the number of operating PCT machines after a peak in the early 1990´s (Hellström 1991, Mattsson 1995), and by the end of the century no such machines were in operational use (cf. Glöde & Bergkvist 2003).

The cleaning heads used on the PCT machines of the 1980´s were in most cases rotary cutters with 2-4 teeth, although saw teeth units, rotating knives and chains mounted on discs were also tested and used (Glöde & Bergkvist 2003). The rotary cutter proved to be the best alternative, and the most used tools during the early 1990´s had diameters from 50 to 80 cm (Adolfsson 1991, Andersson & Mattsson 1993a).

Today, the vast majority of PCT is done with conventional brush saws in Europe. In North America, the situation is similar with a majority of the PCT being carried out with manual or motor-manual equipment (Ryans 1988). Despite the fact that a search among available patents found more than 2300 patents regarding PCT, no solution other than the brush saw seemed to be generally competitive at the end of the 1990´s (Ligné 1999). Although the brush saw has developed significantly over the years, development of other silvicultural measures, such as regeneration and harvesting, has been quicker and more effective resulting in a steadily increasing part of total silvicultural costs related to PCT (Fig. 4).

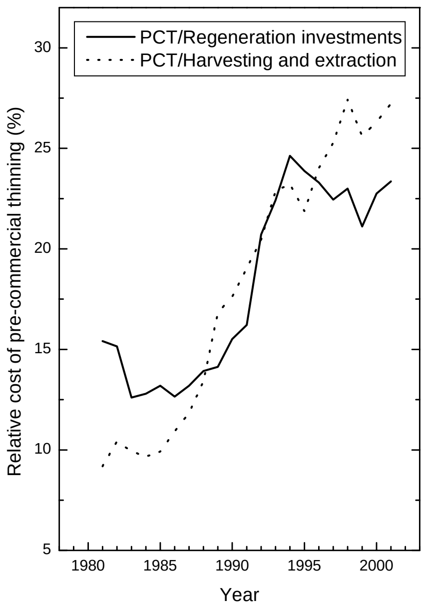

Figure 4. The average cost of pre-commercial thinning ha^{-1} relative to the average cost of harvesting and extraction of 100 m³sob (solid volume over bark) and average regeneration costs ha^{-1} in Sweden, 1981-2001 (Anon.. 1983, 1985, 1990a, 1995a, 2000d, 2003).

Silvicultural and technical aspects of topping

The effects of varying the number of remaining main stems, number of pre-commercial thinnings and timing of the measure (e. g. average height of the stand at the time for PCT) have already been thoroughly tested on a scientific basis. One of few possible ways left to vary the PCT treatment that could yield possible advantages, might be to vary the height and type of decapitation of unwanted secondary stems.

One of the possible advantages of topping is that secondary stems can continue to live and compete, which may promote better tree form, branch quality and diameter development in main stems (cf. Hochbichler *et al.* 1990, Collet *et al.* 1998). Another possible advantage is that the secondary stems may maintain their living biomass for a longer period, favouring biodiversity since, for example, they can provide attractive fodder for browsers, which may also decrease browsing damage to main stems (cf. Danell *et al.* 1985, Löyttyniemi 1985).

Topping may also facilitate the development of mechanised equipment for PCT and increase productivity in motor-manual and manual operations (cf. Bulley *et al.* 1997), since there are fewer obstacles, somewhat lower diameters and better visibility for the operator at a higher level above ground. New methods, such as schematic-geometric PCT, would probably also benefit from the possibility to cut secondary stems at a higher level, where visibility and cutting conditions are better. If it were possible, or even beneficial, from a silvicultural perspective, to cut or break secondary stems at a higher level above ground, it would significantly reduce restrictions on the development of new tools for PCT, and give more opportunities to construct cost-effective tools.

For topping to be an economically and practically sound method, the topped secondary stems must be suppressed or die from natural thinning processes, so that they neither catch up in height with the main stems nor become obstacles at the first commercial thinning. Earlier studies have shown that the smallest trees in a stand are those that are most likely to be self-thinned (Harper 1977, Nilsson & Albrektson 1994), therefore topping could be one way to reduce the competitive status of unwanted stems. However, after cutting at just above ground level, sprouts of secondary stems, of primarily birch, have been reported to grow very quickly and may grow ahead and overtop the main stems (Etholén 1974, Andersson & Björkdahl 1984, Kauppi *et al.* 1988). Therefore, a substantial height lead for main stems is recommended, and warnings against high stumps have been expressed, since sprouts from high stumps might compete even more vigorously than sprouts from lower stumps (Andersson & Björkdahl 1984, Johansson 1992a). Although low diameters (i.e. low proportions of juvenile wood) are desirable from a quality point of view (cf. Anon. 1999b), the diameter of stems in the first commercial thinning is a crucial factor for the productivity of the harvester, so competition from topped secondary stems cannot be too high, otherwise the diameter growth of main stems is likely to be low.

Karlsson & Albrektson (2000, 2001) investigated growth of topped secondary stems of birch and willow three years after treatment with top-cutting and top-breaking in different stands, respectively. Concerning top-cutting, it was concluded that in the lighter topping regime (giving the main stems a height lead of 0.6 m) main stems were still at risk of being caught up in height by the topped secondary stems. In the heavier top-cutting regime (giving the main stems a height lead of 1.1 m) the main stems were not at risk of being caught up in height after three growing seasons (Karlsson & Albrektson 2000). Furthermore, the importance of felling time was highlighted, and further studies on the influence of time of treatment on topped stems were suggested.

Concerning top-breaking, where the treetops were not completely snapped off, the height growth of topped secondary stems was not as aggressive as in the top-cutting experiment. After three growing seasons the main stems in the heavier topping regime (giving the main stems a height lead of 1.7 m), and a vast majority of the main stems in the lighter topping regime (giving the main stems a height lead of 1 m), were not at risk of being caught up in height by the top-broken secondary stems (Karlsson & Albrektson 2001). From this study it was concluded that top-broken secondary stems might have less vigorous height growth than top-cut secondary stems, and further studies on the two methods in the same stand were suggested.

One possible explanation for the less vigorous height growth of top-broken stems is that apical dominance may be maintained, and thus compensatory growth in the plant may be reduced or eliminated (cf. Maschinski & Whitham 1989, Rinne 1994). These studies indicated that topping of secondary stems could be of interest and a practically applicable method with respect to the growth of topped secondary stems. However, investigations on the theoretical advantages, such as improved quality development in main stems, and long-term perspectives on the growth and mortality of the topped secondary stems were still needed.

Objectives

The overall objectives of the work underlying this thesis were to test and evaluate new methods; topping through cutting or breaking the tops of secondary stems, and new techniques (both motor-manual and mechanised) for PCT. The overall believes in this thesis were that topping would be a usable method in terms of height growth and mortality of secondary stems compared to main stems, and that topping would give improved quality development in main stems compared to traditional PCT. Furthermore, topping might enable the development of new tools that could improve the quality and economy of the measure PCT by reducing the time requirements and/or improving the quality of the work. Conditions in young forests submitted to PCT have changed significantly in recent decades and studies of the productivity of today's brush saws in comparison with new mechanised equipment would be of great interest. The specific objectives of the four studies were as follows:

In study I three major questions were addressed. Firstly, is the birch main stem quality better after topping of secondary stems than after traditional PCT or no

PCT? Secondly, are main stems given a small height lead (Karlsson & Albrektson 2000) still at risk of being caught up in height by the secondary stems? Thirdly, are the survival rates for secondary stems reduced, and is the survival of these stems influenced by cutting height?

