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Impact and Productivity of Harvesting while Retaining Young Understorey Spruces in Final Cutting of Downy Birch

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Quite often Norway spruce (*Picea abies* (L.) Karsten) forms an understorey in birch dominated stands in Finland. Advantageous growth conditions for both storeys are present especially in downy birch (*Betula pubescens* Ehrh.) stands on drained fertile peatland. The most common way of regenerating mature Downy birch forest is clear cutting and replanting with Norway spruce, even if vital spruce seedlings or saplings was already growing under the birch. The aim of this study is to investigate the impact of retaining young understorey spruces on the productivity of harvesting and on the quality of the remaining stands in downy birch dominated stands with modern cut-to-length (CTL) machinery. Retaining undergrowth spruces decreased productivity of cutting in managed stands (600 stems/ha) by 6–9 per cent and in unmanaged stands (1200 stems/ha) by 11–17 per cent compared with clear cutting, where the understorey is not considered. Compared with the case where no understorey was present, the decrease in productivity was 10–17 per cent and 21–30 per cent respectively. In forwarding, retaining the undergrowth decreased the productivity of loading phases by 7–14 per cent. Harvesting treatment where spruces were retained produced an adequate stand structure for the future growing stock. Using this method, 14–24 per cent of the original spruces were totally destroyed while 25–44 per cent of spruces were destroyed when they were not considered for harvesting. The spatial variation of the remaining spruces was much better in the treatment where spruces were retained. Our study results shows that in this kind of two storey birch–spruce forests, the harvesting treatment where spruces are retained while cutting is the most acceptable and profitable method. It allows for a vital spruce sapling to continue growing, and avoids regeneration and tending costs or other harmful effects of clear-cut areas such as the freezing of young spruce plants and an increase in the ground water table.

Keywords *Betula pubescens*, harvesting, logging, *Picea abies*, spruce releasing
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1 Introduction

Certain tree species can adjust to grow as undergrowth, i.e. under the shadow of other trees. In boreal forests, spruces are typical representatives of this type of shade-tolerant tree species. In Finland, spruce seedlings can grow in the shadow of broadleaf and coniferous forests (Moilanen and Saksa 1998). In Downy birch (*Betula pubescens* Ehrh.) dominated peatland, ditch drainage increases the growth of birch and improves growth conditions of naturally regenerated Norway spruce (*Picea abies* (L.) Karsten) seedlings (Seppälä and Keltikangas 1978). In these peatland forests, Downy birch forms an overstorey and Norway spruce an understorey. Downy birch growing on peatland produces rather low quality timber that is often inappropriate for veneer or sawing purposes (Verkasalo 1997). Management of Downy birch is therefore aimed at producing pulp wood or fuel wood (Hynynen et al. 2010). Current management recommendations propose only a single commercial thinning and final cutting at the age of 50–60 years (Niemistö 1991).

The most common way of regenerating Downy birch forests is clear cutting and replanting with Norway spruce, even if vital spruce seedlings or saplings is already growing under birch. It is a common belief that modern harvesters are unable to fell trees in a manner that allows for the retention of a vital, evenly-distributed spruce sapling growing after the clear cut. This type of shelterwood removal is also believed to be rather unproductive compared to clear cutting, but very few, if any studies on the impact of this kind of harvesting treatment have been published. In general, the harvesting costs of final cuttings in Downy birch dominated forests are not well-known, especially in dense stands with small stem size.

Assuming it can be shown that it is possible to harvest the birch shelterwood whilst retaining the spruce undergrowth, this may give the forest owner the possibility to save on regeneration costs and speed up the growth of the next tree generation (Mielikäinen and Valkonen 1995, Valkonen and Valsta 2001, Päätalo et al. 2003, Niemistö and Poutiainen 2004), thus leading to better economy of forestry. Planting is only a part of the total regeneration chain and it may be feasible to plant spruces under the birch stand 15–20 years before its final cut, if an adequate natural seedling stand is not present.

Exploitation of the Norway spruce understorey in the regeneration would save the costs of site preparation and planting, and could reduce the export of dissolved nutrients and suspended solids to water courses. After clear cutting, an effective soil preparation is needed because of strong coppicing and wet soil in peatland. Tall and expensive seedlings are used to compete well with ground vegetation and birch sprouts. Despite this, repeated clearing operations are needed during the young stand phase.

