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Productivity of Multi-Tree Cutting in Thinnings and Clear Cuttings of Young Downy Birch (*Betula pubescens*) Dominated Stands in the Integrated Harvesting of Pulpwood and Energy Wood

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Abstract

The purpose of this study was to determine the productivity of multi-tree cutting of pulpwood and energy wood in thinnings and clear cuttings of young downy birch (*Betula pubescens*) dominated stands, along with the time consumption of cutting work phases performed with a medium-sized harvester. On the basis of the time study data collected, tree-specific time consumption and productivity models were prepared for the multi-tree cutting of pulpwood and energy wood in both thinnings and clear cuttings. In the multi-tree cutting time consumption model, productivity was explained in terms of tree volume (dm^3) and harvesting intensity (number of trees removed per hectare). Productivity was expressed in solid cubic metres per effective hour (m^3/E_0h). Harvested assortments in the integrated harvesting included pulpwood with lengths of 3–5 m and energy wood, which consisted of undelimbed tops of pulpwood stems and undersized trees.

As expected, clear cutting enhanced harvesting productivity in comparison with thinning, but multi-tree cutting had only a minor effect on productivity in the case of both harvesting methods due to the low share of multi-tree cutting. In the time study sample plots, the values recorded for multi-tree cutting productivity per effective hour varied between 5.6–17.4 m^3/E_0h in clear cuttings and 4.8–10.9 m^3/E_0h in thinnings, respectively. On average, the harvester head processed 1.2 trees per grapple cycle in clear cutting and 1.1 trees per grapple cycle in thinnings.

The study highlighted the need to improve the suitability of current harvesting equipment for the harvesting and multi-tree harvesting of birch and other trees with bent and crooked stems. This is because harvesting conditions that are more favourable to clear cutting than thinning are the main factors behind the observed leap in productivity: 1) The tree-specific moving time shortened when more trees could be harvested at the same spot than during thinning; 2) The removal of trees was systematic in clear cutting whereas it was selective in thinning; 3) In clear cutting, the remaining tree stand did not hamper the delimbing, cutting or piling of trees.

Key words: Multi-tree cutting, integrated harvesting, peatlands, downy birch, first thinning, clear cutting, pulpwood, coppice forests

Introduction

Downy birch resources and cultivation options in Finland

Downy birch (*Betula pubescens*) is the most common broad-leaved tree species in Finland. According to the results of the Finnish National Forest Inventory, the growing stock volume of downy birch in Finnish forests is 250 million solid cubic metres (m^3), which accounts for 12 % of the total growing stock (Niemistö and Korhonen 2008). The growing stock volume of forests dominated by downy birch, where downy birch accounts for more than 50 % of the volume, is 82 million m^3 and 1.15 million

hectares (Niemistö and Korhonen 2008). Downy birch growing on peatlands and wet mineral soils produces rather low quality timber that is often inappropriate for veneer or sawing purposes, but it is important raw material for the pulp and paper industries and as a fuel. For example, in 2012, Finnish pulp and paper industries consumed 11.7 million m^3 of hardwood (mainly birch), of which 4.1 million m^3 was imported (Anon. 2013).

In traditional pulpwood production, tending to a density of 2,500 seedlings per hectare has been recommended for pure and clearly birch-dominant downy birch stands and commercial first thinning to a density of 1,100 trees per hectare (Niemistö 1991). In pulpwood produc-

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tion, the rotation period of a downy birch-dominated stand is approximately 50 years. The thinning reaction of downy birch promoting diameter growth has been found to be weaker than that of other tree species, especially in peatlands (Niemistö 2013). Downy birch also tolerates shading better than silver birch (*Betula pendula*) (Atkinson 1984, Ferm 1990). The maximum number of trees per hectare that can be grown to the size of pulpwood in downy birch-dominated stands is 2,500-3,000, and even in the very dense downy birch stands, the significant natural drain of pulpwood-sized trees will appear only after the age of 40 years (Niemistö 1991, Niemistö 2013).

The increase in the value of and demand for energy wood has brought about a new and attractive option in the silvicultural management of downy birch stands: a dense downy birch stand is grown without any tending of seedling stands and commercial thinnings for regeneration felling. Final felling with the integrated harvesting method is carried out at the age of approximately 40 years to exclusively produce energy wood or both pulpwood and energy wood (Niemistö 2013). As a comparison, a very light thinning of a young downy birch stand can sometimes lead to a slightly higher yield of stem wood and crown biomass than that of an unthinned downy birch stand. However, low income from thinning removal hardly compensates for the costs of thinning operations. An intensive thinning, on the other hand, reduces the future growth of a downy birch-dominated stand too much. In an unthinned dense downy birch-dominated stand, small trees die before regeneration felling, so the average stem size in the regeneration felling is not significantly smaller and the harvesting costs are thus no higher than in lightly thinned downy birch-dominated stands (Niemistö 2013).

The objectives and implementation of the study

In Finland, timber procurement is based on the cut-to-length (CTL) method and thus conventional CTL forest machinery is used to harvest industrial roundwood and energy wood from tree stands (e.g. Laitila 2012, Ehlert and Pecenka 2013, Petty and Kärhä 2014). Despite the high incidence of downy birch, there is very little published research about the mechanised cutting of downy birch (Lilleberg 1994, Di Fulvio et al. 2011, Niemistö et al. 2012, Fernandez-Lacruz et al. 2013). In earlier harvesting studies, the main focus has primarily been on timber harvesting from pure or clearly conifer-dominant stands (e.g. Sirén and Tanttu 2001, Wester and Eliasson 2003, Kärhä et al. 2004, Kärhä 2006a, Nurminen et al. 2006, Spinelli and Magagnotti 2013, Eriksson and Lindroos 2014). In terms of deciduous trees, CTL logging studies have mainly focused on poplar and eucalyptus or whole-tree harvesting from coppice forests or short rotation fields (Hartsough and Cooper 1999, Spinelli et al. 2002, Puttock et al. 2005, Spinelli et al. 2009, Danilovic

et al. 2011, Picchio et al. 2012, Suchomel et al. 2011, Di Fulvio et al. 2012, Suchomel et al. 2012). Correspondingly, pure Scots pine or conifer-dominant mixture forests have been used in the study of integrated harvesting of pulpwood and energy wood (Jylhä and Laitila 2007, Spinelli and Maganotti 2010, Nuutinen et al. 2011, Kärhä 2011, Lehtimäki and Nurmi 2011, Laitila and Väätäinen 2013a, Laitila and Väätäinen 2013b, Sirén et al. 2013b, Di Fulvio and Bergstöm 2013). Time consumption functions for multi-tree cutting in thinnings and clear cuttings of young downy birch-dominated stands in the integrated harvesting of pulpwood and energy wood have not been previously determined in Finland or in any other country.

In order to update the above-mentioned silvicultural and economic analyses of downy birch-dominated forests (Niemistö 2013), Natural Resources Institute Finland studied the integrated harvesting of pulpwood and energy wood. Cutting was based on a two-pile cutting method, where pulpwood and energy wood fractions are stacked into two separate piles both in cutting young thinning and clear cutting stands. The purpose of the study was to determine the productivity and time consumption functions of multi-tree cutting of pulpwood and energy wood in thinnings and clear cuttings of downy birch-dominated stands, along with the time consumption of cutting work phases performed with a medium-sized harvester. In the time studies, the industrial wood fraction was harvested as delimbed and the energy wood fraction as non-delimbed. According to the time consumption models, productivity was explained in terms of tree volume (dm^3) and harvesting intensity (number of trees removed per hectare). Productivity was expressed in solid cubic metres per effective hour (m^3/E_0h).

