Comparison of two harvesting methods for complete tree removal on tree stands on drained peatlands

Runko- ja juuripuun sekä latvusmassan yhdistelmä- ja erilliskorjuu ojitetuissa suometsissä

Juha Laitila, Kari Väätäinen & Antti Asikainen

Juha Laitila, Kari Väätäinen, Antti Asikainen, Finnish Forest Research Institute, P. O Box 68, FI-80101 Joensuu, Finland, TEL +358 50 391 3255, email: juha.laitila@metla.fi

This case study represents a novel complete wood biomass harvesting method for woody peatlands, which are to be prepared for peat production for energy use. The productivity and cost-efficiency of complete tree harvesting in a peatland forest dominated by Scots pine (*Pinus sylvestris*) was examined in this study. In complete tree harvesting, a single-grip harvester lifts a whole tree with its roots from the ground and divides the tree into stump and stem part sections by cross-cutting. This work method was compared to the conventional harvesting method, wherein the stem wood and stump wood are harvested in separate operations with different machines. The work study was conducted for complete tree cutting and conventional tree cutting by a single-grip harvester. In total there were 97.6 solid cubic metres (m^3) of wood harvested in the study. The harvesting cost of the extracted wood (stump section, stem wood and crown mass) to the road side landing was calculated for both harvesting methods by using time study models of cutting obtained from this study and the separate stump lifting and biomass forwarding models acquired from the literature. According to the results, the complete tree harvesting was cost-competitive to conventional harvesting (including stem wood, crown mass and stump extraction) when the breast height diameter of the trees to be removed was below the range of 16–20 cm.

Keywords: Clear cutting, complete tree harvesting, fuel wood chips, integrated harvesting, peat production, productivity, single-grip harvester, stump lifting, time consumption models

Introduction

About half of Finland's almost 9 million hectares of peatland have been ditched (Nuutinen 2000). The ditch spacing on ditched sites varies between 20 m and 60 m, the ditch depth varies between 70–90 cm, and ditch widths range between 150–200 cm (Heikurainen 1983). Peatland drainage peaked in the 1960s and 1970s, when approximately 4 million hectares were drained for forestry purposes (Lauhanen 2002). The total growing stock on peatlands amounts to 479 million solid cubic metres (m^3). The average volume of the growing stock on peatlands is 87 m^3/ha (Tomppo 2005). The share of Scots pine (*Pinus sylvestris*) of the total stem volume of the growing stock on peatlands is approximately 50% and that of Norway spruce (*Picea abies*) is 25%. The remainder is comprised almost entirely of downy birch (*Betula pubescens*) (Tomppo 2005). Over 50% of peatland forests are still young increment stands in which the trees — depending on the success of ditching and silvicultural treatments — are gradually attaining the dimensions making them suitable for industrial use (Nuutinen 2000). The area-based share of mature stands ready for regeneration is still small, but will increase rapidly in the coming years (Saarinen 2005).

Harvesting sites in peatland areas differ from corresponding upland forest stands in terms of both their terrain and growing stock. The special characteristics of wood harvesting on peatlands include, among others, the poor and greatly varying carrying capacity of the soil, the obstacles formed by the ditches, the long extraction distances, the small volumes harvested, the small size of the trees and their uneven distribution within the stands, and superficial roots not only of spruce, but also of pine and birch (e.g. Högnäs 1986, Eeronheimo 1991, Sirén 2000, Ylimartimo et al. 2001, Ala-Ilomäki, 2005, Ala-Ilomäki 2006, Heikkilä 2007).

In addition to forestry use, peatlands have been ditched and cleared for agriculture and peat production. According to an estimate provided by VTT Technical Research Centre of Finland, the amount of new peat production areas needed by 2020 is 50 000 hectares to meet the needs of energy generation, and 8000 hectares for horticultural and environmental peat in order to compensate for the discontinuation of peat production on old peat extraction sites opened in the 1970s (Flyktman 2009). The proposal presented by the working party that prepared the National Mires and Peatlands Strategy states that peat production should focus only on ditched peatlands and peatlands that have changed significantly from their pristine state (Soiden ja turvemaiden …2011.)

In woody peatland areas, where peat production for energy use will be activated, cost-efficient methods for clearing woody biomass from the site should be developed. When dealing with peatlands carrying large growing stocks, clearing the site is the most expensive stage of the preparatory work, because the tree stumps either have to be lifted out altogether or they need to be ground into pieces and mixed with peat (Suoninen 1983). The clearing of new peat production areas means removing both aboveground and underground woody biomass from the production site. In addition, these sites are ditched using a spacing of 20 m, the site is levelled and the strips are shaped to be convex to promote the drying of the milled peat (Suoninen 1983).

The harvesting of stumps for energy purposes in Finland has increased rapidly in recent years (e.g. Hakkila 2004) and in year 2010 some 1 million m^3 (solid) of comminuted stumpwood were consumed by heating and power plants (Ylitalo 2011). The stumps are uprooted and split using a crawler excavator equipped with a stump extraction head (e.g. Markkila 2005, Backlund 2007, Karlsson 2007, Laitila et al. 2008, Hedman 2008, Lazdins et al. 2009, Jouhiaho et al. 2010, Lindroos et al. 2010, Laitila 2010, Anerud and Jirjis 2011, Erkkilä et al. 2011). The splitting of stump wood into pieces accelerates its drying and increases the speed of the comminution work. Furthermore, the risk of impurities is higher when the stump is not split properly. The relative bulk density of an intact rootstock pile is of the order of 0.1, whereas that of chopped stumps is 2 to 4 times greater (Hakkila 1976). Excavators from 17 to 24 tonnes are used in stump harvesting (Laitila et al. 2010). After seasoning at the stand, stumps are forwarded to roadside landings by forwarders (e.g. Backlund 2007, Karlsson 2007, Laitila et al. 2008, Lazdins et al. 2009, Laitila 2010).

A novel approach for clearing the forthcoming peat production area from wood biomass is to conduct a complete tree harvesting during the cutting operation, either with a single-grip harvester or an excavator-based harvester. In this context, complete tree cutting indicates a sequence of work task operated with one machine, where a whole tree with a stump is lifted from the ground and the tree is then divided into stump and stem part sections by cross-cutting. The conventional harvesting method of woody biomass, where the aboveground woody biomass and stump wood are harvested in separate operations, was chosen as a comparable method for the complete tree harvesting. More specifically, the separate operations are the cutting of the aboveground biomass with the traditional single-grip harvester or the excavator-based harvester and the stump lifting with the excavator.