The profitability of regeneration using existing Norway spruce undergrowth depends on the quality and quantity of healthy seedlings and saplings, harvesting and regeneration costs and the time advantage gained when the harvesting of spruce is brought closer because of the larger plant material. Regeneration costs in Finland vary from EUR 400 to 600 per hectare (Finnish Statistical Yearbook … 2008).

The productivity of harvesting with modern single grip harvesters is intensively studied in the Nordic countries. The focus in previous studies was on establishing a basis for cost calculations (e.g. Kuitto et al. 1994, Brunberg 1997, Nurminen et al. 2006). Numerous studies have also been carried out to analyse the effect of harvester operators (Ovaskainen et al. 2004, Ovaskainen et al. 2006), or to compare the effect of harvesting methods (Lageson 1997, Eliasson et al. 1999, Eliasson 2000, Hånell et al. 2000) or machine types (Glöde 1999, Kärhä et al. 2004) on productivity.

Harvesting productivity increases with increasing stem size. In addition, the productivity of the harvester increases with enhanced harvesting intensity expressed as number of trees removed per hectare. Therefore, productivity is higher in clear cuts than in shelterwood cuttings (Eliasson et al. 1999, Hånell et al. 2000). In thinning, the high density of the remaining trees increases time consumption due to moving the base machine and positioning the harvester head to each tree, thus decreasing productivity (Ovaskainen et al. 2006).

Forwarding has been studied less than cutting. The productivity of the forwarder depends on the cutting method (thinning/clear cutting), average

Table1. Characteristics of the study stands.

Study stand		A Kälviä	B Pyhäjärvi	C Kärsämäki
$N_{(lat)}$		7 070 670	7 072 090	7 104 726
$E_{(lon)}$		334 682	434 156	447 272
Number of plots	n	13	10	10
Birch storey				
Age	years	50	60	75
Number of stems	n/ha	800–2650	440–1300	400–1150
Number of commercial stems	n/ha	800–1260	440–1270	400–1150
Commercially exploitable volume	m^3/ha	94–294	64–244	110–180
Mean height	m	16.9	17.9	18.9
Mean diameter	cm	14–19	17–23	19–24
Mean crown height	m	7.8	9.0	8.9
Spruce understorey				
Age	years	23	18	18
Number of stems	n/ha	2100–2600	1100–2300	1400–1700
Mean height	m	4.0	3.5	3.3
Standard deviation of height	m	1.0	1.5	1.7
Mean height of one hundred biggest trees/ha	m	5.9	5.7	6.2

haulage distances, timber density on the strip road and load volume (Kuitto et al. 1994, McNeel and Rutherford 1994, Gullberg 1997, Brunberg 2004, Nurminen et al. 2006). It has also been reported that the mean pile size, location of piles, and personal qualities of the harvester operator have an effect on the time consumption of forwarding (Väätäinen et al. 2006, Nurminen et al. 2006).

The aim of this study is to investigate the impact of retaining young understorey spruces on the productivity of harvesting and on the quality of the remaining stand in Downy birch dominated stands with modern cut-to-length (CTL) machinery.

2 Material and Methods

A time study was conducted in western Finland in late winter 2008. The material comprised three study stands that were located in Kälviä (stand A), Pyhäjärvi (B) and Kärsämäki (C). The average temperature during the study was 0… +3°C in area A, –7…–12°C in area B and +2…+3°C in area C with an average snow depth of 20 cm, 45 cm and 30 cm respectively. The study stands were all ditched peatland forests with even-aged naturally born Downy birch as the main tree species. The study stands were long-term experiments established in 1976 (areas B and C) and 1986 (area A), to study the growth of birch forests (Niemistö 1991). The main parts of the study stands were planted later with spruces in 1986 (area A) and in 1991 (areas B and C), to study the impact of the density of the birch storey on the growth of understorey spruces (Niemistö and Poutiainen 2004).