Material and Methods

The machinery studied

The study utilised a 6-wheel Komatsu 901.4 harvester with an attached Komatsu 350.1 harvester head capable of multi-tree handling and a CRH 15 crane with a maximum reach of 10 m (Komatsu Forest AB). Multi-tree handling in the Komatsu 350.1 harvester head was based on a software utilising the MaxiXplorer control and information system that enables the synchronising of the feed roller and delimbing knife functions to operate as an accumulating device (Komatsu Forest AB). The harvester was a 2011 model and according to the manufacturer's information, the weight of the Komatsu 901.4 was 15100 kg and the engine power of the 6-cylinder SisuDiesel 66 CTA–2V was 150 kW. The lifting torque of the crane was 156.5 kNm (gross) and the weight of the Komatsu 350.1 harvester head was 960 kg. The height of the harvester head in cutting position was 1440 mm and the maximum feed roller opening was 520 mm (Figure 1). The number

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Figure 1. The Komatsu 350.1 harvester head used in the integrated harvesting of downy birch pulpwood and energy wood. The operation of a harvester head in multi-tree harvesting was based on the synchronising of feed roller and delimbing knife functions

of feed rollers was three, the maximum feeding speed was 5 m/s and cutting was performed with a chainsaw (Komatsu Forest AB).

The time study

The time study data on the integrated harvesting of pulpwood and energy wood was collected from four different stands in Vaala (64°25'N, 26°42'E) in winter and summer conditions from March to December 2013. There were two stands for clear cuttings and two stands for thinnings. All the stands were located on drained peatlands in close geographic proximity – within 10 km Euclidean distance – and all of the time study plots were free of undergrowth. According to the forest management plans, the average height of the trees before cutting at the stands were in the range of 7–17 m and the diameters at a height of 1.3 m were in the range of 5–20 cm. The average initial density was 1948 trees per hectare (SD 523) in the clear cutting time study plots, and 2368 trees per hectare (SD 415) in the thinning time study plots (Tables 1 and 2). The probability of the t-statistics for equal initial densities was 0.0012, indicating unequal stand characters. The 30 to 50-year-old first thinning stands were almost pure downy birch (*Betula pubescens*). The boundaries of the visibly numbered time study plots were marked with ribbons and poles at the stand. The total number of time study plots was 40 in clear cuttings and 25 in thinnings (Tables 1 and 2). The time study plots were 25 m long and the widths equalled the harvester's work path (Laitila 2013a, Laitila 2013b). The area of the time study plots (m²) was calculated on the basis of an average strip road spacing of 16.6 m in clear cuttings and 23.8 m (6 plots) or 20.2 m (19 plots) in thinnings (cf. Chapter: The average spacing and width of strip roads).

During harvesting, terrain conditions on the time study sites were estimated in line with the Finnish classification system (Anon. 1990). The factors assessed were load-bearing capacity, roughness of terrain surface and steepness of the terrain. On the basis of the measurements, the study sites were classified as terrain class 1 (easy conditions). Strip roads were not marked in advance, but they were planned by the harvester-operator during the cut-

ting work. Cuttings were carried out during the daytime (06:00–17:00) and the ground had snow cover of between 5 and 50 cm during the winter experiments. The temperature was -24 to 0 °C during winter experiments and +5 to 15 °C in summer conditions. In thinnings the harvester-operator chose the trees to be removed using the "thinning from below" method, in accordance with silvicultural recommendations (Niemistö 1991, Anon. 1994). All study plots were cut by the same harvester and operator. The harvester-operator was skilful and he had 20 years of work experience in driving wheeled harvesters and six years of work experience in multi-tree cutting using the two-pile method in thinnings and clear cuttings.

In the time studies, the pulpwood fraction was harvested as delimbed and the tops as non-delimbed. Cutting was carried out by application of the multi-tree cutting and the timber fractions were stacked into two separate piles along the strip road (Figure 2). In thinning, the trees were felled mostly perpendicular to the strip road and piles were placed on both sides of the strip road at an angle of approximately 90 degrees (Figure 2). In clear cutting, trees were felled forwards along the strip road, and the piles were placed at the sides of the harvester almost along the harvester moving line (Figure 2).
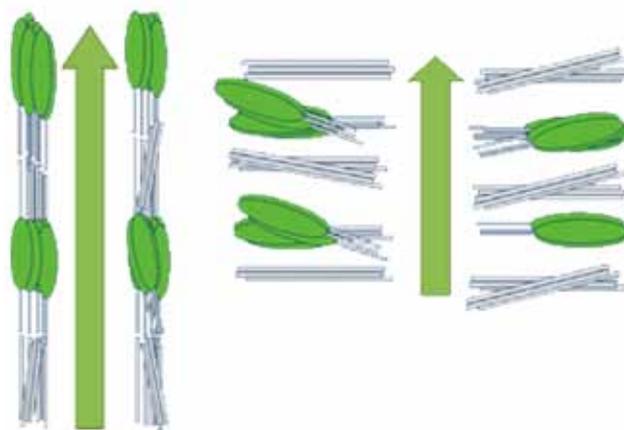

Figure 2. Piling of pulpwood and energy wood fractions in downy birch-dominated clear cuttings (left) and thinnings (right)

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In the experiment, the pulpwood was harvested to the target top diameter of 5–7 cm (over bark) and a bolt length of 3–5 m. In addition, trees that were less than 7 cm but more than 4 cm thick at a height of 1.3 m were considered to be energy wood. The operator visually estimated the diameter of the trees at that height. The target length of the energy wood, harvested as a whole tree, was 5–7 m. The non-delimbed tops of pulpwood stems were stacked with the energy wood into the same pile along the strip road (Figure 2).The energy wood fraction consisted mainly of the non-delimbed tops of pulpwood stems.

The time study was carried out manually with a Rufco-900 field computer (Nuutinen et al. 2008). The working time was recorded through the application of a continuous timing method wherein a clock ran continuously and the times for different phases were separated from each other under distinct numeric codes (e.g. Harstela 1991, Magagnotti et al. 2013). When the entire work process was recorded, the cutting functions had the highest priority, followed by the moving and the arrangement elements. Auxiliary time use (e.g. planning of work and preparations) was included in the work phases in which it was observed. Effective working time was divided into the following work phases:

• Moving forwards: begins when the harvester starts to move forwards and ends when it stops moving to perform another activity. Moving can be divided into driving forwards from one work location to another and moving at the work location.

• Positioning to cut: begins when the boom starts to swing towards the first tree and ends when the harvester head is resting on the tree before the felling cut begins.

• Felling or accumulating the felling: begins when the felling cut starts, and ends when the accumulated tree bunch or tree starts moving to the processing point (the number of trees in each grapple bunch is observed and recorded).

• Transferring the bunch of trees to the processing point. The accumulated bunch of trees is moved next to the strip road for delimbing and cross-cutting. This work phase ends when the feeding and delimbing of the tree(s) starts.