The objectives of the study were to estimate the productivity of complete tree cutting conducted by a conventional single-grip harvester on a peatland site dominated by Scots pine. Moreover, a cost comparison of whole wood harvesting (stump wood, stem wood and crown wood) to road side storage was executed between the novel complete tree harvesting method and the conventional tree harvesting method. The final results of the harvesting method comparison were calculated as the harvesting cost (€ m^{-3}) of the total biomass of a complete tree (roots, stemwood and crown mass) at the roadside landing based on time consumption models for cutting acquired from this study, and the results obtained in earlier work studies of forwarding and stump extraction (Asikainen et al. 2001, Väätäinen et al. 2007, Laitila et al. 2008, Laitila 2010).

As a means of determining the difference in the cutting productivity of whole stems between the compared methods, a comparative time study was conducted in which trees were cut individually using a medium-size single-grip harvester and in which the method of processing the trees (cross-cutting, delimbing and piling of crown mass) was the same in both work methods. Based on the time study data, tree-specific time consumption models were formulated.

Material and methods

The plots of the comparative time studies

The comparative time studies took place on a ditched Scots pine-dominated peatland stand, where the ditch spacing was 60 m. The time study plots were 50 m long and 15 m wide (the measured width of the harvester's working strip in the study) and were located in four parallel lines between the ditches. The total number of time study plots was 20 (4 x 5), that is, 10 plots per compared cutting method. The working methods were alternated after each time study plot. The basis for the stand selection was to create similar cutting conditions for both cutting methods, i.e. where the number of factors affecting the work would be minimal and the influence of the working method on work performance would be the main focus (Table 1, figures 5 & 6). The boundaries of the time study plots were marked by means of ribbons and poles at the stand. The size of trees decreased the closer they were to the centre of the stand.

The breast height diameter (d1.3) of each tree, including bark, was marked in tags on the front side of the tree before beginning cutting.

Table 1. Breast height ($d_{1.3}$) diameter distributions of the cut trees in the conventional cutting and complete tree cuttings in the experimental stand.

Taulukko 1. Koemetsiköstä korjattujen runkojen läpimitta-jakaumat kokopuukorjuussa ja tavanomaisessa korjuussa.

Breast height cutting diameter ($d_{1.3}$), cm	Conventional cutting stem number	Complete tree stem number
5	0	2
6	11	17
7	9	12
8	17	22
9	17	20
10	20	17
11	12	7
12	25	24
13	29	35
14	20	32
15	28	37
16	28	31
17	18	27
18	25	24
19	18	18
20	16	20
21	7	12
22	10	11
23	12	7
24	6	3
25	6	3
26	7	5
27	1	0
28	1	0
Total stem number	343	386
Mean tree $d_{1.3}$, cm	15.1	14.5

The diameters were recorded during the time study from these tag markings. The accuracy of the breast height diameter measurement was 1 cm and the measurement height was regularised to be exactly 1.3 m. In addition to the breast height diameter (d1.3), the tree heights of 145 systematically selected sample trees from each diameter class were measured. The accuracy of the tree height measurement with a hypsometer was 10 cm. All the harvested trees were Scots pine and the time study material comprised 729 trees. Of that amount, 386 trees were lifted from the ground with their roots attached in connection with cutting and 343 trees were harvested in a conventional way. The breast height diameter (d1.3) of harvested trees in the plots ranged from 5 to 28 cm (Table 1), the measured height from 6.2 to 19.3 m (Fig. 1) and the number of trees per hectare from 293 to 1423 (Fig. 5).

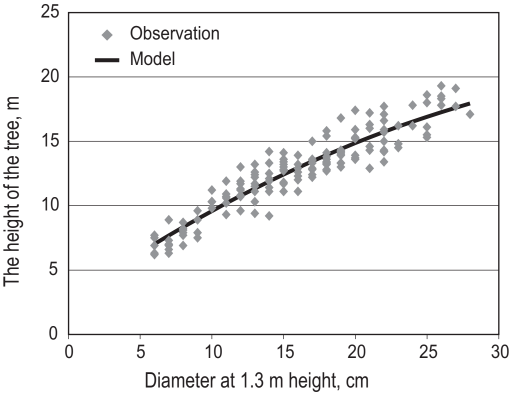

Fig. 1. The model for the Scots pine tree height as a function of breast height diameter ($d_{1.3}$) in the experimental stand on a drained peatland in Central Finland.

Kuva 1. Pituuskoepuiden pituudet rinnankorkeusläpimitan suhteen koemännikössä ojitusalueella Keski-Suomessa..

The estimation of the cutting removal

In order to estimate the total cutting removal of wood biomass in the time studies, a model for the tree height was constructed (Fig. 1). The model was based on the sample tree measurements on the time study plots. The breast height diameter ($d_{1.3}$) was the independent variable for the height of Scots pine:

$$H_{Scots\ pine\ tree} = 2.705 + 0.768x - 0.008x^2 \quad (1)$$

where,

$H_{Scots\ pine\ tree}$ = *the height of the Scots pine tree, m*

x = *the diameter at the breast height* ($d_{1.3}$), *cm*

$r^2 = 0.87$

The volumes of the above and belowground tree components of Scots pine (roots, stump, stem wood, stem bark, foliage, and living and dead branches) were calculated by the biomass functions of Repola et al. (2007) and the basic densities produced by Hakkila (1978). The complete tree biomass was calculated as a function of breast height diameter ($d_{1.3}$), tree height and living crown length (Repola et al. 2007). The length of the living crown of the sample trees was not measured and therefore in the assessment the length of the living crown was estimated to be 40% of the tree height (Repola et al. 2007).

The comparative time study of the cutting methods

The time studies took place on 22 and 23 November 2010 in Saarijärvi (62°34′N, 24°47′E), Central Finland. The time studies were carried out in natural light during the daytime (8:00–16:00). The sky was cloudless and the temperature was –15 C°. The ground had snow cover of 15 cm during the experiments and the falling snow from the tree slightly restricted visibility in the tree grabbing and felling/lifting phase (Fig. 12). The soil was totally unfrozen during the time studies.

The machine used in the study was a Ponsse Cobra HS 10 eight-wheel harvester equipped with a Ponsse HN 125 sliding boom harvester crane and a Ponsse H53 harvester head (Fig. 12). The harvester was a 1996 model that had been thoroughly renovated recently. According to the manufacturer's information, the weight of the Ponsse Cobra HS 10 was 11 350 kg and the engine power of the Perkins 1006-6TW HP was 145 kW. The crane had a maximum reach of 10 m and the lifting torque (gross) was 155 kNm. The weight of the Ponsse H53 harvester head was 850 kg. The harvester's tyres were 600 x 22.5 and the front bogie was equipped with tracks.