The objective of study II was to examine the growth of downy birch trees (*Betula pubescens* Ehrh.) that were cut or broken at half the stand mean height, or just above ground level, in various seasons of the year. In addition, tree survival rates and post-treatment damage (types and frequencies) to the stems were studied.

The objective of study III was to examine the time requirements for new motor-manual and mechanised pre-commercial thinning techniques, and the damage they cause to main stems, in comparison with the conventional brush saw in an experimental stand.

The objective of study IV was to compare mechanised and motor-manual PCT regarding productivity and damage to remaining main stems under field conditions. Furthermore, an analysis of factors that influence time consumption for each of the two tools was included.

Materials & methods

Sites

All field experiments described in this thesis (I, II and IV) were established in the county of Västerbotten, Sweden (Fig. 5, Table 1). This region has permanent snow cover for 140-220 days, from November - April (Anon. 1995b). The vegetation period is on average 120 – 170 days and temperature sums vary from 700-1100 day-degrees (Anon. 1990b, 1995b). Tree species studied were downy birch, Scots pine, silver birch (*Betula pendula* Roth) and willow (*Salix spp.*, species not separated). Together with Norway spruce, the above-mentioned Scots pine, downy birch and silver birch are the most common species in Swedish forests (Anon. 1996b, 2004a).

Study I

The experiment was established in a naturally regenerated 7-year-old stand on former farmland (an old potato field, site 2) (Table 1). Stand densities varied between 17000 and 41000 stems ha^{-1} higher than 1.3 m, of which downy birch accounted for 74%, willows for 21% and silver birch for 5%. The two birch species and the different species of willows were considered collectively as birches and willows, respectively.

A randomised complete block design was used, in which 12 gross plots of 15 × 15 m, with net plots of 8 × 8 m in the central part, were marked out. The plots were sorted into three blocks on the basis of stand density and within the blocks four treatments were randomly assigned to the plots. The treatments applied were: cutting of all secondary stems just above the ground, cutting of all secondary stems at a height of *c*. 40% (71 cm) and 70% (120 cm) of the mean height of the main stems (179 cm) and no PCT at all.

Before treatment main stems in the gross plots were selected among dominating and co-dominating birches at a spacing of approximately 1.8 × 1.8 m, resulting in about 20 main stems per net plot. After treatment, 20 secondary stems of birch and 20 of willow were selected using an imaginary grid with a spacing of 1.8 × 1.8 m and a randomised starting point.

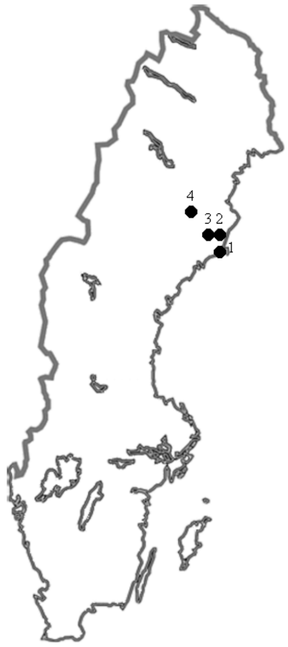

Figure 5. Geographical locations, in Sweden, of experimental field studies discussed in this thesis. For further details see Table 1.

Table 1. *Descriptive data for experimental sites discussed in this thesis, for geographical locations see Fig. 5*

Site:	Study:	Altitude (m a.s.l.)	Temperature sum (day-degrees) [a]	Vegetation period (days) [a]	Average length of snow cover (days) [b]	Site Index [c]	Time of establishment
1	II	15	1004	165	150	T 23	Nov 1998
2	I	70	910	150	165	G 26	June 1994
3	II	245	846	140	180	T 23	Nov 1998
4	IV	265	815	135	190	T 21	June 2002

[a] according to Anon. 1990b
[b] according to Anon. 1995b
[c] according to definitions by Hägglund & Lundmark 1987

The experiment was inventoried on six occasions from 1994 to 2000, and results from the first five occasions (1994 to 1996) are presented by Karlsson & Albrektsson (2000). The treatment responses of both main and secondary stems were evaluated by analysis of variance using the following variables: height, height increment since 1996, damage frequency and survival rate. For main stems only, the following variables were used to analyse stem quality and treatment response: diameter at breast height (1.3 m), height/diameter ratio, live crown height, number of forks per stem, proportion of stems without forks, diameter of the thickest branch, proportion of straight stems, proportion of stems without forks or damage and proportion of straight stems without forks or damage.

Since there were differences in starting height among the main stems, height in spring 1994 was tested as a covariate and included in the model when it lowered the mean square of the error (MSE) and/or had a *p*-value<0.2. To determine differences between treatments, Tukey´s studentised range test was used. For analysing differences in response variables within treatments between main stems and secondary stems of either birch or willow, and between secondary stems of birch and willow, paired sample *t*-tests were used. One-tailed *t*-tests were used to investigate differences between main and secondary stems. Between secondary stems of birch and willow, two-tailed *t*-tests were used (Zar 1999). Generally, differences were considered significant if $p<0.05$ and tending to be significant if $p<0.1$.

Study II

Two field experiments were established (Table 1) in stands that contained on average 20000-25000 stems ha^{-1}. More than 90% of the stems were naturally regenerated downy birch, which was the only species studied.

Both experiments were established with an identical two-factor (treatment × time of treatment) randomised complete block design. Three hundred sample trees were selected in each of the two stands, using a systematic spacing (3 × 3 m) with randomised starting point, among dominant and co-dominant birches. The sample trees were marked with permanent colour at breast height, and diameter and height were registered. In each stand the sample trees were then sorted into six blocks according to surrounding basal area within a radius of 0.8 m.

Three treatments were applied: top-breaking at “half tree height”, top-cutting at “half tree height” and traditional cutting just above ground level. “Half tree height” was defined as half the average height for the selected sample trees in each experiment, which were 1.55 and 1.75 m, respectively. All branches and twigs were broken or cut at the same level as the stem and top-broken stems were not completely snapped, leaving a connection between the top and the root.

The three times of treatments applied were: frozen conditions (March-April); dormant conditions (May) when temperatures were above 0° C, but before the beginning of shoot elongation; and growing conditions (June) when shoots had elongated about 3 cm.

At each site, control stems were left without treatment, resulting in a total of 10 combinations of treatment and time of treatment. Within a block the trees were randomly assigned to one of the 10 combinations, giving a total of five trees per combination and block.

The experiments were inventoried at the end of September in 1999, 2000 and 2001. Tree height and leading shoot length were recorded as well as damage and survival. For top-broken trees survival of the top was also registered.

The effects of treatment and time of treatment were evaluated by analysis of variance. Analyses of variance were performed using two models: the first to analyse the two-factorial randomised complete block design and the second to enable comparisons with the untreated control stems. Significant interaction terms in the first model were analysed with graphical methods and by numerical ranking of the mean values over blocks, treatment or time of treatment. To determine differences between treatments, Tukey´s studentised range test was used for balanced designs. When the design was unbalanced, due to missing values, least square means were calculated and differences were analysed with multiple *t*-tests with Bonferroni corrections (Zar 1999). Generally, differences were considered significant if $p<0.05$ and tending to be significant if $p<0.1$.