• Delimbing and cross-cutting: begins when the feeding rolls start to roll the tree(s) and ends when the last cross-cutting is done and the remaining tree top(s) is/are moved to the pile from the harvester head.

• Arranging stems, tops and whole trees into piles: arrangement of timber fractions into piles, with similar timber assortments kept together in the pile (separately outside the processing phase).

• Moving backwards: Begins when the harvester starts to move backwards and ends when it stops moving to perform another activity. Moving can be divided into driving backwards at the work location and speeding up the boom movements by moving the base machine backwards at the work location as necessary.

• Delays: time that is not related to effective work (repairs and maintenance, phone calls, etc.).

The data analysis was conducted for effective working time only (E_0h), in order to avoid the confounding effect of delay time, which is typically erratic (e.g. Spinelli and Visser 2008). The studies were also too short to record representative delay times.

Measurement of the timber volumes harvested

The time study's plot-wise mass and volume of harvested timber fractions (for both pulpwood and energy wood) were measured during forwarding using a crane scale. Forwarding was completed immediately after cutting trials with a Ponsse Wisent forwarder equipped with a Ponsse LoadOptimizer crane scale, with an accuracy of 2 kg. The forwarder's crane model was the PonsseK70+. Pulpwood and energy wood were forwarded as separate timber assortments. The harvested pulpwood and energy wood was weighed first during loading at the time study plot and a second time at the roadside landing when unloading the full load. The weighting value at the roadside landing was used as a correction factor for the plot-wise weighting values. The purpose of the weighing at the roadside landing was to improve on the accuracy of the first plot-wise value because unloading conditions at the roadside landing are more constant compared to loading in the forest. The values for green tonnes of pulpwood and energy wood were converted to solid cubic metres (m^3), yielding green density values of birch and pine pulpwood and birch-dominant whole trees (Anon. 2010, Lindblad et al. 2010). There are seasonal variations in green density values of harvested timber and in March, 935kg/m^3 were used for birch pulpwood, 923 kg/m^3 for pine pulpwood and 900 kg/m^3 for birch-dominant whole trees (Anon. 2010, Lindblad et al. 2010). In September, the equivalent values were 866 kg/m^3, 912 kg/m^3, 900 kg/m^3 and in December 946 kg/m^3, 959 kg/m^3, and 1000 kg/m^3 respectively (Anon. 2010, Lindblad et al. 2010).

In clear cuttings, the total number of trees harvested during the time study was 3234 and of the total volume, 98.3 m^3 were considered to be birch pulpwood, 9.2 m^3 pine pulpwood and 76.4 m^3 non-delimbed energy wood. In thinnings, the total number of harvested trees was 1870 and of the total volume 58.7 m^3 were birch pulpwood, 11.5 m^3 pine pulpwood and 27.1 m^3 non-delimbed energy wood, respectively. The average forwarder payloads of pulpwood and energy wood were 9.3 m^3 and 4.7 m^3 (full), and the payloads were noted to be equal both in thinnings and clear cuttings.

The average volume (dm³) of trees harvested on a time study plot was calculated by dividing the cutting removal (m^3) by the number of trees harvested. On the clear cutting time study plots (Table 1), the average volume of the harvested trees varied in the range of 16–96 dm³

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(mean 58 dm^3), the harvesting intensity was 1,253–4,072 harvested trees per hectare (mean 1948 trees/ha), and cutting removal was 49–211 m^3/ha (mean 111 m^3/ha). On the thinning time study plots (Table 2), the average volume of the harvested trees varied in the range of 28–69 dm^3 (mean 50 dm^3), the harvesting intensity was 475–2,101 harvested trees per hectare (mean 1,408/ha), and cutting removal was 23–109 m^3/ha (mean 63 m^3/ha).

Table 1. Basic stand data for time study plots 1–40 in clear cuttings

Plot number on clear cuttings	Removal, trees per hectare	Cutting removal, m³/ha	The share of assortments from the cutting removal: birch, pine & energy wood	Average volume of harvested trees, dm³
1	1879	146	48%; 9% & 43%	78
2	1711	111	45%; 7% & 48%	65
3	1421	91	43%; 13% & 44%	64
4	2096	104	21%; 22% & 56%	50
5	1976	89	15%; 8% & 77%	45
6	2289	81	20%; 10% & 70%	35
7	1542	76	27%; 10% & 62%	49
8	1759	59	20%; 15% & 65%	34
9	1711	100	12%; 27% & 60%	58
10	1590	85	39%; 9% & 53%	53
11	1253	61	23%; 17% & 60%	49
12	1470	92	21%; 27% & 52%	62
13	1711	78	33%; 3% & 64%	45
14	1783	107	29%; 7% & 65%	60
15	1421	77	53%; 0% & 47%	54
16	1807	117	39%; 11% & 49%	65
17	1518	114	53%; 3% & 43%	75
18	1735	101	54%; 0% & 46%	58
19	1927	118	62%; 1% & 37%	61
20	1446	77	63%; 7% & 30%	53
21	2217	72	51%; 0% & 49%	33
22	2409	75	58%; 0% & 42%	31
23	2602	77	56%; 0% & 44%	30
24	3228	105	39%; 6% & 55%	33
25	1686	49	40%; 4% & 55%	29
26	1807	58	37%; 0% & 63%	32
27	1759	66	39%; 13% & 47%	37
28	4072	66	0%; 0% & 100%	16
29	2048	164	75%; 1% & 25%	80
30	2168	181	75%; 0% & 25%	84
31	2000	176	70%; 0% & 30%	88
32	2241	147	71%; 0% & 29%	66
33	2192	211	73%; 1% & 27%	96
34	1662	153	77%; 0% & 23%	92
35	1952	172	72%; 3% & 25%	88
36	1494	91	78%; 0% & 22%	61
37	2385	178	66%; 0% & 34%	74
38	1446	119	63%; 0% & 37%	82
39	2000	190	79%; 2% & 19%	95
40	2506	196	73%; 0% & 27%	78
Mean	1948 trees/ha (SD 523)	111 m³/ha (SD 43)	48%; 6% & 46% (SD 20;8;16)	58 dm³ (SD 21)

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**Table 2.** Basic stand data for time study plots 1– 25 in thinnings