The harvester operator was a forest machine entrepreneur who had 13 years' experience of driving forest machines and almost three months' experience of applying a work method in which trees are lifted from the ground with their roots attached in connection with the cutting operation. In the experiment, the pulpwood was harvested with a minimum top diameter of 6 cm and a bolt length of 3–5 m. The dimensions of the small-sized logs were 3.1 and 4.3 m for the length and 11–22 cm for the top diameter. The bucking lengths of the conventional logs were 4.3, 4.6 and 4.9 m, and the minimum top diameter was 15 cm.

The time study was carried out manually using the Rufco-900 field computer (Nuutinen et al. 2008). The working time was recorded by applying a continuous timing method where a clock runs continuously and the times for different elements are separated from each other by numeric codes (e.g. Harstela 1991). The accuracy of the Rufco-900 field computer was 0.6 s (Nuutinen et al. 2008). The harvester's working time was divided into effective working time (E_0h) and delay time (Haarlaa et al. 1984, Mäkelä 1986), which is a common method employed in Nordic work studies. When the entire work process was recorded, the cutting functions had the highest priority, then the moving and the arrangement elements. Auxiliary times (e.g. planning of work and preparations) were included in the work phases in which they were observed. Effective working time was divided into the following work phases:

— Moving: begins when the harvester starts to move and ends when the harvester stops moving to perform another activity. Moving can be divided into driving forward or reversing, either from one working location to another or moving inside the working location.

— Steer out the boom and grab of the tree: begins when the boom starts to swing towards a tree and ends when the harvester head is resting on a tree before either the felling cut or lifting the tree begins.

— Felling: begins when the felling cut starts and ends when the feeding and delimbing of the stem starts.

— Lifting: starts after the harvester head has grabbed the tree at a height of 2–4 m. After loosening the tree from the ground, the harvester head is moved down the stem and the tree is lifted up by the vertical movement of the harvester crane. The stem is used as a lever when loosening roots from the ground.

— Moving the tree to the side of the strip road: the uprooted tree is moved next to the strip road in an upright position in order to cut off the stump.

— Cross-cutting of the stump: begins when the cross-cutting of the stump starts and ends when the stump drops down and the feeding rolls start to run.

— Processing of the tree and piling of the logging residues: consists of delimbing, bucking and piling. Begins when the feeding rolls start to run and ends when the last bucking cut is made. Piling is defined as piling of tops and branches beside the strip road integrated with cutting and arranging logs into piles and keeping similar log assortments together in the pile.

— Moving of roundwood, tops and branches: bunching and sorting roundwood outside the processing phase and moving tops and branches away from piles.

— Clearing: clearing of undergrowth.

— Delays: time that is not related to effective work, e.g. repairing and maintenance, phone calls, etc.

In the cutting experiment, the rootstocks were piled on the left side of the strip road and logging residues, logs and pulpwood were piled on the right. Logs and pulpwood were piled parallel to the strip road. Logs, pulpwood, rootstock and logging residues were bunched into large piles, because large-sized piles remain visible even after heavy snowfalls. The carrying capacity of the soil can be improved by delaying forwarding until the compacted strip roads are frozen, and the harvested wood can be forwarded efficiently later without resulting in unnecessary waiting times. The total amount of cut roundwood, measured by the harvester's measurement device, was 97.6 m^3 in the cutting experiment; 47.2 m^3 of roundwood were cut using the conventional method and 50.4 m^3 using the complete tree method.

Data analysis

The recorded time study data and the measured stand data were combined as a data matrix. The time consumption of the work phases in the conventional and complete tree cutting was

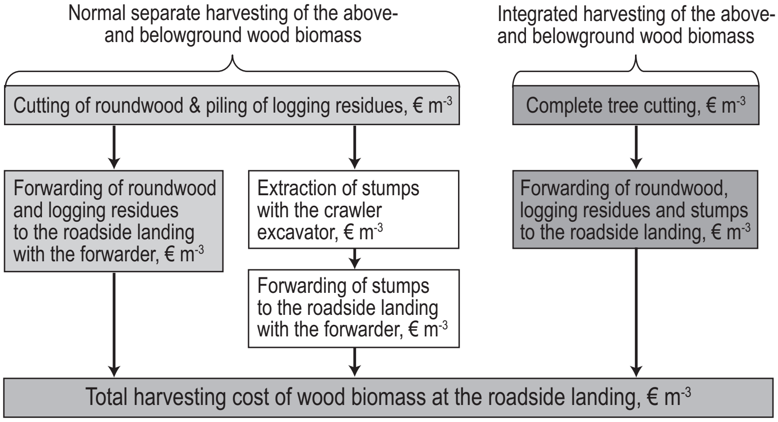

Fig. 2. The main work stages of the above and belowground wood biomass harvesting chains.

Kuva 2. Kokopuubiomassan korjuun keskeiset työvaiheet.

formulated by applying a regression analysis, in which the cutting conditions (diameter at 1.3 m height and density of cutting removal) were independent variables. The different transformations and curve types were tested in order to achieve symmetrical residuals for the regression models and to ensure the statistical significance of the coefficients. The SPSS statistical application was used to carry out a regression analysis to estimate the cutting productivity. The calculation unit for effective time (E_0h) consumption for moving and cutting was seconds per tree. In the data analysis, the following work phases were included in the cutting time: Steer out the boom and grab of the tree, Felling, Lifting, Moving the tree to the side of the strip road, Cross-cutting of the stump, and Processing of the tree and piling of the logging residues. The work phase of moving was included in the moving time.

The cost comparison of harvesting methods

Machinery and productivity parameters of the cost comparison

The harvesting costs of wood biomass (roots, stemwood and crown biomass) when the peatland stand is prepared for peat production were calculated in terms of the harvesting cost at the roadside landing (€ m^{-3}) as a function of the breast height diameter ($d_{1.3}$) of cutting removal. In complete tree cutting, the harvesting of the above and belowground wood biomass was carried out by a medium-sized harvester (Fig. 2) and the productivity of the cutting work was based on the results of the comparative time study reported herein. The figures for the forwarding productivity of the roundwood, logging residues and stumps from the clearcut with a medium-sized forwarder were calculated by using the time consumption models presented in studies by Väätäinen et al. (2007), Asikainen et al. (2001) and Laitila (2010).