Each area consisted of several rectangular study plots with an area of 0.1 ha. The amount of live overstorey Downy birch varied from 400 to 2000 stems/ha. Norway spruce understorey was growing rather evenly in all areas in terms of tree height and spatial variation. The study plots were inventoried tree by tree after the 2007 growing season (Table 1). Within each plot, the location, the diameter at breast height (dbh) of each birch tree and the height of the undergrowth spruces were measured. In addition, tree height and the base of the living crown of a certain number of sample trees (birches) were also measured. Areas A and C also included plots that did not have any understorey spruces.

Study plots were harvested using three different treatments. In the first treatment, the harvester driver cut overstorey birches in a manner that after the cutting operation a vital spruce sapling is retained (R = spruces are retained). Using this

Table 2. Definitions of work elements of cutting.

Work element	Definition
Moving (t_{mov})	Begins when the harvester starts to move and ends when the harvester stops moving to perform some other activity. Moving includes driving forward or reversing.
Positioning-to-cut (t_{pos})	Begins when the boom starts to swing towards a tree and ends when the harvester head is resting on a tree and the felling cut begins. Returning the harvester head towards the base machine after the last cross-cut is included into this phase of the next tree.
Felling (t_{fell})	Begins when the felling cut starts and ends when the feeding rolls start to turn on the stem.
Processing (delimbing, cross-cutting, bunching and sorting logs) (t_{proc})	Begins when the feeding rolls start to run and ends when the last bucking cut is made and the last log is dropped onto the pile. Bunching is defined as arranging logs into piles and sorting is defined as keeping similar wood assortments together along the processing phase.
Clearing (t_{clear})	Clearing of disturbing undergrowth and felling of unmerchantable trees.
Moving logs, tops and branches ($t_{arrange}$)	Moving tops and branches to the strip road and away from piles, and bunching and sorting logs and piles (outside the processing phase).
Delays	Time that is not related to effective work, e.g. repairing and maintenance, phone calls etc.
t_{tree} , t_{trees}	Tree dependent work elements of cutting, $t_{tree} = t_{pos} + t_{fell} + t_{proc}$ (s/tree) $t_{trees} = t_{pos} + t_{fell} + t_{proc}$ (s/m^3)
t_{cut}	Cutting in total $t_{cut} = t_{pos} + t_{fell} + t_{proc} + t_{clear} + t_{arrange} + t_{proc}$ (s/m^3)

option it is possible to damage a certain number of spruces providing a vital, evenly-distributed number of saplings is retained to grow. In the second option, the harvester driver works as efficiently as possible and does not consider spruce understorey while working (S = spruces are not considered). A stratified random selection principle was followed when selecting the harvesting treatment for each study plot so that both treatments were carried out equally in low and high density stands. Study plots having no spruce understorey formed the third treatment (O = no spruces).

Twenty-metre wide harvesting plots were placed in the middle of the original study plots. The boundaries of the harvesting plots as well as harvesting strip road were signed prior to harvest. All plots were cut with the same harvester, which was operated by the same driver during the study. The harvester used in the study was a mid-sized John Deere 1070/745 with a boom reach of 10 m. The driver had previous experience of all the studied harvesting treatments.

The harvesting work was filmed with a digital video camera from the starting point of the study plot until the end, but for no longer than one hour per plot. Birches were cut into three-metre long pulpwood logs (minimum SED 6 mm). The volume of each log and stem was measured by the harvester and stored by the harvester computer in the STM-format. Since the clocks of the harvester computer and digital video camera were synchronised, it was possible at a later date to combine the right stem with the the right work phase and time element.

After harvesting, the piles of pulpwood logs formed during the time study were inventoried. The size, assortment and location of each pile in relation to the strip road distance were determined. At the same time, the length of the harvesting strip was measured in order to calculate the area of the harvesting plot (length × 20 m).