Plot number on thinnings	Mean diameter of remaining trees, cm	Mean height of remaining trees, m	Basal area of remaining trees, m²	Number of remaining trees per hectare	Cutting removal, trees per hectare	Cutting removal, m³/ha	The share of assortments from the cutting removal: birch, pine & energy wood, %	Average volume of harvested trees, dm³
1	17	14.3	14	1000	2101	109	37%; 19% & 39%	52
2	13	13.2	10	800	1126	33	36%; 11% & 48%	29
3	14	11	15	1000	2050	82	32%; 11% & 51%	40
4	15	12.9	13	800	1815	86	44%; 7% & 44%	47
5	19	16.2	13	800	1529	94	35%; 31% & 31%	62
6	14	14	14	1000	1681	76	34%; 19% & 42%	45
7	16	13.4	14	1000	1822	73	55%; 18% & 28	47
8	13	16	13	1000	1782	102	62%; 11% & 27%	68
9	12	14.9	10	800	1644	82	79%; 0% & 21%	59
10	10	11.6	10	1000	1307	67	72% ;4% & 24%	61
11	14	13.9	13	1000	1584	73	75%; 4% & 20%	54
12	15	14.9	11	800	1307	77	70%; 5% & 25%	69
13	11	13.4	14	1000	1782	75	81%; 0% & 19%	50
14	11	12.8	13	800	1267	73	54%: 27% & 19%	68
15	20	15.9	13	800	1960	109	45%; 36% & 19%	65
16	14	14.2	14	1000	931	46	74%; 4% & 22%	59
17	11	12	13	1000	1267	52	73%; 3% & 24%	48
18	11	11	15	1000	1109	37	52%; 8% & 40%	39
19	10	11.6	9	1000	1525	45	72%; 0% & 28%	35
20	9	11.5	10	1200	1564	42	70%; 0% & 30%	32
21	10	11.4	7	1000	970	23	67%: 0% & 33%	28
22	9	11.6	7	1000	851	26	77%: 0% & 23%	35
23	12	11.5	13	1200	475	24	47%; 39% & 14%	60
24	10	12.9	9	1000	931	31	82%; 0% & 18%	39
25	10	12.9	9	1000	812	35	80%: 0% & 20%	50
Mean	12.8 cm (SD 3.0)	13.2 m (SD 1.6)	11.8 m² (SD 2.4)	960 trees/ha (SD 115)	1408 trees/ha (SD 430)	63m³/ha (SD 27)	60%; 10% & 30% (SD 17;12;10)	50 dm³ (SD 13)

Inventory of the harvesting quality

Tree data was collected after timber harvesting from two circular 50 m² sample plots, situated as presented in Figure 3 on the time study plots. From the sample plots, the number of remaining trees, mean height (m), mean diameter at 1.3 m height (cm) and basal area (m²) were recorded (Table 2).

In addition to basic tree data, both the width and the spacing of strip roads were measured at 40-metre intervals along the strip road. Their width was measured using the SLU method, in which the distances to the nearest trees were measured at right angles from the middle of the strip road, at intervals of 10 m on each side (Björheden and Fröding 1986). The measurement point on the trees was the cutting level, and the width of the strip road was the sum of the two distances (Björheden and Fröding 1986). These measurements were accurate to within 1 cm. The
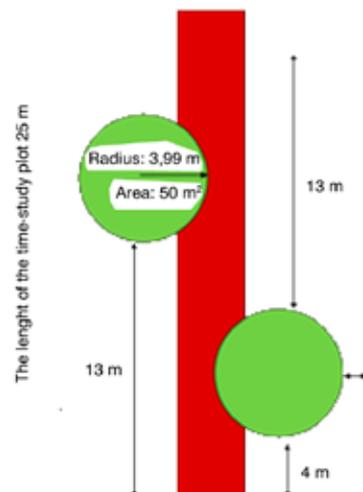
Figure 3. Location of the sample plots for stand measurements in the time study areas in thinnings

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distance between two parallel strip roads was measured at right angles from the middle of the left-hand strip road to the middle of the right-hand strip road. The accuracy of these measurements was 10 cm.

Data analysis

The recorded plot-wise time study data and the measured harvested timber volumes were combined as a data matrix. The time consumption of the main work elements in the multi-tree cutting was formulated through the application of regression analysis in which the harvesting conditions (volume of harvested trees and number of trees harvested per hectare) were independent variables. Several transformations and curve types were tested, so that we could achieve symmetrical residuals for the regression models and ensure the statistical significance of the coefficients. The regression analysis was carried out using the SPSS statistics package, and characteristics of regression models are detailed in Table 3. The unit for calculation of effective time consumption was seconds per tree, and multi-tree cutting productivity was expressed in solid cubic metres per effective hour (m^3/E_0h). In the regression modelling, the work phases of multi-tree cutting were combined into three main work elements: moving, accumulating felling, and processing (Table 3). In moving, the time spent moving, also in reverse, was included. In accumulation, the work phases of positioning to cut, accumulating felling, and transferring the bunch of trees to the processing point were included. Delimbing and cross-cutting, and the arrangement of stems and tops into piles were included in the main work element of processing.

Results

Distribution of work phases and the cutting productivity in the time study

In the time study of thinning and clear cutting, delimbing and cross-cutting represented 36–43 % of the total effective working time in multi-tree cutting of downy birch-dominated stands, and the share of felling or accumulating fellings was 13–16 % (Figure 4). The proportion of the positioning-to-cut phase was 23–28 %. Moving or driving in reverse between work locations represented 7–11 % of the effective working time (Figure 4). Transferring the bunch of trees to the processing point took 9–11 % of the effective working time, and arranging timber assortments into piles took 1–2 % (Figure 4).

Cutting productivity per effective hour (m^3/E_0h) increased as the volume of the harvested trees rose (Figure 5). On the time study sample plots, the lowest and highest values recorded for multi-tree cutting productivity per effective hour were 5.6 m^3/E_0h and 17.4 m^3/E_0h in clear cuttings and 4.8 or 10.9 m^3/E_0h in thinnings, respectively (Figure 5). As for trees, the highest and lowest values recorded for cutting productivity per effective hour were 345 and 153 trees/E_0h (mean 203 trees/E_0h) in clear cuttings and 126–198 trees/E_0h (mean 153 trees/E_0h) in thinnings, respectively. Because the tree volume had an impact on the number of trees that fitted into the harvester head, the number of grapple loads processed by means of the multi-tree method (i.e. at least two trees in the grapple at a time) decreased as the trees' volume increased (Figure 6). On average, the harvester head processed 1.2 trees per grapple cycle, while grapple loads processed by means of the multi-tree method accounted for 16 % of all time study data in clear cutting and 1.1 trees in thinnings per grapple cycle and for 14 % of all time study data.

The time consumption models for the main work elements

Regression models were formulated for the time elements of moving, processing and accumulating felling and for the number of trees in the grapple during accumulating felling (Table 3).

Moving time (T_{moving}) was dependent on the number of trees harvested (Figure 7). The moving time per tree harvested decreased as the number of trees harvested per hectare increased; in such cases, it was possible to cut
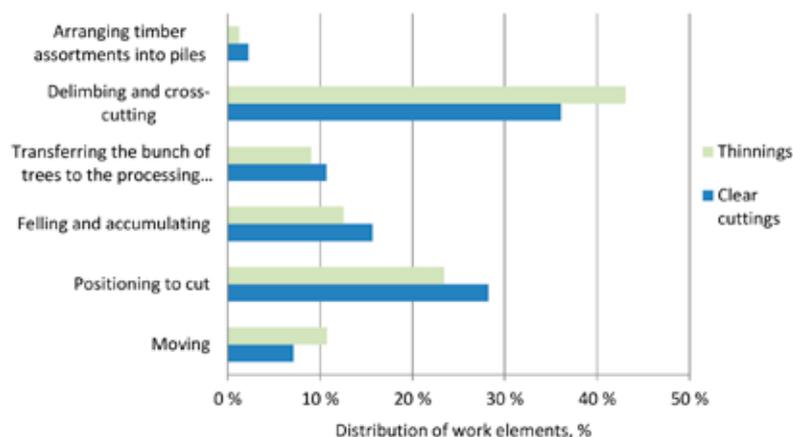
Figure 4. Distribution of work elements when thinning or clear cutting downy birch-dominated stands in the integrated harvesting of pulpwood and energy wood. Total effective working time (E_0h) recorded