In conventional harvesting, i.e. normal separate harvesting of the above and belowground wood biomass, the cutting of roundwood and piling of logging residues was performed with a medium-sized harvester (Fig. 2) and the harvester's productivity was based on the results of the comparative time study. The stump extraction was modelled with a crawler excavator equipped with an extraction-splitting device (Fig. 2). The productivity of the stump extraction was based on the time consumption models of Laitila et al. (2008). The time consumption model (Laitila et al. 2008) is made for spruce stumps but in this case it was considered to be valid, because on peatlands the root system of pines spreads out close to the ground surface (Hakkila 1976). In the assessment, the breast height diameter of the trees ($d_{1.3}$) was converted to the stump diameter using a factor of 1.33 (Hakkila 1976). The forwarding productivity of the roundwood, logging residues and stumps from clearcut sites with a medium-sized forwarder were calculated by using the time consumption models acquired from the studies of Väätäinen et al. (2007), Asikainen et al. (2001) and Laitila (2010).

The medium-sized harvester's productivity of effective hour (E_0h) was converted to productivity of operating hour ($E_{15}h$) by the coefficient of 1.25 in the case of both conventional cutting and complete tree cutting. In stump extraction, the excavator's effective hour (E_0h) productivity was converted to operating hour productivity ($E_{15}h$) by the coefficient of 1.2. The figures for the forwarding productivity of roundwood, logging residues and stumps were converted to operating hour productivity ($E_{15}h$) by the coefficient of 1.2. The operating hour productivity coefficients for machines were based on the authors' estimates, as follow-up study data was not available and the data from the roundwood cutting was considered invalid for this study.

The payload of the medium-sized forwarder was set at 7.0 m^3 for logging residues, i.e. branches and tops in both conventional harvesting and complete tree harvesting. The payload was set at 10.0 m^3 for roundwood in complete tree harvesting and 13.0 m^3 in conventional harvesting. The payloads of stumps were 5.0 m^3 in complete tree harvesting and 8.0 m^3 in conventional harvesting. In complete tree harvesting, the payloads of roundwood and stumps were assumed to be smaller because the breaking up of the soil surface in connection with lifting impairs the soil's carrying capacity and makes forwarding more difficult when conducting complete tree harvesting. Also, intact rootstocks are bulky, and the soil remaining on the intact stumps further reduces the size of the useful load in forwarding.

Hourly cost of the machinery

The operating costs (excluding VAT) of the medium-sized harvester and forwarder were calculated per operating hour ($E_{15}h$) using the common machine cost calculation method (e.g. Harstela 1993) and costs were presented in euros (€). The costs included both time-dependent costs (e.g. capital depreciation, interest expenses, labour costs, insurance fees and administration expenses) and variable operating expenses (e.g. fuel, repairs, service and machine transfers). In addition to the annual total cost, 5% was added to take the risk of entrepreneurship and the profit margin into account. The values used are presented in Table 2.

The lifespan of the harvester was 15 000 operating hours and the forwarder's lifespan was 16 000 operating hours. Annual depreciation was 23% and annual operating hours were 2500 in the case of both the harvester and the forwarder. The lifespan of the harvester head was 7000 operating hours and annual deprecation was 35%. When calculating capital costs, an interest rate of 2.6% was used. The purchase prices (VAT 0%) of the harvester, harvester head and forwarder were €300 200, €52 800 and €254 000 respectively. The data used in Table 2 was taken from the study by Väätäinen et al. (2010) and updated to the current cost level using "MEKKI", the cost index of forest machinery produced by Statistics Finland (http://www.stat.fi/til/mekki/yht_en.html).

The operating hour cost of the crawler excavator equipped with an extraction-splitting device was based on the study by Laitila et al. (2010) and updated to the current cost level using "MEKKI", the cost index of forest machinery produced by Statistics Finland (http://www.stat.fi/til/mekki/yht_en.html). The operating hour cost of the 18-tonne crawler excavator equipped with an extraction-splitting device (Laitila et al. 2008) was €60 $E_{15}h^{-1}$ in this study.

Table 2. Data used in the calculation of the hourly costs of a medium-sized harvester and forwarder.

Taulukko 2. Tutkimuksessa käytetyt keskikokoisen harvesterin ja kuormatraktorin vuosikustannukset kustannuslajeittain.

Cost item	Annual costs of the harvester, €	Annual costs of the forwarder, €
Wage cost	39 640	36 644
Indirect wage cost	26 400	24 405
Work travel expenses	9 875	9 875
Fuel, oil and lubricant costs	23 407	20 648
Service and repair costs	26 845	17 214
Relocation costs	11 200	11 200
Depreciation	52 372	28 578
Interest	6 272	4 115
Insurance	2 730	1 900
Administration	7 500	4 850
Risk and profit margin, 5%	10 312	7 971
Total costs (VAT 0%)	216 553	167 400
Operating hour cost, $E_{15}h^{-1}$	86.6	67.0

Stand conditions in the harvesting method cost comparison

The harvesting method cost comparison was made as a function of breast height diameter ($d_{1.3}$) in the range of 5–27 cm (Fig. 3). The heights of the harvested trees ($H_{\text{Scots pine tree}}$) were calculated as a function of the breast height diameter ($d_{1.3}$). The number of trees per hectare decreased when the breast height diameter ($d_{1.3}$) of the harvested trees increased (cf. Kärhä 2006, Hynynen 2008). In the cost comparison, the number of harvested trees (trees per hectare) was calculated as a function of the breast height diameter ($d_{1.3}$):

$$N_{Number\ of\ trees} = -50x + 1850 \quad (2)$$

where

$N_{Number\ of\ trees}$ = *the number of harvested trees /ha*

x = *the diameter at the breast height ($d_{1.3}$), cm*

The volumes of the above and belowground tree components of Scots pine (roots, stump, stem wood, stem bark, foliage as well as living and dead branches) were calculated by the biomass functions of Repola et al. (2007) and the basic densities produced by Hakkila (1978).

In the harvesting method cost comparison, trees with a diameter of less than 9 cm at breast height were considered to be logging residues (Fig. 3). The cutting removal of wood biomass assortments varied as a function of the breast height diameter (Fig. 3): stem wood 44–223 m^3 ha^{-1}, logging residues 17–63 m^3 ha^{-1} and rootstock 1.5–50 m^3 ha^{-1}. The forwarding distance was set at 300 m (e.g. Asikainen et al. 2001).

Results

The relative time consumption of working elements in the time studies

In the time studies, the moving time between working locations represented 8% of the effective working time in complete tree cutting (Fig. 4). The proportion of the work element steer out the boom and grab of the trees was 21%. The lifting of the trees and the processing of the trees constituted 18% and 38% of the effective working time in complete tree cutting. The moving of trees to the side of the strip road and processing of the trees both represented 8% of the effective working time (Fig. 4).