Study III

Four prototypes, three motor-manual and one mechanised, were tested in an experimental rig together with a conventional brush saw in 2000. The motor-manual prototypes were all designed by Husqvarna AB and based on two-stroke engines giving 38% of the power of the brush saw engine (Study III, Fig. 3a-e). The motor-manual prototypes were: a hacksaw, a pole saw with an angled brush saw shaft together with a modified chainsaw blade and chain (PS1) and a pole saw with a modified straight shaft together with a modified chainsaw blade and chain (PS2). The two pole saws had identical cutting heads with chain lubrication. All motor-manual tools were carried in a harness. The mechanised prototype was designed by Vimek AB and based on a modified 3-tonne, 1.6 m wide forwarder (Vimek 606). The machine had articulated steering and the rear part had a single-axle with Ackerman steering. The cutting device, placed in the tip of the 5 m parallel boom, was based on a newly developed circular cutting-squeezing device with a diameter of 0.65 m (EP 1 157 605) (Study III, Fig 4).

An experimental rig was built to allow identical stands to be constructed where the tools could be tested. The rig consisted of 10 identical modules, each with a central hole for the main stem and 12 holes where secondary stems could be placed, that were connected to a complete rig. In the central hole a Scots pine was placed as a main stem, and stems of downy birch were placed in the surrounding holes as secondary stems. The positions for the secondary stems in the 12 holes were randomly distributed under specific restrictions in order to get a realistic spread, and the positions were identical for all tools. Five densities of secondary stems were tested (1, 2, 3, 4 and 5 secondary stems per module), resulting in 10-50 stems in total. Each tool, except the hacksaw prototype, which had a maximum cutting diameter of *c*. 2.2 cm, was tested with three diameters of secondary stems:

2, 4 and 6 cm at the butt end of the stem. Each combination of tool, diameter of secondary stems and number of secondary stems was tested four times.

100 downy birch stems of each diameter for each tool were randomly selected in order to assess possible differences in the morphology and size of the trees. No differences concerning height, diameter and number of branches, respectively, were found.

Total time for cutting all the secondary stems in the rig and the amount of damage caused to main stems was recorded. One person operated all the motor-manual tools and another person operated the mechanised prototype.

The effects of the tools on time consumption were evaluated by analysis of variance, for each combination of number of secondary stems, diameter and tool. The effect of diameter and number of secondary stems on time consumption for each of the tools was also analysed by analysis of variance, following logarithmic transformation to avoid violating assumptions of normality and constant variance. Tukey`s studentised range test was used to analyse differences. Differences between the tools in the amount of damage caused to the main stems were analysed with Friedman`s rank test, to avoid violating assumptions of normality and constant variance (Zar 1999). Generally, differences were considered significant if $p<0.05$.

Study IV

A conventional brush saw (Husqvarna 252 RX) and a mechanised prototype (the same as in study III) were included in a comparative time study in a stand regenerated with planted Scots pine, although >80% of the numbers of stems were naturally regenerated downy birch. 100 parcels were established in parts of the stand where a need for PCT was identified. In each parcel (6 × 20 m), the total number of stems of the species present was recorded. Height and diameter at breast height of 40 systematically chosen sample trees were recorded and the terrain in the parcels was classified according to Berg (1991).

Based on mean height the parcels were sorted into five equal groups. Every group was then sorted according to density of stems into 10 subgroups, of two parcels, giving a total of 50 pairs of parcels. Within each pair, the two tools were randomly assigned to one of the parcels. The mean parcel in the study had 10981 stems ha^{-1} and a height of 3.69 m.

The PCT was carried out under daylight conditions in a fully leaved stand. The brush saw was operated by two experienced workers, and the mechanised prototype by the most experienced driver available at that time (who had *c*. 300 hours of experience). Instructions were given to leave 2200 main stems ha^{-1} and to avoid damaging the main stems as far as possible. No marking of main stems was done beforehand. If delays occurred they were not included in the total time.

After PCT the number of remaining main stems and secondary stems, here stems shorter than half the mean height of the parcel’s main stems, were counted. All visible damage to the remaining main stems was also recorded.

Results were analysed with analysis of covariance in two steps. In the first step covariates and factors were used, if they were considered logical and independent from other covariates. In the second step all insignificant (p>0.05) factors as well as factors not usable for predictions were removed in order to develop suitable reduced models for predictive purposes. Three separate sets of analyses were made in these two steps. The first analysis included both tools to detect differences between them, while the other two were separate analyses of factors that influence time consumption for each of the two tools. To test differences between the tools in the first set of analyses, *t*-tests were used. Generally, differences were considered significant if p<0.05.

For details on the material and methods used, see the Material and methods sections in studies I-IV.

Results and discussion

Study I

Treatment had no effect on survival rates or damage frequencies on main stems. No significant differences in height of the main stems between the treatments were observed, but the diameter at breast height seemed to decrease with increased competition from secondary stems, in accordance with established findings (cf. Oliver & Larson 1990).

Treatment had, or tended to have, effect on all the quality variables tested for main stems. The treatment "topping at 70%" (resulting in a main stem height lead of 0.6 m) gave the best, and traditional PCT just above ground the worst, results with respect to all of the above-mentioned quality variables. Topping at 70% gave more than twice as many faultless main stems (1130 potential crop trees ha^{-1}) compared to the traditional treatment (480 potential crop trees ha^{-1}). The treatments "topping at 40%" (resulting in a main stem height lead of 1.1 m) and no PCT at all seemed to give somewhat similar results concerning quality of main stems, placing them at an intermediate level between the other two treatments. There is a belief that stands treated with traditional PCT will give high yields of merchantable timber, but low timber quality (Anon. 1993). Topping might be an attractive alternative to traditional PCT in terms of quality development of main stems.

Main stems of birch were taller and also grew more rapidly in height than secondary stems of both birch and willow. Three years after treatment, it could not be concluded that main stems in the "topping at 70%" treatment were out of risk of being overtopped by the topped secondary stems (Karlsson & Albrektson 2000). However, seven years after treatment, it could be concluded that main stems in the "topping at 70%" treatment were also clearly out of risk of being overtopped by the topped secondary stems. Height growth of the secondary stems seemed to be similar between the two species complexes studied, birch and willow, but reactions to the treatment in terms of survival differed significantly.

Survival rates of secondary stems of birch seemed to increase with increased height of the cutting, and no cutting at all resulted in the highest levels of survival. In contrast, the survival rates of secondary stems of willow neither increased nor decreased in any of the four treatments, indicating a high level of tolerance to shading and decapitation: an effect that has also been described earlier (cf. Bergman 2001).

The high survival and low levels of damage among main stems in the untreated control was somewhat surprising, especially since the parcels had high stand densities. On the other hand, the lowest mean height, mean diameter and average height growth among the main stems in the untreated parcels might suggest that levels of damage and mortality may increase with time. However, it can be seen as an indication of the importance of choosing main stems among the dominant and co-dominant stems, and that dominating stems at an early stage will probably remain dominant, even if no measure is taken (cf. Andersson 1963, Kikuzawa 1988).

The higher height/diameter ratio observed among main stems in the "topping at 70%" treatment and no treatment indicates that these treatments may increase the risk of calamities such as mechanical damage from snow or wind pressure (cf. Persson 1972, Huuri *et a.l* 1987). No such tendency was observed in this study, possibly because the main stems received support from surrounding secondary stems (cf. Harrington & DeBell 1996).

Study II

Survival among the treated stems was significantly lowest for the traditionally cut stems in both experiments. However, there was a strong tendency (p<0.056) for damage frequencies to be lower among traditionally cut stems, compared to the other two treatments, implying that survival rates may also become lower among topped stems. No major differences between top-broken and top-cut stems with respect to survival or damage were observed, and stems that were not treated, control stems, showed 100% survival.