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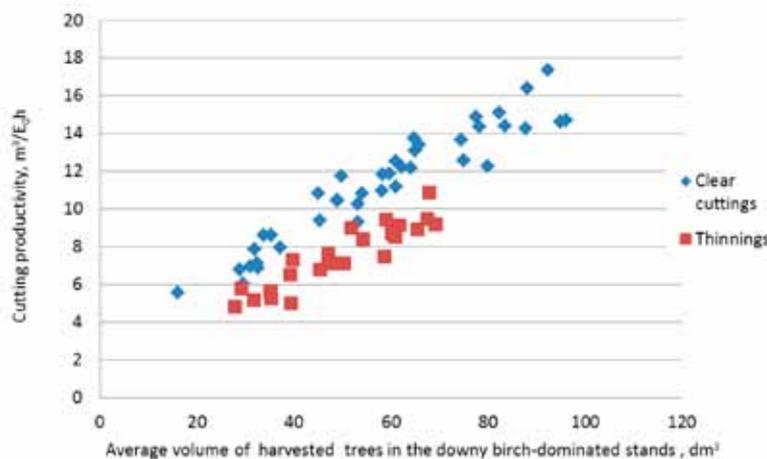
Figure 5. Cutting productivity recorded for the time study plots by average volume of harvested tree in thinnings and clear cuttings of downy birch-dominated stands
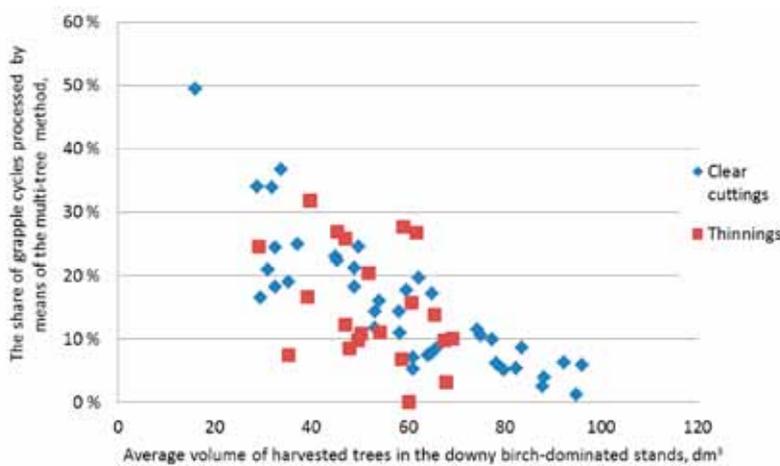
Figure 6. The percentage of multi-tree cutting recorded for the time study plots by average volume of harvested tree in the integrated harvesting of pulpwood and energy wood in thinnings and clear cuttings of downy birch-dominated stands

Table 3. Statistical characteristics of regression models

Work phase model	Dependent variable	r^2	F-test F-value	p	N	Term	Constant/Coefficient Estimate	Std. error	t-test t-value	p
Moving in thinnings	$T_{Moving\ T}$	0.141	3.626	0.070	25	Constant $ln(x_{1T})$	6.873 -0.605	2.282 0.317	3.012 -1.904	0.006 0.070
Moving in clear cuttings	$T_{Moving\ C}$	0.544	44.060	<0.001	40	Constant $1/x_{1C}$	-0.023 2375.117	0.198 357.826	-0.119 6.638	0.906 <0.001
Accumulating felling in thinnings	$N_{Number\ of\ trees\ in\ the\ grapple\ T}$	0.049	1.088	0.309	25	Constant $1/x_{2T}$	1.064 3.960	0.080 3.797	13.236 1.043	<0.001 0.309
	$T_{Accumulating\ felling\ T}$	0.032	0.738	0.400	25	Constant x_{3T}	12.456 -1.667	2.221 1.940	-0.859 5.608	0.400 <0.001
Accumulating felling in clear cuttings	$N_{Number\ of\ trees\ in\ the\ grapple\ C}$	0.768	125.749	<0.001	40	Constant $1/x_{2C}$	0.958 11.044	0.022 0.985	43.400 11.214	<0.001 <0.001
	$T_{Accumulating\ felling\ C}$	0.167	7.632	0.009	40	Constant x_{3C}	12.599 -2.455	1.055 0.889	11.941 -2.763	<0.001 0.009
Processing in thinnings	$T_{Processing\ T}$	0.514	23.298	<0.001	25	Constant x_{2T}	4.628 0.116	1.240 0.024	3.733 4.827	0.001 <0.001
Processing in clear cuttings	$T_{Processing\ C}$	0.738	107.174	<0.001	40	Constant x_{2C}	1.799 0.090	0.540 0.009	3.328 10.352	0.002 <0.001

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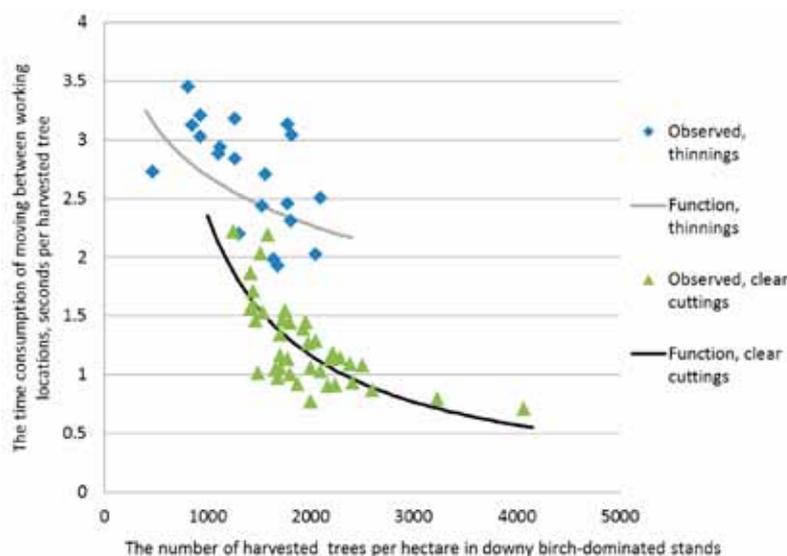
Figure 7. The time consumption of moving between work locations in thinnings and clear cuttings of downy birch-dominated stands as a function of trees harvested per hectare

more trees from a single work location. For thinnings, the time consumption of moving was formulated as:

$$T_{moving\ T} = 6.873 - 0.605ln(x_{1T}),$$

where

$T_{moving\ T}$ = time for moving between work locations in thinnings, expressed in seconds per tree;

x_{1T} = the number of trees harvested in thinnings, trees per hectare;

$r^2 = 0.141$.

For clear cuttings, the time consumption of moving was formulated as:

$$T_{moving\ C} = -0.023 + 2375.177 \times 1/x_{1C},$$

where

$T_{moving\ C}$ = time for moving between work locations in clear cuttings, expressed in seconds per tree;

x_{1C} = the number of trees harvested in clear cuttings, trees per hectare;

$r^2 = 0.544$.