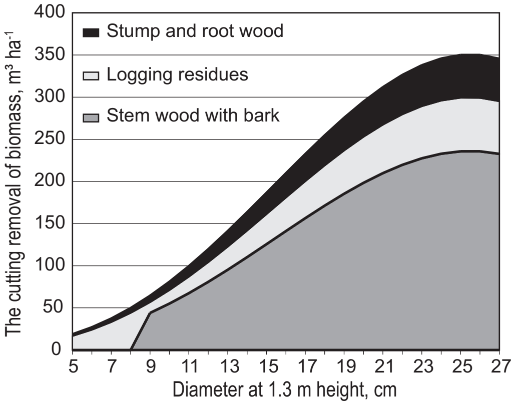

Fig. 3. The cutting removal of wood biomass assortments as a function of breast height diameter ($d_{1.3}$) in the harvesting method comparison.

Kuva 3. Hakkuupoistuman biomassalajit runkojen rinnankorkeusläpimitan mukaan.

In conventional cutting, the moving time between working locations was 7% of the effective working time, while the proportion of tree processing was 47%. Steer out the boom and grab of the trees and the felling of the trees both accounted for 23% of the effective working time (Fig. 4).

The time consumption models and productivity of the cutting methods

Moving time was dependent on the intensity of tree removal per hectare (Fig. 5). The moving time per tree decreased when the number of processed trees increased. The moving time between working locations as a function of the removed trees was the same for both cutting methods:

$$T_{Moving} = 10.868 - 1.328\ln(x) \quad (3)$$

where

T_{Moving} = *moving between working locations, second per tree*

x = *the number of harvested trees / hectare*

$r^2 = 0.46$

Cutting time was dependent on the breast height diameter ($d_{1.3}$) of the removed trees and

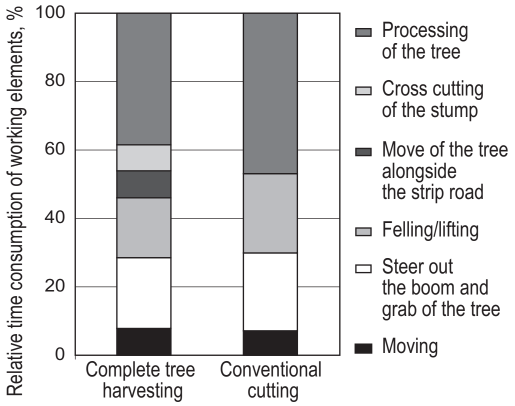

Fig. 4. The relative time consumption of working elements in complete tree cutting and conventional cutting.

Kuva 4. Kokopuukorjuun ja tavanomaisen puunkorjuun työvaiheiden ajanmenekki.

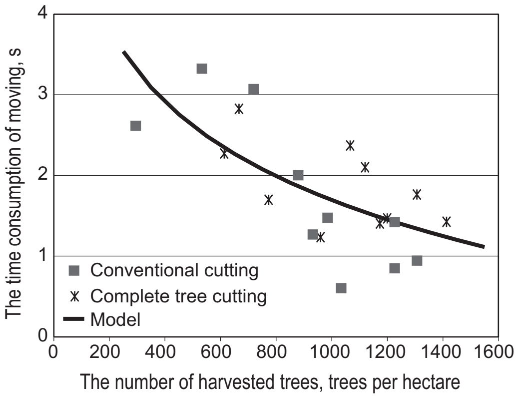

Fig. 5. Time consumption of moving between working locations as a function of the harvested trees per hectare.

Fig. 5. Työpisteiltä toiselle tapahtuvan siirtymisen ajanmenekki korjattujen runkojen runkolukua kohden hakkuissa.

cutting time increased when the size of the harvested trees grew (Fig. 6). The time consumption model for complete tree cutting was:

$$T_{Complete\ tree\ cutting} = 3.69x - 0.228x^2 + 0.007x^3 - 1.707 \qquad (4)$$

where

$T_{Complete\ tree\ cutting}$ = *cutting time in complete tree cutting, second per tree*

x = *diameter at 1.3 m height, cm*

$r^2 = 0.60$

The time consumption model for conventional cutting was:

$$T_{Conv.\ cutting} = 8.778 + 0.623x + 0.01x^2 \qquad (5)$$

where

$T_{Conventional\ cutting}$ = *cutting time in conventional cutting, second per tree*

x = *diameter at 1.3 m height, cm*

$r^2 = 0.58$

The total effective time (E_0h) per tree in complete tree cutting and conventional cutting was obtained by adding up moving time and cutting time.

In complete tree cutting, the cutting time consumption per tree was higher compared to conventional cutting and the difference increased, especially when the breast height diameter ($d_{1.3}$) was more than 19 cm (Fig. 6). Both cutting methods were equally productive up to a breast height diameter of 17–19 cm when considering the gain in wood volume when cutting complete trees (Fig 7). In the case of thicker trees, the productivity of complete tree cutting levelled out whereas the cutting productivity of conventional cutting continued to grow (Fig 7).

Harvesting costs

The cost of cutting

The cutting costs of complete tree harvesting and conventional harvesting were calculated according to the harvester's hourly cost presented in Table 2. Furthermore, a sensitivity analysis was carried out in which the harvester's operating hour cost in complete tree cutting was 10% or 20% higher than that presented in Table 2 (Fig. 8). According to the results, the cutting costs of complete tree cutting were 1–3 € m^{-3} higher than the cutting costs in conventional cutting (Fig. 8).

The cost of stump extraction

The extraction cost of stumps was included in the cutting cost in complete tree harvesting (Fig. 8 and 9). In complete tree cutting, the handling unit

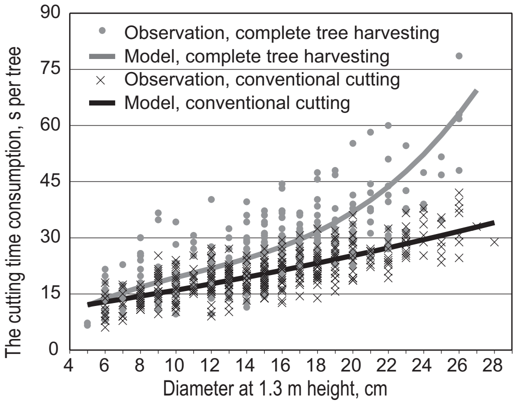

Fig. 6. Time consumption of conventional cutting and complete tree cutting as a function of the breast height diameter ($d_{1.3}$) of removed trees.

Kuva 6. Kokopuukorjuun ja tavanomaisen puunkorjuun ajanmenekki korjattujen runkojen rinnankorkeusläpimittaa kohden.