Effects of time of treatment were more complex and lower survival for stems treated in a growing condition were observed in one of the experiments. No effect of time of treatment was observed on the damage frequencies. The tendency for survival to be lower amongst stems treated in a growing condition was probably a result of the reduced first post-treatment growing season, resulting in lower height growth and competitive status (cf. Haveraaen 1963, Johansson 1992b).

Height growth after three years seemed to be similar for all the treated stems, although height growth in individual years differed significantly between the treatments. Traditionally cut stems showed the most extreme reactions, resulting in high height growth in the first season and the most severe decline in height growth in the third season (cf. Kauppi *et al.* 1988). When comparing height growth of treated stems with untreated control stems, no significant differences were detected after three years. No major differences in growth between top-broken and top-cut stems were observed after three years, although there were some differences after the first season, when a tendency towards higher height growth for top-cut stems was observed. Karlsson & Albrektson (2001) suggested that top-breaking might result in less vigorous height growth of secondary stems than top-cutting, something that could not be confirmed in this study. However, the design was different in the present study and no tops of top-broken stems survived the first winter, giving a very short period of retained apical dominance, and thus little scope for height growth of the leading shoot (cf. Maschinski & Whitham 1989, Rinne 1994).

Effects of time of treatment on height growth were obvious after three years, where the ranking between times of treatments were similar in both experiments: treatment in growing condition < treatment in dormant condition < treatment in frozen condition. These differences were significant in all cases in one experiment, but in the other experiment only treatment in growing condition could be significantly separated from the other two. The pattern after three years with respect to effects of time of treatment on height growth could also be seen in individual years. Height growth of control stems after three years could not be significantly separated from height growth of any combination of treatment and time of treatment in either of the experiments.

Leading shoot length was affected by treatment and the reactions varied over the years. Due to significant interactions between treatment, time of treatment and blocks the effects could not be fully investigated in one of the experiments, but the trends seemed to be similar in the two experiments. Traditionally cut stems had the greatest leading shoot length in the first season and the shortest leading shoot length in the third season. One interesting observation, however, was that traditionally cut stems had the greatest average leading shoot length after three seasons, but the lowest average height growth. This discrepancy might be explained by between-treatment differences in the frequency of aborted shoot tips. Shoot-tip abortion is common in the genera *Betula* (Zimmerman & Brown 1974), and terminal bud abortions have previously been reported to occur less often in trees that have been treated with simulated browsing (Danell *et al.* 1985). These results highlight the importance of distinguishing between the two parameters height growth and leading shoot length.

Effects of time of treatment on leading shoot length occurred in the first two seasons, at least in one of the two experiments. Rankings were the same (treatment in growing condition < treatment in dormant condition < treatment in frozen condition) as for effects of time of treatment on height growth. The third growing season, untreated control stems had significantly longer leading shoots than all treated stems, irrespective of time of treatment, in one experiment and the longest average leading shoot in the other experiment, although they could not be significantly separated from the treated stems.

For total tree height after the first three seasons there were significant differences in both experiments between untreated control stems and all treated stems, the untreated control stems being significantly taller than the treated stems. Together with the finding that control stems also had the greatest leading shoot length the third season, these results suggest that the treated stems were probably adversely affected by their treatment and were at risk of being outgrown by the control stems, as also indicated by the higher survival and lower damage frequencies amongst the control stems.

Study III

For all motor-manual tools, time consumption increased with increased numbers of stems and increased diameter of stems ($p<0.001$). A tendency for the time requirements per stem to be lower for the highest density (50 stems) than for the other densities was detected for the PS2, especially for trees of the two higher diameters. This may reflect the point at which the possibility to cut more than one stem at the same time starts to significantly affect the time requirements. Increased time consumption with increased diameter and/or number of stems was expected (Bergstrand *et al*. 1986, Marntell 1989). Although time requirements varied in absolute terms, the relationships between time consumption and both number of stems and diameter of stems were broadly linear and similar for all the motor-manual tools (Study III, Fig 7). The effects of increases in diameter and numbers of stems for the mechanised prototype were less clear. There seemed to be some kind of a threshold at approximately 30 stems, beyond which the time consumption rose more slowly with further increases in density of stems. This is consistent with findings in older studies of selective mechanised PCT, although the levels of the threshold may vary (Freij & Tosterud 1990, Brunberg 1991). The threshold effect is probably due to the fact that at densities around 10000-15000 stems ha^{-1}, corresponding to 20-30 stems in this study, the felling head has to be moved over the entire area treated, and thus the time required for boom work is maximised. This also implies that the size of the felling head could be of great importance.

The hacksaw could not compete with the other tools and was not capable of handling stems of larger diameter than 2.2 cm. The operator also stated that it was difficult to control, and not ergonomically suitable for the task. The relative efficiency of the tools in terms of time consumption was broadly similar for diameters 4 and 6 cm, but there were other and greater differences for the lower diameter stems (2 cm). The mechanised prototype was the fastest, or one of the fastest, at all densities with diameters 4 and 6 cm. However, for the 2 cm diameter trees, the mechanised prototype was one of the slowest of all the tools, except for the lowest density tested. Time consumption for the conventional brush saw and the PS2 were similar, the only statistically significant difference appearing with the lowest diameter (2 cm), for which the brush saw was the faster at densities of 20 and 40 stems. For the 4 and 6 cm diameters, the PS1 was the slowest (or one of the slowest), tools at all densities tested.

There were significant differences between the pole saws with respect to time requirements, and the only apparent explanation for the difference was in the configuration of the saws, since the motors and cutting devices were identical. The different configuration of the handles on the PS2 enabled the operator to go sideways in the stand more easily, which probably made him more flexible. To balance the PS1 a longer part of the tool had to be behind the handles, and thus also behind the operator, which probably made it somewhat harder to control.

When comparing the pole saws with the conventional brush saw it is important to remember that the pole saws had only 38% of the engine power of the brush saw. Nevertheless, the pole saw with a straight shaft (PS2) seemed to be a competitive alternative, regarding time requirements. One also has to remember that the conventional brush saw has been developed over the last 50 years, while the pole saws have only recently been developed as PCT tools.

No statistically significant difference in the damage frequency amongst main stems could be detected between the mechanised prototype (5.2%) and the conventional brush saw (4.8%), but there were significant differences with respect to damage frequency between the brush saw and both of the pole saws (1.7 and 1.2%). This was probably partly due to better visibility at a higher cutting-level and partly attributable to the protective hook at the tip of the blade attached to the pole saws. Furthermore, a chain will not give kickbacks to the same extent as a circular saw, and the protective hook as well as the more flexible stems at a higher level above ground offered the operator the ability to drag stems away from the main stem with the pole saw before cutting them. The mechanised prototype was believed to damage more stems than the conventional brush saw, which could not be verified. Since the machine stood still, damage caused by the chassis and wheels of the moving machine could not be assessed, but this would probably cause additional damage to the remaining main stems. However, damage caused by the boom and felling head was lower than in earlier studies of mechanised PCT (cf. Petré 1984, Lindman 1987).

The productivity figures were consistent with the most recently available Swedish productivity targets for motor-manual brush saw PCT (Bergstrand *et al.* 1986), for the lower diameter (2 cm), but not for higher diameters (4 and 6 cm) (Study III, Fig 8). Since representation of taller stems, implying higher diameter, was poor in the study reported by Bergstrand *et al.* (1986) one could suspect that these productivity targets need to be revised since numbers of stems ha^{-1} before PCT and average height at the time for PCT has increased significantly during the last decades (Fig. 2) (Study III, Fig 2a).