The most important productivity factors in multi-tree cutting were the average tree volumes and the number of trees in the harvester head per grapple cycle. The latter value ($N_{Number\ of\ trees\ in\ the\ grapple}$) was predicted on the basis of the average volume of the harvested trees (Figure 8). The time consumed in accumulating fellings per harvested tree ($T_{Accumulating\ felling}$) was dependent on the number of trees in the harvester head in a grapple cycle (Figure 9):

For thinnings, the time consumption of multi-tree cutting was formulated as:

$$N_{Number\ of\ trees\ in\ the\ grapple\ T} = 1.064 + 3.96 \times 1/x_{2T},$$

where

$N_{Number\ of\ trees\ in\ the\ grapple\ T}$ = the average number of trees in the harvester head per grapple cycle in thinnings;

x_{2T} = the average volume of the harvested trees in thinnings, dm^3;

$r^2 = 0.049$.

$$T_{Accumulating\ felling\ T} = 12.456-1.667x_{3T},$$

where

$T_{Accumulating\ felling\ T}$ = the time for positioning to cut, accumulating felling, and transferring the bunch of trees to the processing point in thinnings, expressed in seconds per tree;

x_{3T} = the average number of trees in the harvester head per grapple cycle in thinnings;

$r^2 = 0.032$.

For clear cuttings, the time consumption of multi-tree cutting was formulated as:

$$N_{Number\ of\ trees\ in\ the\ grapple\ C} = 0.958 + 11.044*1/x_{2C},$$

where

$N_{Number\ of\ trees\ in\ the\ grapple\ C}$ = the average number of trees in the harvester head per grapple cycle in clear cuttings;

x_{2C} = the average volume of the harvested trees in clear cuttings, dm^3;

$r^2 = 0.768$.

$$T_{Accumulating\ felling\ C} = 12.599 - 2.455x_{3C},$$

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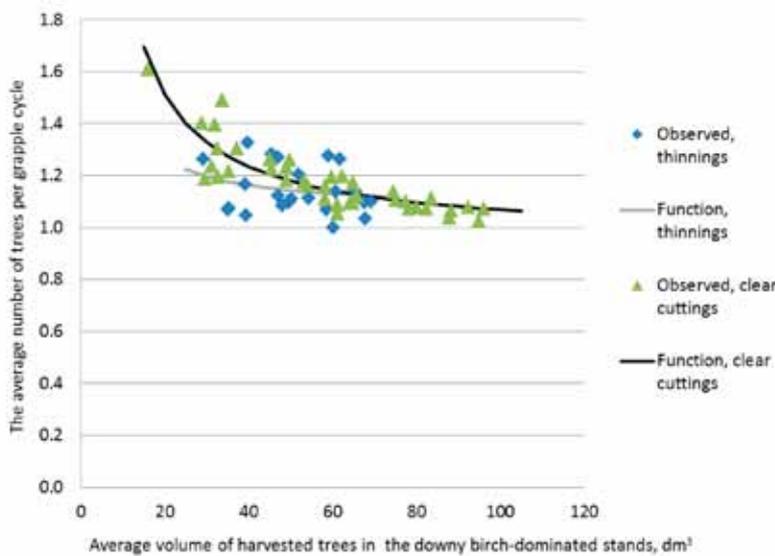
Figure 8. The number of trees harvested per grapple cycle in thinnings and clear cuttings of downy birch-dominated stands as a function of average tree volume, dm³
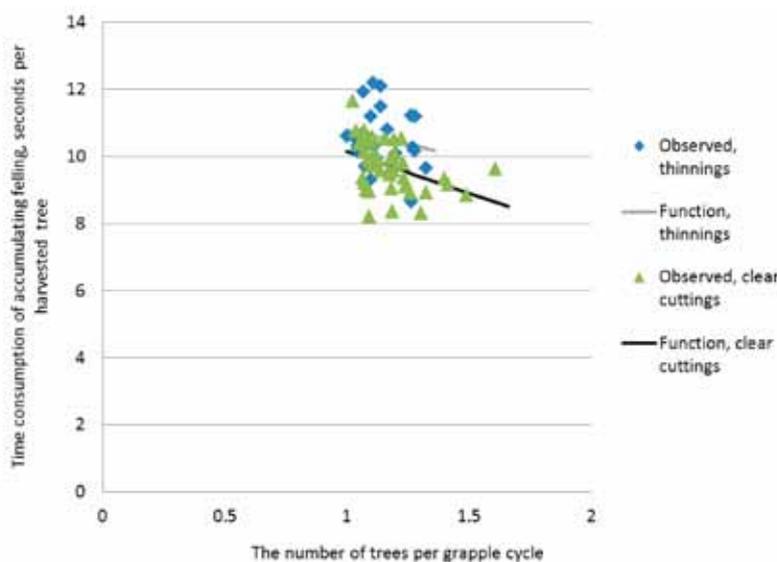
Figure 9. The time consumption of stands as a function of trees per grapple cycle. accumulating felling (more precisely, positioning to cut + accumulating the felling + transferring the bunch of trees to the processing point) per tree harvested, in thinnings and clear cuttings of downy birch-dominated

where

$T_{Accumulating\ felling\ C}$ = the time for positioning to cut, accumulating felling, and transferring the bunch of trees to the processing point in clear cuttings, expressed in seconds per tree;

x_{3C} = the average number of trees in the harvester head per grapple cycle in clear cuttings;

$r^2 = 0.167$.

Processing time per harvested tree ($T_{Processing}$) was modelled from the average volume of harvested trees (Figure 10):

For thinnings, the time consumption of processing was formulated as:

$$T_{Processing\ T} = 4.628 + 0.116x_{2T},$$

where

$T_{Processing\ T}$ = time consumption of multi-tree processing in thinnings, expressed in seconds per tree;

x_{2T} = the average volume of the harvested trees in thinnings, dm³;

$r^2 = 0.514$.

For clear cuttings, the time consumption of processing formulated as:

$$T_{Processing\ C} = 1.799 + 0.09x_{2C},$$

where

$T_{Processing\ C}$ = time consumption of multi-tree processing in clear cuttings, expressed in seconds per tree;

x_{2C} = the average volume of the harvested trees in clear cuttings, dm³;

$r^2 = 0.738$.

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The productivity of the multi-tree cutting and validity of results

The total time consumption (E_0h) of multi-tree cutting per harvested tree (T_{Total}) was obtained by adding up the time consumption values for the three main work elements as follows:

$$T_{Total} = T_{Moving} + T_{Accumulating\ felling} + T_{Processing}$$

The number of harvested trees per effective hour (trees/E_0h) was calculated by dividing 3600 seconds by the total time consumption of a harvested tree (T_{Total}). Effective hour productivity expressed as a number of trees harvested (trees/E_0h) was converted to solid cubic metres (m^3/E_0h) by multiplying the number of harvested trees with the average volume of the harvested trees (x_2).

Figure 11 describes the effective working time productivity (m^3/E_0h) of the multi-tree cutting when the harvesting intensity was 3,000, 2,000 or 1,000 trees per hectare in clear cuttings and 1,500 or 1000 in thinnings. The average volume of harvested trees was within the range of 15–100 dm^3 in clear cuttings and in 15–70 dm^3 thinnings. Calculations using the time consumption model (T_{Total}) showed that the harvesting intensity has a rather nominal effect on the cutting productivity compared to the average volume of harvested downy birch (Figure 11). According to the results, the cutting productivity per effective hour increased almost linearly with the growth in the average volume of harvested downy birch (Figure 11). In clear cuttings, productivity was about 30–50% higher than cutting productivity in thinnings (Figure 11).