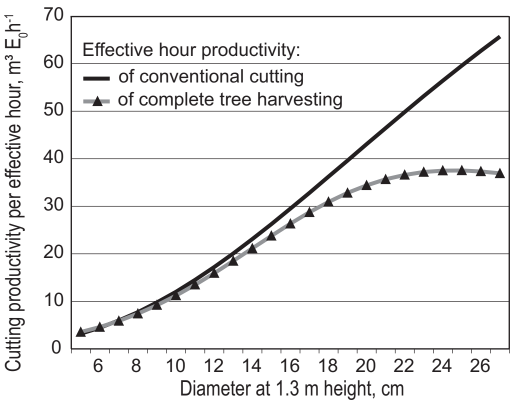

Fig. 7. The effective time productivity (E_0h) of conventional cutting and complete tree cutting as a function of breast height diameter ($d_{1.3}$).

Kuva 7. Kokopuukorjuun ja tavanomaisen puunkorjuun tehokas käyttötuntituotos (E_0h) korjattujen runkojen rinnankorkeusläpimittaa kohden.

(rootstock + stem wood + crown biomass) was at least tens of litres, whereas in small diameter classes ($d_{1.3}$) in conventional stump extraction with an excavator the costs were high due to the small stump volume and removal (Fig. 3 and 9). However, the difference in the extraction costs decreased as a function of the breast height diameter ($d_{1.3}$) increase.

The cost of forwarding

The forwarding costs of the stumps and roundwood were higher due to the smaller forwarder's payload in complete tree harvesting (Fig. 10). The forwarding costs of logging residues were the same in both conventional and complete tree harvesting (Fig. 10). In the cost comparison, trees with a breast height diameter ($d_{1.3}$) of less than 9 cm were considered logging residues, which increased the removal of logging residues, improved forwarding productivity and decreased forwarding costs (Fig. 10).

The harvesting cost of wood biomass at the roadside landing

The results of the harvesting method comparison were calculated as the harvesting cost (€/m^{-3}) of the total biomass of a tree (roots, stemwood and crown biomass) at the roadside landing based on the productivity and cost parameters and time consumption models for conventional cutting and complete tree cutting reported here (Fig. 11). According to the results, complete tree harvesting was the most cost-efficient method up to a breast height diameter ($d_{1.3}$) of 20 cm when the peatland site was prepared for peat production. When the harvester's hourly cost was 10% higher compared to conventional ($d_{1.3}$) cutting, complete tree harvesting was the most cost-efficient method up to a breast height diameter ($d_{1.3}$) of 18 cm and 16 cm, when the harvester's hourly cost was 20% higher than in conventional cutting (Fig. 11).

Discussion

According to the results, the complete tree harvesting of wood biomass, where the stump lifting is integrated with the roundwood cutting, kept the costs below the costs of conventional harvesting carried out on a pine-dominated peatland site when the breast height diameter ($d_{1.3}$) of the pine trees to be removed was below the range of 16–20 cm. However, the advantages of multiple-tree processing (e.g. Bergkvist 2003) are lost in complete tree cutting, as the trees have to

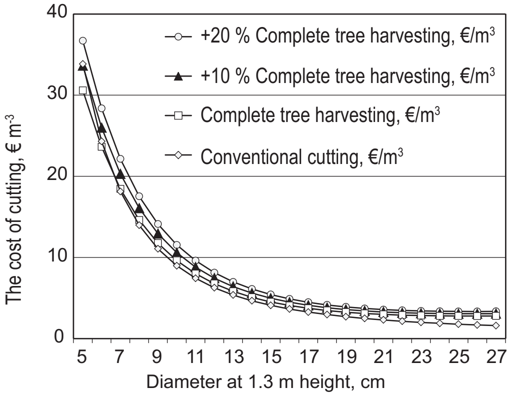

Fig. 8. The cost of conventional cutting and complete tree cutting as a function of breast height diameter ($d_{1.3}$) when the removal of trees is 500–1600 trees per hectare.

Kuva 8. Kokopuukorjuun ja tavanomaisen puunkorjuun hakkuukustannukset korjattujen runkojen rinnankorkeusläpimittaa kohden kun poistuma on 500–1600 runkoa/ha.

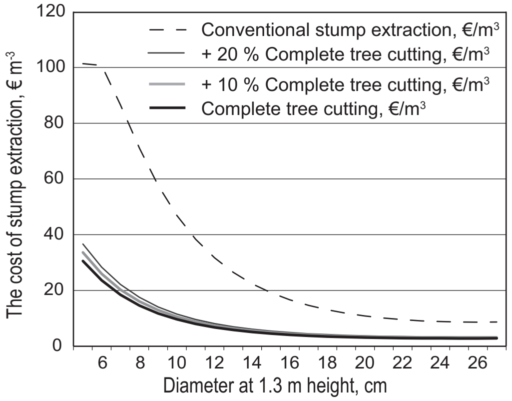

Fig. 9. The cost of stump extraction as a separate operation or integrated with complete tree cutting as a function of breast height diameter ($d_{1.3}$) when the removal of trees is 500–1600 trees per hectare.

Kuva 9. Kantojen korjuun kustannukset erillisenä toimenpiteenä sekä toteutettaessa osana kokopuukorjuuta korjattujen runkojen rinnankorkeusläpimittaa kohden kun hakkuupoistuma on 500–1600 runkoa/ha.

be lifted singly. The advantages of multiple-tree processing are at their maximum when the breast height diameter is within the range of 5–13 cm; the productivity of timber cutting improves by 10–20% when compared to single-tree cutting (e.g. Bergkvist 2003). On the other hand, cutting with the rootstock included means greater harvest volume and thereby improves the productivity of cutting when compared to cutting based on multiple-tree processing.

Time consumption formulas and productivities received from the field study were based on the output of one forest machine operator; one site and one machine, and therefore do not represent the full Nordic range of productivity. Several studies have shown that the operator has the most significant effect on cutting productivity (e.g. Sirén 1998, Ryynänen and Rönkkö 2001, Ovaskainen et al. 2004, Väätäinen et al. 2005, Kariniemi 2006, Purfurst and Erler 2006). Nevertheless, the reported results give novel trends and estimates for the performance characteristics as well as relative differences in work performance between complete tree cutting and conventional cutting. In addition, it is presumed that the number of experienced operators available for the study is rather limited, especially in the early phase of developing new methods and devices. In order to guarantee the reliability of the reported observations, the results must be compared with the results of similar case studies, and efforts should be made to verify the observed phenomenon (Hellström and Hyttinen 1996).