Study IV

Motor-manual PCT with a conventional brush saw was faster then PCT with the mechanised prototype. The average stand in this study (height 3.69 m and 10816 stems ha^{-1}), which is equivalent to the average stand subjected to PCT in Sweden today (Fig. 2), required 5.24 and 6.19 hours ha^{-1} using the motor-manual and mechanised method, respectively. The motor-manual PCT left on average 2805 main stems ha^{-1} (of which 2.1% were damaged) and 548 secondary stems ha^{-1}. The mechanised PCT left on average 2475 main stems ha^{-1} (of which 1.3% were damaged) and 565 secondary stems ha^{-1}. Instructions to leave 2200 main stems ha^{-1} were exceeded by 27.5% and 12.5% by the brush saw and the machine operators, respectively. The amount of stems left accords well with current trends in Sweden (Fig. 2). The finding that the mechanised prototype left fewer stems might be due to the operator adhering more closely to the instructions, and/or a result of the fact that visibility increases as stand density decreases (cf. Andersson & Mattsson 1993b).

The finding that the mechanised prototype damaged fewer remaining main stems was not expected. The levels of damage caused by the motor-manual method were in accordance with earlier studies (Petré 1984) and study III. The levels of damage caused by the machine were lower than both those found in earlier studies of selective PCT machines (Petré 1984, Wästerlund 1988, Andersson & Mattsson 1993b), and the levels recorded in study III. This is probably attributable to the new type of felling head and the possibility to use both articulated- and single-axle steering making the machine more flexible. Earlier PCT machines were equipped with cutting devices based on rotating flexible flails that caused damage to main stems from thrown cutting debris (Freij 1991, Glöde & Bergkvist 2003), which should be eliminated with this new type of felling head. Furthermore, the damage caused by earlier machines straddling main stems was avoided with this winding technique (cf. Freij 1991). Another possible explanation for the low levels of damage caused by the machine is that the operator may have concentrated on avoiding damage instead of minimising time consumption.

The initial belief that increased stand density and average height of the stand would favour the mechanised prototype could not be verified since the difference between the two tools was constant. Results from study III indicated that increased diameter, highly correlated to increased height, should favour the mechanised prototype, although there might be other height-dependent factors that affect time consumption, which could not be assessed in study III due to the experimental design. One such factor could be visibility, which decreases significantly when a stand reaches 4-5 metres average height (cf. Freij 1991).

Slope (classes 1-2) and surface structure (classes 1-3) (cf. Berg 1991) did not hinder the machine significantly. The reduced model for the machine included number of stems ha^{-1}, average height of stems and height/diameter ratio. Although the mechanised prototype can be expected to handle more severe conditions than earlier machines, due to its size and combined steering abilities, it is likely that the time requirements of the prototype will be affected by more severe terrain conditions (cf. Freij 1991).

For motor-manual PCT, significant effects of terrain were found: an increase in slope from class 1 to slope class 2 increasing time consumption by on average 0.64 hours ha^{-1}. There were also significant differences between the two operators: one operator was on average 0.66 hours ha^{-1} faster than the other. The reduced model included number of stems ha^{-1}, average height of stems, height/diameter ratio and a dummy variable that was given the value 0 for slope class 1 and the value 1 for slope class 2. Here, the effect of operator was removed since it is not of interest for general estimations of time consumption. An alternative model was also developed that included number of stems ha^{-1} × average height of stems, height/diameter ratio and a dummy variable for slope class. The adjusted R square parameter for these two models was similar (Adjusted R square > 0.765), but generally high in comparison with earlier studies (cf. Lidberg & Svensson 1971, Bergstrand *et al.* 1986).

Methods used

The design of study I might be questionable from two main perspectives: the choice of species studied and the definition of quality. It was apparent that topping, especially at a high level above ground, had a positive effect on the quality of the main stems compared to traditional PCT, in a downy birch stand. High quality saw timber of downy birch is, however, demanded only locally in some regions of Sweden in small amounts (cf. Anon. 2004a). The most important species in Swedish forestry for production of high quality saw timber is Scots pine (Anon. 2004a), and the relevance of these results for stands with main stems of Scots pine is difficult to asses. Generally, forks and stem straightness are not major problems affecting Scots pine, but high live crown height, low diameter of the thickest branch and low proportions of juvenile wood are desirable since they will give high proportions of "branch-free" wood in the most valuable bottom log (Anon. 1999b).

Since a low level of competition from secondary stems will give the main stems greater opportunities to expand the width of their crowns, produce more branches and increase their stem diameter, it is likely that the same mechanisms that resulted in increased quality in the topped treatments in study I will also apply in young stands of Scots pine (cf. Pettersson 1992) and silver birch (cf. Cameron *et al*. 1995, Niemistö 1995). The diameter of the thickest branch in Scots pine is dependent on initial spacing and is strongly correlated to stem diameter at breast height (Persson 1977, 1994). Therefore, the tendency for the diameter of main stems to be lower in the topped treatments is another indication that they might give higher quality than the main stems in the traditional treatment.

Although downy birch is not a big commercial species for timber production in a large scale in Sweden (Anon. 2004a), or other parts of the world, it grows and develops fast during early stages of stand development, giving results in a short period of time. Since this experiment is the oldest available with topping included as a treatment, and downy birch might be the most common species to be treated as a secondary stem in Swedish forestry, the choice of species studied seems appropriate.

The design of study II, in which individual stems rather than whole stands were treated, does not enable the results to be fully generalised up to stand level. Therefore, the results will probably not give a comprehensive indication of factors such as damage patterns caused by browsers or other agents in topped stands. Furthermore, shading of the treated stems was probably more pronounced, causing them to receive less warmth and light, in this study than they would in topped stands. However, the spread of treatments and times of treatments that blocking according to surrounding basal area allowed should have ensured that a full spectrum of conditions from no shading to almost full shading were present for all combinations of treatment and time of treatment. The sample size, for using analyses of variance in the survival analysis, was rather small for the normal approximation, but may still be satisfactory since analysis of variance is such a robust procedure.

The experimental design used in study III has both advantages and disadvantages. This type of study ensures that comparisons between different tools can be made under equal circumstances. Therefore, the correlations between time requirements for the different tools with the diameter and number of stems, and the relative capacities of the tools, should be adequately studied with this type of design. However, one should be cautious about extrapolating the absolute results into production norms for real stands in the field concerning either time requirements or levels of damage.

A comparison between the time requirements for the conventional brush saw obtained in study III and the most recently available Swedish productivity targets resulted in a constant relationship, and similar figures, for low diameters and low densities (Bergstrand *et al*. 1986). But time requirements for the brush saw in study III increased more relative to the productivity targets of Bergstrand *et al*. (1986) with increasing numbers of stems and diameter of stems. The opposite results were obtained in study IV, where effective time consumption for motor-manual PCT was lower compared to earlier available studies (Lidberg & Svensson 1971, Bergstrand *et al*. 1986). This discrepancy between the results from study III and study IV supports the theory that experimental studies might be preferable when the aim is to compare tools relative to each other. If the main aim is to develop productivity standards, full-scale field studies are probably preferable.