Figure 12 compares the cutting productivity recorded and modelled for the time study plots as a function of average volumes of harvested trees in thinnings and clear cuttings of downy birch-dominated stands. The results showed that time consumption models fit well to the time study data recorded and models do not systematically give over- or underestimates for the cutting productivity of downy birch-dominated stands either in thinnings or clear cuttings (Figure 12).

Figure 10. The time consumption of multi-tree processing in thinnings and clear cuttings of downy birch-dominated stands as a function of average tree volume
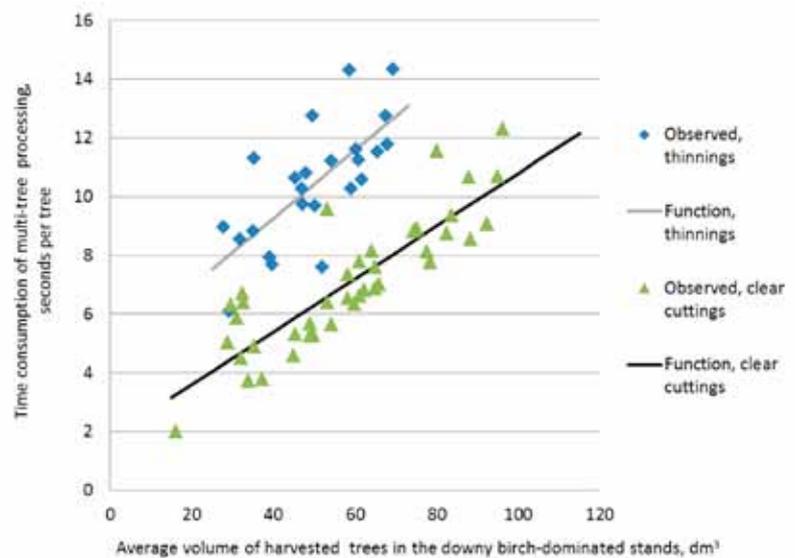
**Figure 11.** Cutting productivity (m^3/E_0h) in the integrated harvesting of pulpwood and energy wood as a function of average tree volume and number of trees harvested per hectare in thinnings and clear cuttings of downy birch-dominated stands

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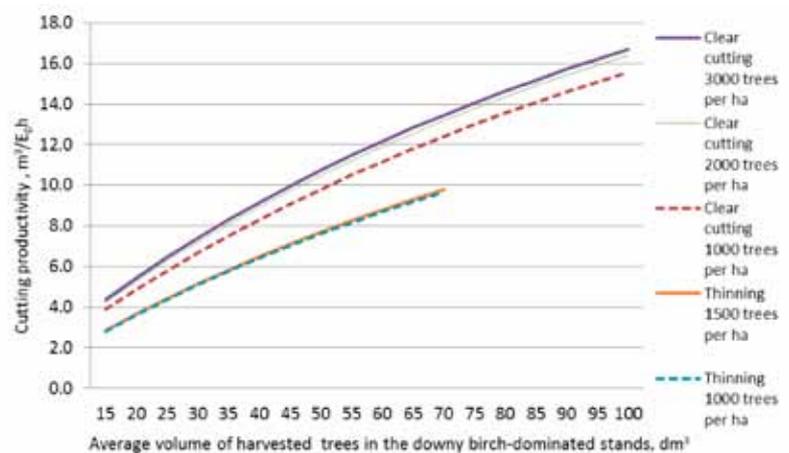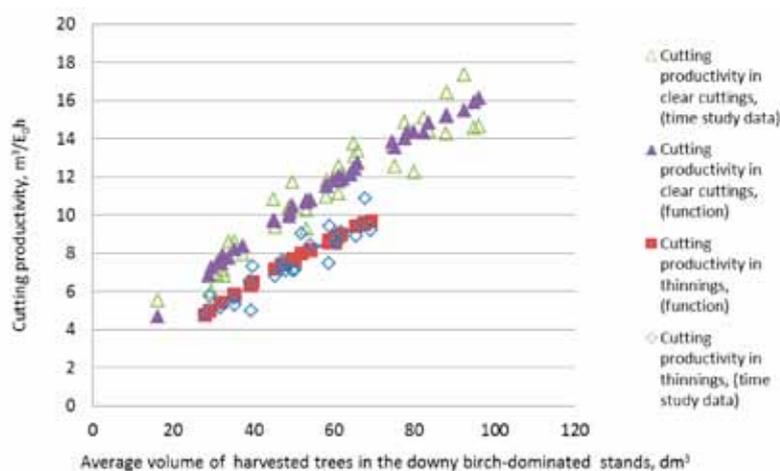
Figure 12. Cutting productivity recorded and modelled for the time study plots as a function of average volumes of harvested trees in thinnings and clear cuttings of downy birch-dominated stands

The average spacing and width of strip roads

The average strip road spacing observed on the first time study thinning stand was 23.8 m (SD 2.1 m) and on the second stand it was 20.2 m (SD 2.4 m). The deviances of strip road spacing between two drained peatland stands were caused by the different spacing of the ditches on the stands. The average distance between the strip roads were significantly ($p = 0.004$) different from the recommended minimum spacing of 20 m for thinnings (Anon. 2003). The average width of the strip roads was 422 cm (SD 25 cm) on thinnings, somewhat more than the recommended maximum width of 400 cm (Anon. 2003). The harvesting quality (Table 2) achieved the recommended silvicultural standards in thinnings (Niemistö 1991, Anon. 1994). The average strip road spacing observed on the clear cutting stands was 16.6 m (SD 1.0 m).

Discussion and Conclusions

As expected, clear cutting enhanced harvesting productivity when compared with thinning, but multi-tree cutting only had a minor effect on productivity in the case of both harvesting methods due to the low percentage of multi-tree cutting. Multi-tree cutting accounted for 16 % of all the time study data in clear cuttings and 14% in thinnings. Compared to studies in Scots pine stands (e.g. Lehtimäki and Nurmi 2011, Kärhä 2011, Laitila and Väätäinen 2013b, Petty and Kärhä 2014), the proportion of multi-tree cutting and cutting productivity was significantly lower. For example, in the thinning study by Laitila and Väätäinen (2013b), grapple cycles processed by means of the multi-tree method accounted for 57 % of all time study data and cutting productivity were 5-6 m³/E₀h higher than the productivity level of this study. Since downy birch stems are often bent and crooked, they are ill-suited to multi-tree cutting using feeding and delimbing harvester heads. This led to the fairly frequent use of the single-tree method when processing downy

birch. In multi-tree cutting, non-simultaneous feed-in of trees is a common problem, i.e. the delimbed trees do not pass through the grapple at the same pace (Heikkilä et al. 2006). This results in unwanted variation in the lengths and top diameters of harvested timber.