The power required to unearth the rootstock varies according to tree species, the type of rootstock, rootstock diameter, the soil and the method used in unearthing the rootstocks (e.g. Spinelli et al. 2005, Laitila et al. 2008, Lindroos et al. 2010). When conducting timber cutting with the rootstock included, the tree stem can be used as a lever to loosen the rootstock, and thus significantly less power is needed than when lifting the rootstock directly (Lindroos et al. 2010, Hakkila 1989). As an idea, the harvesting of stumpwood in connection with the harvesting of stemwood is not new (e.g. Koivulehto 1969, Ahonen and Mäkelä 1972, Koch and Coughran 1975, Hakkila 1976, Jonsson 1978, Jonsson 1985). Indeed, the novelty value of the technique reported here lies in the fact that the work was done using a structurally standard single-grip harvester, whereas special equipment has been used in earlier experiments. A study conducted in Sweden (Lindroos et al. 2010) revealed that the lifting capacity of the loader of a

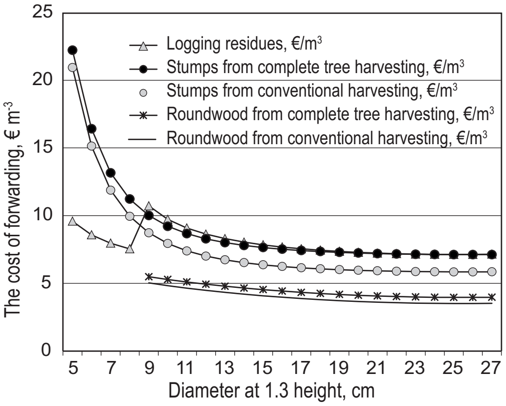

Fig. 10. The forwarding costs of logging residues, stumps and roundwood from the cutting sites of conventional harvesting or complete tree harvesting as a function of breast height diameter ($d_{1.3}$), when the forwarding distance is 300 m and removal of trees = 500–1600 trees per hectare.

Kuva 10. Hakkuutähteiden, kantojen ja runkopuun metsäkuljetuksen kustannukset kokopuukorjuussa sekä tavanomaisessa puunkorjuussa korjattujen runkojen rinnankorkeusläpimitan suhteen kun keskikuljetusmatka on 300 m ja hakkuupoistuma on 500–1600 runkoa/ha.

powerful harvester and of a forwarder (273 kNm or 155 kNm) are in general sufficient for lifting spruce stumps in one piece with stump diameters of up to 61 cm and 32 cm, respectively.

Timber cutting with the rootstock included exposes the harvester's sliding boom crane to extraordinary loads (Fig. 12), and fuel consumption increases when compared to conventional timber cutting. Instead of using wheeled harvesters, excavator-based harvesters can also be used in the complete tree cutting on sites where peat extraction is due to begin. The lifting power and especially the durability of the boom of such units are considerably greater than those of conventional harvesters or forwarders. In addition, due to the lower purchase price of an excavator, the cost of running an excavator-based harvester is less than that of a conventional harvester (Väätäinen et al. 2004, Bergroth et al. 2006, Hallongren 2010).

Considerable amounts of peat and raw humus remained on the stumps in complete tree cutting during time studies, because the stumps cannot be shaken or chopped up in connection with the cutting work (Fig. 12). Presumably the soil remaining on intact stumps reduces the size of payload in forwarding, and affects the drying of stumps in storage piles and the amount of organic fine material in fuel chips. When crushing or pre-crushing peat and humus containing stump and root wood, dust or even a dust fire might also be an obvious problem.

In Finland, the majority of stumps are crushed either at the plant or in terminals, whereas the majority of small-diameter trees and logging residues are chipped at roadside landings (Kärhä 2011a). Until now, the crushing of stumps has been performed with heavy, often stationary crushers. In smaller plants, the construction of a stationary crusher is not economically feasible. In addition, the transportation of stumps calls for a biomass truck with solid side panels and bottom, and economic transport distances are short owing to small potential payloads (Ranta and Rinne 2006, Laitila et al. 2010). Recently, effective mobile crushers suitable for the comminution of stumps at roadside landings have been introduced (Kärhä 2011a, Kärhä 2011b, von Hofsten and Granlund 2010). The truck-mounted crusher is used in a similar manner to mobile chippers in the chipping of logging residues and small-diameter trees. The crusher moves from landing to landing, with the crushed material transported to the end-user by trucks (Asikainen 2010).

In the time studies, complete tree cutting typically resulted in the splitting or splintering of the butt ends of the trees when the stumps were sawn off (Fig. 12). Splintering reduces the length of the usable section of the log or spoils the log entirely. Splits in the butt end are not a problem if the stemwood is harvested for use as pulpwood or energy wood. Furthermore, the log proportion of stemwood harvested from peatland sites is usually significantly smaller than that of stemwood harvested from upland sites because of defects (Eeronheimo 1991). The breaking up of the soil surface in connection with lifting (Fig. 12) impairs the soil's carrying capacity and makes forwarding more difficult when conducting complete tree harvesting. When the harvesting of stumpwood is conducted separately from roundwood harvesting, the soil surface is broken up when lifting the stumps, by which time the bulk of the stemwood has already been removed.

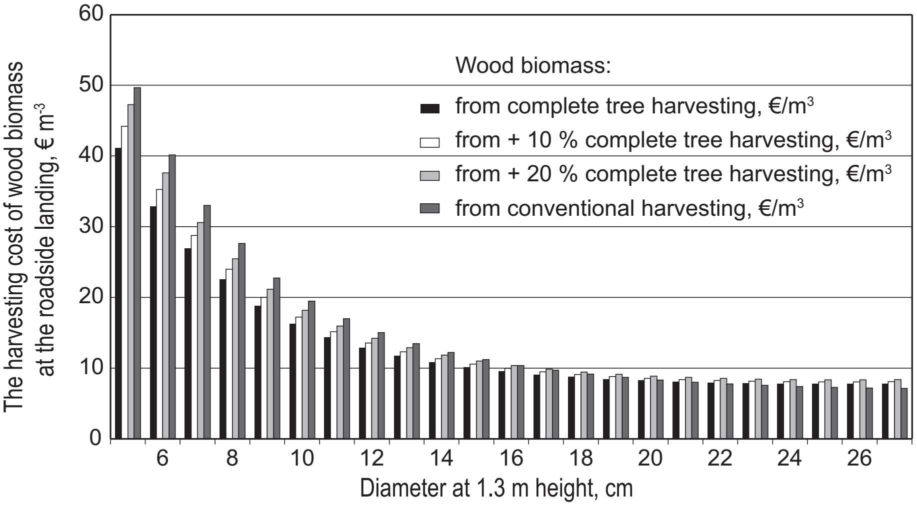

Fig. 11. The average harvesting cost of wood biomass (logging residues, roundwood and stumps) at the roadside landing as a function of breast height diameter (d1.3), when the forwarding distance is 300 m and removal of trees amounts to 500–1600 trees per hectare.