The problem with the results being highly dependent on the operator is partly removed with this experimental design, since the choice of main stems and route through the stand (for the motor-manual operator) is predefined. For the mechanised prototype, the levels of damage could not be fully assessed since the machine did not move around in the stand. However, building a larger experimental stand in which a machine could move around would be possible. One big advantage with the experimental design is that it allows single variables to be varied in order to isolate the effects of single factors. Furthermore, the cost of a study is not irrelevant and the experimental design is often cheaper than full-scale field studies. The experimental design can also be copied exactly, for example to test and compare new tools with previously tested tools.

Time consumption for all tools examined in study III was strongly affected by the number and diameter of stems and the interaction term (number of stems × diameter of stems) ($p<0.001$). The interaction term was significant for all tools and the explanation is probably, with the possible exception of the mechanised prototype, the fact that variance increased with increased number and/or diameter of stems. This type of significant interaction term is typical for time study data and “right-opening megaphone distributions”, caused by the positive correlation between variation and the magnitude of independent variables, are to be expected in this type of studies (Weisberg 1985).

It is important to remember that the results from study III concern only one operator and that the PS2 obviously suited him and his working technique better than the PS1. To further develop the pole saw as a PCT tool, more operators have to be tested and different working techniques and patterns should be evaluated. The problem with the results being highly dependent on the operator was even more pronounced in study IV. The significant difference between the two well-trained motor-manual operators is an indication of the importance of the operator in forestry work (cf. Bergstrand *et al*. 1986, Samset 1992).

Earlier studies also highlight the importance of the operator in mechanised PCT work, where variations in productivity for fully trained drivers varied up to 50% (Kjöstelsen 1989, Freij 1991). There are also several studies concerning other types of forestry machine work indicating that time requirements is highly dependent on operator (± 40%) and work method (± 10%) (Sirén 2001, Andersson & Eliasson 2004). Furthermore, Gellerstedt (1997) states that operating a PCT machine is probably the most intensive type of forestry machine work, implying that productivity might be more dependent on the operator than in other types of mechanised forestry work. However, only one operator and one work method was studied for the mechanised equipment and since the operator was the only one available with any experience at all of operating this type of machine, no other options were available.

Although the operator was satisfied with and believed in his working methods, no tests have been done to ascertain that his approach was optimal. Furthermore, the operator had worked with the machine only for about 300 hours, indicating that he might not be fully trained or able to use the machine in the most efficient way (cf. Barnes 1980). Sirén (2001) noted that high productivity and low levels of damage to residual stems were highly correlated in thinning operations. Since the level of damage after PCT with the mechanised prototype was low, there might be reason to believe that the operator was also productive in terms of time consumption. However, this conflicts with the suspicion that the operator of the mechanised prototype focused more than the motor-manual operators on avoiding damage.

Survival of topped stems

For topping to be deployed in practice it is essential that the treated stems are not only outgrown, but also that they die and vanish by the time of the first commercial thinning. Their continued presence would increase the costs of the harvesting operation in the first commercial thinning by reducing visibility and accessibility, and probably also reduce yield due to reductions in the average diameter of the main stems (cf. Richardson 1993, Eliasson & Lagesson 1999).

Sprouts from higher stumps tended to live longer than sprouts from shorter stumps (studies I and II), which is consistent with earlier studies (Kvaalen 1989, Karlsson & Albrektson 2001). There are probably several reasons for the more vigorous development and higher initial survival of sprouts from higher stumps, including the following: temperatures tend to be higher at a higher level above the ground (Johansson 1986), there is more available light (Johansson 1986, 1987), and greater numbers of dormant buds are retained (Johansson 1987), together with more green parts that can produce carbohydrates (Fitzgerald & Hodinott 1983). Since a majority of the mortality among treated downy birch stems in study I occurred after the third growing season, it seems likely that there will also be significant decreases in the numbers of surviving treated stems in the material examined in study II (cf. Kvaalen 1989).

After three years in study I, survival rates for topped stems were higher (> 96%), although damage frequencies were also higher (> 50%) (Karlsson & Albrektson 2000), than in study II where survival rates varied between 84 and 92% and damage frequencies varied between 13 and 20%. These reasons are probably due, at least partly, to the different design of study II resulting in more pronounced shading, which may have accelerated the mortality process. Other possible explanations might be connected to the average height handicap at the time of treatment, which was higher in study II than in study I, and the origin of the stems, since stems in study I were exclusively of seed origin while stems in study II probably originated from both seeds and stumps.

The finding that the mortality of willows did not significantly increase or decrease following any of the treatments in study I highlight the importance of also considering species when topping is to be carried out. It is likely that shade-tolerant species, such as Norway spruce, will have a high tolerance to topping, and mortality of topped spruces will probably be very low. Therefore topping would probably not be an attractive alternative in stands of Norway spruce or stands with high numbers of willows if the desire is to eliminate secondary stems. However, one might not want the secondary stems to die and vanish in the future if wood has value for energy purposes.

An early (2-3 m average height), light topping followed by a commercial thinning (6-8 m average height) with extraction of energy wood leaving *c*. 2000 main stems ha^{-1} might be an attractive alternative in the future (cf. Bergsten *et al*. 2004). With this type of program the problems associated with damage caused by moose browsing on main stems would probably be reduced (cf. Lavsund 2003). Furthermore, the first measure would probably be cheap compared to today's PCT and the second measure could be performed with more expensive equipment since it would also generate income (cf. Bergsten *et al* 2004). Since the desire with this program would be to keep the secondary stems alive, the cutting height might have to be raised and this could also promote higher quality in main stems. However, it is important to remember that cost-effective equipment for this type of measures has not yet been developed (cf. Ligné 1999) and extraction of biomass from young stands will probably also reduce the growth of, as well as giving higher damage frequencies on, residual main stems (cf. Anon. 1992).

Height growth of topped stems

Cutting the apex of a tree breaks its apical dominance and thus enhances compensatory growth (Maschinski & Whitham 1989, Rinne 1994). The same reaction to broken apical dominance has also been reported following browsing by herbivores (Krefting *et al*. 1966, Danell *et al*. 1985). The reactions of secondary stems cut in study I, however, represented a continuum of height growth that was positively correlated with stump height, especially during the first years (Karlsson & Albrektson 2000). This conflicts with the findings of Kvaalen (1989), who found a negative correlation between height growth and stump height (0-60 cm) during the first three growing seasons. Johansson (1992b) found no correlation at all between stump height (25-75 cm) and height growth.

The continuum of height growth observed in study I was probably a result of the amount of plant tissue removed (cf. Hjältén *et al* 1993). The stems were cut in June, leading to a “reduced” growing season, leaving little time for recovery. These results imply that the time when birches are felled may have a strong influence on their sprouting, and traditional PCT during the summer (June – July) is known to result in lower numbers of sprouts and also shorter sprouts compared to cutting earlier in the year (Haveraaen 1963, Etholén 1974, Ferm 1990).

Generalising the results from study II is difficult and risky since changes in the rankings between height growth responses to different times of treatments may continue as the stand develops. However, the lower height growth of stems treated in a growing condition supports the theory that felling time has a strong influence on the sprouting of birches, and this could be due, at least partly, to the removal of green tissue in which the tree has already invested resources such as carbohydrates and chlorophyll (cf. Donnely 1974, Kramer & Kozlowski 1979). The later time of treatment also caused greater loss of mass for the trees, since their shoots had started to elongate. The difference concerning height growth between stems treated in dormant and frozen conditions is more difficult to understand. One possible explanation is the relation between leaf area and carbohydrate allocation described by Donnely (1974). Leafs consume carbohydrates until they have reached about half their final size, after which they produce more than they consume. Thus, losses of resources may be more severe in dormant stems, and much more severe in stems treated in a growing condition, than in frozen stems, since dormant and growing stems have probably started to allocate carbohydrates to buds with the potential to form leafs and new twigs, and these resources are more or less removed with the cutting or breaking of the stem.