Table 3. Definitions of work elements of forwarding

Work element	Definition
Driving empty(t_{de}):	Begins when the forwarder leaves the landing area and ends when the forwarder stops at the first loading stop (and the operator begins to move the grapple loader to start loading).
Loading (t_{load}) Including sub-phases:	Begins when the operator starts to move the grapple loader from the bunk and ends when the grapple loader is rested on the bunk after the last grapple load of the loading stop is put into the bunk.
Actual loading (t_{load_a})	Actual loading includes 1) Reaching the pile 2) Lifting the grapple load into the bunk
Miscellaneous loading activities (t_{load_m})	Miscellaneous loading activities includes 1) Sorting and handling the logs on the ground 2) Sorting and handling the logs in the bunk 3) Relifting of logs fallen while loading
Driving while loading (driving between loading stops) (t_{drwl})	Begins when the grapple loader is rested on the bunk and the operator prepares to move to the next loading stop. Ends when the forwarder stops at the next loading stop and the operator starts to move the grapple loader in order to begin loading.
Driving loaded (t_{dl})	Begins when the grapple loader is rested on the bunk after the last grapple load of the last loading stop and the bunk is full. Driving loaded ends when the forwarder stops at the landing area and the operator starts to move the grapple loader in order to unload.
Unloading (t_{unload})	Begins when the forwarder stops at the landing area and the operator starts to move the grapple loader. Unloading ends when the last load is lifted onto the pile and the grapple loader is resting on the empty bunk. Unloading includes following sub-elements: 1) Moving the empty grapple loader into the bunk 2) Lifting the grapple load onto the landing pile 3) Sorting and handling the logs in the bunk 4) Sorting and handling the logs on the landing pile 5) Lifting of logs fallen while unloading
t_{drive}	$t_{drive} = t_{de} + t_{dl}$
Delays	Time that is not related to effective work, e.g. repairing and maintenance, phone calls, etc.

Haulage was carried out in each plot by a John Deere 1100C forwarder, which was operated by the same driver throughout the study. The forwarder was not filmed throughout but certain time study samples from each work phase were filmed. Due to technical problems, the loading of 28 out of 33 plots was successfully recorded. The driving speed of a full load was calculated from eight loads and that of an empty load from four loads. Unloading was filmed from nine loads. The volume of load was estimated visually by comparing the amount of load to the full load of 9 m^3.

After harvesting, spruce saplings of all study plots were re-inventoried in the summer of 2008. Since the location and height of each spruce were determined in the previous autumn, it was sufficient to simply grade each tree according to the following classification: 1 = not damaged, 2 = slightly damaged but vital enough to grow and 3 = destroyed.

A new tool to facilitate the analysis of the video material was developed using Microsoft Visual Basic language in Excel software. In the analysis tool, a video clip is browsed in an Excel sheet and the work element boundaries are determined by the researcher during browsing. By using the time signature in the video clip, the start and end times of each work element are recorded together with

Table 4. Explanatory variables used in the models.

Abbreviation	Description
N_{spruce}	Number of spruces at the original understorey, n/ha
N_{trees}	Number of merchantable stems, n/ha
V_{stem}	Merchantable stem size, dm
V_{stand}	Merchantable volume, m^3/ha
V_{mean}	Mean size of merchantable stems, dm^3
$L_{saplings}$	Cumulative sum of the length of understorey saplings (km/ha) calculated as a product of mean height * number of saplings
R	A variable indicating whether spruces are retained while harvesting, otherwise R = 0
S	A variable indicating whether spruces are not considered while harvesting, otherwise S = 0
O	A variable indicating that no spruces are present while harvesting, otherwise O = 0
F	A variable indicating whether birch stem is forked or broken while processing or not F = 1, birch stem is forked or is broken while processing otherwise F = 0

the code of the work element. The video clip can be viewed quickly, forwarded and rewound or viewed in slow motion when needed. The record for each work element can be double-checked and edited afterwards using the recorded time signature in the video clip.

A special program was developed to retrieve data from the harvester computer files in order to output tree species, volume, and number of logs for each stem. In peatland, Downy birch tends in many cases to develop multiple stems. It is up to the harvester operator to decide whether to register these stems as a tree or separate trees. Therefore, extra control of the video clips was required to fit the right stems to the right time consumption data.

All activities associated with the cutting of a single tree were considered as a working cycle for cutting and those activities associated with forwarding one load were considered as a working cycle for forest haulage. The cycles were broken down into work elements (Tables 2 and 3).

Data analysis

In thinnings as well as release cuttings, the time consumption of tree harvesting is affected by the characteristics of the trees that are removed and the trees left growing. In our study, special attention was also directed at the working method. We had tree study stands that included several plots with varying density of birch understorey and birch overstorey due to earlier treatments. This meant that we have four types of predicting variables in our time consumption models: 1) characteristics referring to treatment (spruces are retained, spruces are not considered or no spruces are present), 2) tree characteristics (e.g. stem size, dm^3) 3) working location-dependent (plot) characteristics (e.g. number of trees/ha) and 4) stand characteristics. The explanatory variables are presented in Table 4.