Fig. 11. Hakkuutähteiden, kantojen ja runkopuun korjuun tienvarsikustannukset kokopuukorjuussa sekä tavanomaisessa puunkorjuussa korjattujen runkojen rinnankorkeusläpimitan suhteen kun keskikuljetusmatka on 300 m ja hakkuupoistuma on 500–1600 runkoa/ha.

The terrain mobility of forestry machinery can be improved and the surface pressures exerted by the machinery can be reduced on soils with poor carrying capacity by the following means (Airavaara et al. 2008): 1) wider tracks and tracks having less impact on the soil; 2) extending the carrying surface of the tracks by means of auxiliary wheels; 3) extending the width of individual wheels by means of pair wheels or widened wheels; 4) wider tyres; 5) reduced tyre pressure. Furthermore, the success of the operation can be influenced by the effective positioning of strip roads, by the size of the loads and the number of times individual strip roads are driven on (Lamminen 2008, Airavaara et al. 2008, Väätäinen et al. 2010), as well as by conducting the harvesting in two stages. In two-stage wood harvesting, the cutting is carried out when the soil is still unfrozen; the stacks of wood are then marked, and extraction is performed in winter when the soil is frozen. In the past, when motor-manual cutting was common, this was the usual method (Heikkilä 2007). Eeronheimo (1991) was of the view that extraction on peatland sites using wheeled machinery requires that either the soil be frozen to a depth of 20 cm if there is no snow, or that there is snow cover of more than 40 cm. In average years, the number of days when these conditions are met is 60 along the south coast of Finland and about 120 in and around Oulu in Northern Finland.

The research results were promising for complete tree harvesting. However, this cutting method is new and the data collected in this study is not comprehensive, and this hinders the generalisation of the results. Nevertheless, practical trials are worth continuing, especially with regard to excavator-based harvesters. In addition to the practical productivity of cutting work in complete tree cutting, the fuel consumption and durability of the boom sections and the harvester head should be monitored and the harvester's real operating hour costs should be determined in comparison with conventional wood cutting methods. Furthermore, experiences connected to success in the forwarding of roundwood, logging residues and stumps on overturned peatland sites should be collected. In particular, the savings and the benefit potential to be obtained through

Fig. 12. Complete tree cutting with a Ponsse Cobra single-grip harvester in the experimental stand of this study (Photo: Juha Laitila).

Kuva 12. Kokopuukorjuuta Ponsse Cobra –yksioteharvesterilla koemetsikössä. (Kuva: Juha Laitila).

complete tree cutting should be looked into in both preparatory work carried out on sites where peat production is due to begin and during peat production. Moreover, other important questions requiring answers remain. How much does the removal of stumps improve the shaping of peat production sites and peat milling, and reduce the number of breakdowns? What is the maximum stump size below which stumps do not hinder preparatory work on peat production sites?

The share of regeneration cuttings on peatland sites is due to significantly increase during the next few years and decades (Saarinen 2005). As regards stump harvesting, the wood harvesting method examined here is also worth testing on regular forestry land. Compared to stumps on upland sites, the advantage of stumps on peatland sites is that these stumps are free of stones and mineral soil. In addition to the problem of forwarding, small payloads in long-distance transportation can become a problem unless stumps can already be pre-crushed or crushed to provide ready-to-use combustion material at the roadside landing.

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Tiivistelmä: Vertailututkimus runko- ja juuripuun sekä latvusmassan yhdistelmä- ja erilliskorjuusta ojitetulla suolla

Tutkimuksessa selvitettiin hakkuutyön tuottavuus ja puubiomassan korjuukustannukset kokopuukorjuussa, jossa maanpäällinen ja maanalainen puubiomassa korjataan samalla kerralla juurineen talteen ja kustannuksia verrattiin tavanomaisen puunkorjuun vastaaviin, jossa maanpäällinen puubiomassa ja kantopuu korjataan talteen erillisinä työvaiheina. Koko puubiomassan korjuuta tehdään etenkin valmisteltaessa suoaluetta turvetuotantokäyttöön. Tuottavuuseron selvittämiseksi näiden kahden hakkuutavan välillä tehtiin vertaileva aikatutkimus, jossa hakkuu tehtiin yksinpuin keskiraskaalla hakkuukoneella ja juurakon nostoa ja kasausta lukuun ottamatta puun prosessointitapa (katkonta, karsinta ja latvusmassan kasaus) olivat samat. Tutkimus suoritettiin yhdessä ojitetussa rämemännikössä, johon rajattiin koealoja aikatutkimusta varten. Aikatutkimuskoealoilta mitattuja puita oli yhteensä 729 kappaletta. Koealan puista 386 korjattiin juurineen hakkuutyön yhteydessä ja 343 sijaitsi ns. tavanomaisen hakkuutavan koealoilla. Aikatutkimuskoealoilla hakkuupoistuman rinnankorkeusläpimitta vaihteli välillä 5–28 cm ja pituuskoepuiden pituus oli 6,2–19,3 m. Hakkupoistuman tiheys oli 293–1413 puuta /ha

Aikatutkimusaineistojen pohjalta laadittiin puukohtaiset ajanmenekkimallit, joiden avulla verrattiin hakkuutapojen ajanmenekkiä, tuottavuutta ja kustannusta hakkuupoistuman rinnankorkeusläpimitan suhteen. Korjuutapavertailun tulokset laskettiin puun kokonaisbiomassan (juuret, runkopuu ja latvusmassa) korjuukustannuksena (€ m^{-3}) tienvarsivarastolla hakkuun ajanmenekkimallien ja aiemmin julkaistujen metsäkuljetustutkimusten ja kantojen korjuututkimusten sekä koneiden käyttötuntikustannuslaskelmien perusteella.

Tutkimuksen mukaan hakkuuseen integroidulla kantojennostolla oli mahdollista alittaa erilliskorjuun kustannukset. Vertailulaskelman mukaan integroitu korjuu oli kannattava menetelmä rinnankorkeusläpimittaan 20 cm saakka, kun hakkuukoneen käyttötuntikustannus oli sama kuin normaalilla hakkuutavalla. Jos hakkuukoneen käyttötuntikustannus oli 10 % kalliimpi kuin perinteisellä hakkuutavalla, niin integroitu korjuu on kannattava menetelmä hakkuupoistuman rinnankorkeusläpimittaan 18 cm saakka. Kun hakkuukoneen käyttötuntikustannus oli 20 % kalliimpi, niin integroitu korjuu oli kannattava hakkuutapa rinnankorkeusläpimittaan 16 cm saakka.

Tulosten perusteella integroitu kokopuukorjuu osoittautui kustannuksiltaan lupaavaksi menetelmäksi puubiomassan korjuussa turvemaalla.

Received 6.3.2013, accepted 6.6.2013