However, in this study, non-simultaneous feeding led to interruptions in only a few cases, due to the operator's skills in selecting trees suitable for multi-tree cutting. Like tree bends and curves, forked stems also prevent multi-tree cutting: it has been found that processing takes around 50% longer in the case of single-tree harvesting than in the usual felling, delimbing and piling of non-forked timber (Niemistö et al. 2012). In this study, the number of forked trees impeding cutting was limited to individual trees, since the harvested stands were mainly at the first thinning stage, i.e. they were rather small in size.

As regards clear cutting of downy birch-dominated stands, the results are consistent with those of Niemistö et al. (2012), when compared with the clear cutting of downy birch on a site where there is no need to retain or account for the understorey. In the harvesting study by Niemistö et al. (2012), downy birch serving as shelter trees for spruce were harvested using a medium-sized thinning harvester (John Deere 1070/745) and the single-tree method. The time study stands marked for cutting in the Niemistö et al. (2012) study were located in Kärsämäki, Pyhäjärvi and Kälviä, i.e. in fairly close geographic proximity to the stands situated in Vaala (50, 90 and 160 km Euclidean distance).

Lilleberg (1994) noted that as the share of downy birch increases, the possibilities of applying multi-tree cutting to final cuttings in Northern Finland decrease, whereas a higher number of trees per hectare and a higher share of conifers increase the same opportunities. In time studies conducted on Swedish final cutting sites dominated by conifer trees and small-dimensioned tree stands (120–220 dm³ under bark), multi-tree harvesting has been found to enhance work productivity in comparison to the

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single-tree method by 4–16%, in line with the decrease in the stem size of the trees (Brunberg 2012). Long-term follow-up studies have recorded an average productivity increase of 5% in the same harvesting conditions (Brunberg 2012). According to Sirén et al. (2013b) and Brunberg (2012), reasons for the low utilisation of multi-tree harvesting include the distribution of harvesting intensity over several tree species, the presence of a spruce understorey and, in some cases, the operators having little experience of this work method.

The fact that downy birch tops were forked and thick-branched favoured the harvesting of the downy birch energy fraction as non-delimbed whole trees over delimbed stems (cf. Laitila and Väätäinen 2012). From the forwarding point of view, tree sections should be as long as possible in order to maximise the load size of the forwarder (Björheden 1997). Payload is one of the most important productivity and cost factors in forwarding, and the lengthening of the forwarded timber is the easiest way to increase its size. The disadvantages are that the excessive lengthening of forwarded timber complicates the mobility and loading work. Furthermore, the forwarders tend to become tail-heavy (Laitila et al. 2007).

All study plots were cut by the same harvester and operator. This is both advantageous and disadvantageous. When machine and operator are the same, we can eliminate the effect that is caused by these factors, but on the other hand, the generalisation of harvesting productivity is restricted. Due to a limited number of time study plots, stands, operators and machines, the results do not represent the nationwide time consumption and productivity level of harvesting in young downy birch-dominated stands. However, the regression models presented provide novel productivity estimates of modern multi-tree harvesting system in typical harvesting conditions for cost calculations and different types of simulation and modelling purposes.

In the formulated regression models for time elements and grapple sizes, the predicted variables were the same as in corresponding formulas in earlier studies (Siren 1998, Ryynänen and Rönkkö 2001, Nurminen et al. 2006, Laitila and Väätäinen 2013b). Nevertheless, in some functions the predictors were not statistically significant (p-value > 0.05). This could be particularly noted in part of the models of the thinning method (see Table 3). Therefore, mostly as a result of the relatively limited amount of observations and lack of other possibly predicting variables in the formula, some of the presented regression functions do not fit well with the recorded observations.

Several studies have shown that the operator has the most important impact on harvesting productivity (e.g. Sirén 1998, Ryynänen and Rönkkö 2001, Kariniemi 2006, Väätäinen et al. 2005, Ovaskainen 2009, Purfurst 2010, Palander et al. 2012). Previous studies have also shown

that productivity curves based on follow-up studies are significantly lower than productivity curves calculated on the basis of time studies (Mäki 1999, Ryynänen and Rönkkö 2001, Sirén and Aaltio 2003). The reasons for this include the fact that time studies based on brief work on sample plots do not fully correspond to real-world work throughout the year. Accordingly, a long-term follow-up study would give a more reliable picture of productivity in practice, as well as of the functional and technical utilisation rate of the base machine and harvester head in variable stand conditions at different times of the year (Sirén 1998, Ryynänen and Rönkkö 2001, Kariniemi 2006, Sirén and Aaltio 2003, Väätäinen et al. 2005, Spinelli and Visser 2008, Purfurst 2010, Eriksson and Lindroos 2014).

Peatlands are very problematic from the bearing capacity point of view. Therefore, logging operations on peatlands in Finland are mainly carried out during the coldest weeks in winter time. With regard to harvesting logistics, it would be interesting to examine whether clear cutting facilitates the transformation of some peatland stands marked for cutting in winter into stands marked for cutting in summer (Ala-Ilomäki 2006, Ala-Ilomäki et al. 2011, Sirén et al. 2013a). This is because, compared to thinning, clear cutting allows greater freedom in the location of forwarding routes on site, as well as in organising route schedules, thus decreasing the soil disturbances (cf. Uusitalo et al. 2015).

According to Heikkilä (2007), more efficient utilisation of peatland forests requires determined efforts to prolong the harvesting season, since seasonal variation in harvesting results in high harvesting and timber storage costs, and complicates the recruitment of a professional workforce. On the basis of the simulation study by Väätäinen et al. (2010), it was found that year-round harvesting of timber from peatlands resulted in higher employment among operators and higher utilisation rates for machinery. It also provided the opportunity to increase the annual harvesting volume without adding to the amount of harvesting equipment. A survey of experts conducted by Metsäteho suggests that the prerequisites for increasing the efficiency of timber harvesting in young forests include better harvesting conditions and the rationalisation of harvesting (Oikari et al. 2010). Greater harvesting efficiency has the aim of lowering unit costs. In practical terms, this means harvesting more timber within the same time unit, or at a lower cost per operating hour.

Harvesting conditions in thinnings and clear cuttings of young downy birch-dominated stands are not similar because the purpose of thinnings is to regulate the spacing of vital trees as well as to improve quality properties, such as uniformity, reduced branchiness, and better stem form of the remaining stand. Thinning from below also salvages suppressed, damaged and dying trees that would otherwise be lost through natural mortality. Thinning im-

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proves the physical logging conditions of future cuttings, whereas in clear cuttings both the high and poor quality trees are removed simultaneously. For example, in our study the harvesting intensity was 1,253–4,072 harvested trees per hectare in clear cuttings and in thinnings the harvesting intensity was 475–2,101 harvested trees per hectare. In clear cuttings, the cutting removal and the volume of harvested trees is higher.

The study highlighted the need to improve the suitability of the current harvesting equipment fleet for the harvesting and multi-tree harvesting of birch and other bent and crooked trees. This is because harvesting conditions more favourable to clear cutting than thinning are the main factors underlying the observed leap in productivity: 1) The tree-specific moving time shortened when more trees could be harvested on the same spot than during thinning, 2) The removal of trees was systematic in clear cutting while it was selective in thinning, 3) In clear cutting, the remaining tree stand did not hamper the delimbing, cutting or piling of trees. Factors enhancing the efficiency of forwarding include better working conditions and higher removal per hectare than in the case of thinning.

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