Time requirements for PCT

Effective time consumption for motor-manual PCT in study IV was lower than in earlier reports (Lidberg & Svensson 1971, Bergstrand *et al.* 1986). However, the difference in time consumption between the earlier studies and study IV increased with increased stand mean height, and there was no difference in results between Bergstrand *et al.* (1986) and study IV in this respect at a mean stand height of 2 metres (Study IV, Fig 2). Since earlier studies were carried out during times when young Swedish forests were not so dense (Fig. 2), and when the measure were executed earlier (lower stand height) as well as the tools were less developed than they are today, there is reason to believe that these productivity targets might no longer be completely valid (Bergstrand *et al.* 1986). The fact that the differences between earlier studies and study IV are not constant also supports the idea that they are not a result from operators, but more likely a result of development of tools and methods, and changes in conditions.

The differences in time requirements between study IV and earlier reports probably reflect advances in motor-manual PCT since the latest study in 1986. The features of the brush saw that have been most improved during the last 20 years are the blades, its weight (which have been reduced) and harness (which is now more ergonomic) (cf. Anon. 2004b). The organisation and planning of motor-manual PCT work has probably also developed during these last decades, but the effects of these improvements could not be assessed in this study.

In addition to the traditionally recognised influencing factors, average height and stand density, the height/diameter ratio proved to be an important factor explaining time consumption for PCT in study IV. Although the height/diameter ratio was found to be positively correlated with stem density and negatively correlated with average height, combinations of these two variables could not replace the height/diameter ratio in this model. Generally, the adjusted R square value of the models was increased by 7-18 percent when the height/diameter ratio was included. This suggests that the height/diameter ratio explains something not available from combinations of other correlated factors. Since no earlier studies, to my knowledge, have suggested the height/diameter ratio as an important factor explaining time consumption for PCT equipment, this has to be further investigated. It would also be possible to isolate the effect of the height/diameter ratio, and investigate it further, with the experimental design used in study III.

A recent study on geometric mechanised PCT tools also highlights the problem with productivity if only cutting below the lowest living branch of secondary stems is allowed (Bergkvist *et al*. 2004). All mechanised solutions used for PCT in Sweden have been designed to work selectively. Nevertheless, early studies indicated that a geometric, or a combination of selective and geometric, PCT could be a competitive alternative (Bäckström 1972, Hägglund 1973, Friberg 1974). The motives against geometric PCT were concerns regarding growth effects on main stems and this has also been studied on a number of occasions (Pettersson 1986, 2001). Earlier studies on geometric PCT have stated that the method gives acceptable biological results and also a possibility to vary the spacing from quadratic to rectangular without causing significant growth or quality losses (Pettersson 1986, Davidsson 2002, Bergkvist & Glöde 2004). Lindman (1984) found that up to 40% of the costs could be saved using a geometric technique rather than a selective technique, but still no appropriate machines have been tested to date. Samsets law of development leaps could probably be applied in this case, suggesting that slow increases in nominal operating costs, coupled with stagnant productivity in established machines and methods, drive forward new methods and machinery so that productivity tends to increase in steps (Samset 1966).

Financial aspects of PCT

As expected and well described in earlier studies of selective PCT machines, results from study III indicated that the mechanised prototype was most competitive in dense and large diameter stands (cf. Freij & Tosterud 1990, Freij 1991). The mechanised prototype requires a significantly greater investment than motor-manual tools and thus its productivity must be higher in order for the machine to be economically viable. In this context it is probably extremely important that the machine only works in stands, or parts of stands, where it will be most productive, which demands precise and rigorous planning. Several earlier studies also suggest that a combination of machine and motor-manual workers will provide the best option both economically and qualitatively, and there is no evidence that this would not be the best approach for this mechanised prototype too (Freij & Tosterud 1990, Mattsson *et al*. 1991).

The cost for PCT with the two methods tested in study IV depends on cost and productivity per unit time, and the mechanised equipment will have a higher cost per unit time. This implies that the mechanised solution must have significantly higher productivity in order to be viable, which could not be proven in study IV. At the present moment it seems unlikely that the higher cost and lower productivity could be compensated by any other factors. It is also important to remember that the productivity of the mechanised prototype in study IV was compared to recent data on productivity of motor-manual PCT. If it had been compared with the older data, of Bergstrand *et al*. (1986) for example, as earlier selective mechanised pre-commercial equipment has been, the comparison and results would have been significantly more advantageous for the mechanised prototype, especially in stands with a higher average height (>4 m).

Since PCT is a measure that does not directly generate income, the viability of the operation is highly dependent on the cost of the tools used and there is little room for expensive solutions. The selective PCT machines used earlier in Sweden were often based on modified small single-grip harvesters (Glöde & Bergkvist 2003). This type of advanced base machine would today have an investment cost of about 2 million SEK, and would have to be extremely productive, compared to motor-manual workers, in order to justify the high investment costs (especially if it is not able to work all year around on PCT due to snow conditions). The cost of the mechanised prototype examined in studies III and IV would be about 25-30% of the cost of a small single-grip harvester, and thus it would not have to be as productive as the more expensive machines. A broad comparison between the motor-manual alternative, the mechanised prototype and the PCT machine based on a small single-grip harvester can be made from simple calculations on the costs of PCT with the respective tools. A motor-manual worker today will cost about 200 SEK hour^{-1} (Hedman 2004, Sjödin 2004), the mechanised prototype about 400 SEK hour^{-1} (Sjödin 2004) and the machine based on a small harvester about 600 SEK hour^{-1} (Hedman 2004). Average costs for PCT of one hectare in Sweden today are about 2300 SEK (Anon. 2004a), which gives the different tools specific time limits ha^{-1} if their costs are to equal to or lower compared to the brush saw (Fig. 6). To build a selective PCT machine under today's conditions that will lower the cost of the operation significantly compared to motor-manual PCT will probably be very difficult, especially if it is based on expensive base machines such as harvesters. There are at least two ways to approach this problem: to obtain an income from the operation or to develop schematic methods to facilitate the removal of a majority of the secondary stems. Current circumstances, with increasing numbers of secondary stems, favour both of these approaches (Fig. 2). Another possible way to develop the PCT measure might be to automate the tools used, which would more or less eliminate the large cost of an operator (cf. Vestlund 2001). Vestlund estimated the potential use of at least 300 autonomous machines in Sweden, if the technique can be developed into practical use (Vestlund 2001).

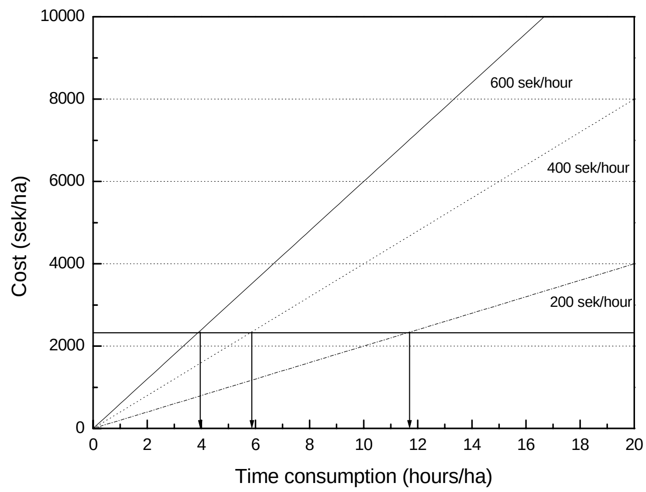

Figure 6. Time consumption for tools with a cost of 200, 400 and 600 SEK hour^{-1} given an equal cost for PCT. The marked line refers to the average cost for PCT of one hectare in Sweden 2004 (Anon. 2004a).

The ideas developed by Juhlin Dannfelt (1947) and Sundin *et al.* (1955) to adapt the PCT program to the regeneration measures are perhaps more relevant today than ever, with increasing numbers of stems ha^{-1}. Of course, the requirements for satisfactory regeneration cannot be violated, but if several methods are possible the one giving less stems ha^{-1} should be chosen in order to decrease the costs of PCT. PCT should perhaps once again be seen as a part of the regeneration costs, and the cost of both regeneration and PCT should be considered when choosing the best and most cost-effective way to create the new stand.

Conclusions

Reviewing developments, it is remarkable that PCT concepts have changed so little over the last century. Today's recommendations are almost identical to the ones given almost a hundred years ago and not much new alternatives to the traditional PCT are available. However, young forest stands that were considered extreme, with respect to parameters such as the number of stems ha^{-1} (Fig. 2), 20 years ago are more or less standard today. This development calls not only for the development of tools and methods, but also for broad studies, since it will not be possible to generalise the results if tests are not carried out under conditions that seem extreme today but may be standard in the future.

Survival among topped secondary stems of downy birch was generally high in the first three years after topping, but decreased significantly in the following four years. A level of top-cutting where the main stems obtained a height lead of at least 0.6 m (30 %), was possible in stands of downy birch from a growth perspective, but there were still concerns that the secondary stems may represent obstacles in later commercial thinnings. When the main stems achieved a greater height lead (1.1 m or 60 %), the survival among secondary stems of downy birch was lower and most likely also fewer problems with secondary stems representing obstacles later on. Birch and willow reacted in different ways to topping, where willows were the more tolerant species group with higher survival seven years after treatment.

The assumed theoretical advantage of topping (that it would promote a better tree form and branch quality in the main stems) seemed to be valid for main stems of downy birch. Topping at a higher level above ground was preferable if quality was to be maximised, but a somewhat lower level might be preferred if risks of calamities, such as damage by snow or wind, were to be minimised, growth of main stems maintained and future commercial thinnings facilitated, suggesting 50-60% of the average main stem height to be a suitable practical level for cutting when stands are *c*. 2-3.5 metres in height. Thus, the generality of the conclusions of topping as a broadly used method is difficult to gauge, since the effects of topping will probably vary with initial and remaining stand density, stand height, species composition and time of treatment.

The time of year when PCT was carried out affected the growth and survival of secondary stems of downy birch, regardless of whether they were cut traditionally at ground level or topped. Survival and height growth were lowest for stems treated in growing conditions (summer) and highest for stems treated in frozen conditions (winter). Stems cut traditionally at ground level had the highest height growth in the first season, but also the lowest survival and fastest decline in growth in the following seasons, resulting in treatment having no effect with respect to height growth, irrespective of cutting height and type of decapitation after three growing seasons. The long-term growth effects of top-cutting and top-breaking of secondary birch stems seem to be essentially identical.

Despite having much less powerful engines, prototype machines designed for motor-manual PCT through topping are available that can compete with the traditional brush saw, both in terms of damage caused to remaining main stems and time requirements. Results indicate that the approach of cutting stems at a higher level could have advantages, which should improve the total benefits of PCT if the costs and time requirements for executing the measure were equal to those of the conventional brush saw.

Experimental studies also suggest that there is a mechanised prototype that can compete, especially in dense (>15000 stems ha^{-1}) and high butt end diameter (4-6 cm) stands, with the traditional brush saw without damaging more main stems. However, although the high quality of work, in terms of damage to main stems, achieved with the mechanised prototype was confirmed in a field study, its high productivity obtained in the experimental study could not be confirmed in the field study. Field studies also indicated that productivity standards in terms of time requirements of motor-manual PCT might underestimate the productivity of today’s equipment. Furthermore the height/diameter ratio might be an important factor explaining time requirements for both mechanised and motor-manual PCT.

Future research

The results from study I indicate that topping might be an attractive alternative to traditional PCT concerning quality development of main stems. However, similar studies on more commercially important species, such as Scots pine, are needed. Study I and II also suggest that the topping of secondary stems can be controlled to ensure that they are dead and gone by the time of the first commercial thinning. However, more studies on the effects of topping with varying initial and remaining stand density, stand height, species composition and time of treatment, especially in pine-dominated stands, are needed in order to confirm these results. One of the most interesting theoretical advantages of topping is the possibility it provides to decrease browsing pressure on main stems from moose, since browsing by moose is considered to be one of the largest quality problems associated with Scots pine and the birch species. Therefore, there is an urgent need to investigate the interaction between moose and topped stands. Furthermore, if the aim is to keep topped secondary stems alive for energy wood production, studies have to be conducted in order to examine the effect of cutting height and species composition on survival and biomass production of topped secondary stems.

The problem with the results being highly dependent on the operator was clearly detected in study IV. Conditions during the course of this study did not enable any other operators to be included in the study. Today, however, more and better trained operators are available. Therefore, further studies on the mechanised prototype could be performed to evaluate work methods, and a number of trained operators should be tested to asses the influence of the operator on machine productivity and levels of damage to the residual stand.

Study III indicates that the cost of motor-manual topping will probably be equal to, or even lower than, traditional PCT. However, when comparing the tools in study III it is important to also consider ergonomic factors, which were not tested or estimated in the study. Therefore, studies on the ergonomics of the pole saws should be executed with the background that the somewhat lower price of the pole saws gives some scope for development and modification that could improve their ergonomics.

The results concerning time requirements for the mechanised prototype in study IV, and the discrepancy between the time requirements for the brush saw in studies III and IV relative to the existing productivity standards, indicate that time consumption for the tools might not have been adequately measured with the experimental design. Therefore, it would be of great interest to study the tools that were found to be competitive in study III, e. g. PS2, in field studies.

It would be of great interest to collect further data on the productivity of the brush saw in denser and older stands in order to develop new productivity standards for PCT with brush saws, and to obtain relevant figures for assessing the comparative productivity of new types of tools.

One of the possible advantages with topping is the possibility it offers to leave higher stumps in mechanised PCT, allowing the cutting device to work at a level where visibility is better and there are fewer obstacles. Since topping can also be carried out with a moderate layer of snow, it is important to investigate the importance of felling time on the development of topped secondary stems across a wide range of times of year. Furthermore, equipment for topping should be tested and evaluated under winter conditions. Expensive equipment, e. g. mechanised equipment, for PCT will be affected economically by the fact that it cannot work in the traditional way with short stumps year-around in large parts of Scandinavia and North America, due to snow conditions. Therefore, topping could be one way to increase the time period that mechanised equipment could be used and thus also improve the economic viability of such machines. Since some mechanised prototypes for both selective and schematic PCT are available today, this possible advantage with topping could be studied. Schematic PCT machines have been discussed since the 1970´s, but never tested scientifically in Sweden, it would be of great interest to test such solutions in the context that high stumps might be acceptable.

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