The time consumption of each working phase was analysed using hierarchical linear mixed models. Let i be the treatment, j be the study stand, k be the working location (plot) and l the tree that is being cut. Tree-level models predict the time consumption of individual work elements while processing one individual tree (s/tree). Plot-level models predict the time consumption of each work element at the plot level (s/m^3). Corresponding random effects were included into the models.

The basic form of the tree-level models was:

$$t = b_0 + Treatment_i + b\,X + u_{jk} + e_{ijkl} \qquad (1)$$

where

t Time consumption of a working phase [s/tree]

b_0 Constant

$Treatment_i$ The effect of the working method i (fixed factor)

b (Row) vector of the (fixed) regression coefficients

X (Column) vector of the continuous and binary explanatory variables

u_{jk} Random term for interaction stand × plot *

e_{ijkl} Residual term

* Random term ‘stand’ were dropped out from the tree-level models, since the fittness of the models (according to AIC crierion) that included stand effect were poorer than the models without it.

and plot-level models as

$$t = b_0 + Treatment_i + b\,X + u_j + e_{ijk} \qquad (2)$$

where

t Time consumption of a working phase [s/m^3]

u_j Random term for stand j

e_{ijk} Residual term.

The number of undamaged spruces after birch harvesting was analysed using a similar plot-level model approach.

3 Results

3.1 Effect of Retaining Spruce Saplings on Working Methods and Characteristics of Saplings Remained Growing

In plots where spruce saplings are retained, the harvester has less flexibility in the felling of trees and less space to move whole trees and pile logs. Therefore the distances between the piles are shorter, thus resulting in a smaller number of logs in a pile (Table 5). The harvester operator in this study had a tendency to place more piles on the left-hand side and that tendency was markedly greater in plots were spruces were not considered or present at all. It seems that the harvester operator placed the piles removed from the strip road on the left-hand side of the strip road whenever possible.

A re-inventory to analyse the damage to spruce saplings showed that in all study stands less spruces are damaged and destroyed when the objective is to retain spruces during harvesting (Table 6).

The share of undamaged trees ($N_{spruce\_undamaged}$) can be predicted by the number of original birch overstorey trees (N_{trees}) and number of original understorey trees (N_{spruce}) prior to harvest (Table 7). With both predictors, the increase in original density decreased the share of the undamaged spruce saplings. On the other hand, the denser the original spruce understorey, the higher the number of undamaged saplings after harvesting.

There was no statistical difference in the mean height of undamaged and destroyed trees. However, it was noticed that damaged trees were shorter than undamaged and destroyed trees, the difference being greater in areas where the treatment used where spruces were retained while harvesting.

When examining the future of the sapling, we cannot completely focus on the number of spruces competent for future stand growth, but spatial variation of the saplings within the stand is also very important. Figs. 1a and 1b show the spatial variation of the destroyed, damaged and undamaged spruces in two plots. It can be deduced that damaged and undamaged trees that should form the

Table 5. Characteristics of study plots, logs processed and their location. Treatments: R = spruces are retained, S = spruces are not considered, O = no spruces.

Stand	Plot	Treatment	Stand density N_{trees}	Stand removal V_{stand}	Number of logs	Mean vol. of logs	Mean dist. between the piles	Number of piles	Number of logs per pile	Share of piles in left hand side
No	No		n/ha	m^3/ha	n/ha	m^3	m	n/ha	n	%
A	17	R	980	148.4	3160	0.047	1.1	520	6.1	35
A	18	R	1081	197.5	3203	0.062	1.6	311	10.3	65
A	20	R	804	94.5	2339	0.040	1.1	429	5.1	54
A	21	R	1262	209.7	3488	0.060	1.1	417	8.4	51
A	22	R	1150	242.7	3338	0.073	0.9	350	9.1	46
A	25	R	1133	254.5	2844	0.089	1.0	367	7.5	58
B	2	R	1255	167.9	4064	0.041	1.5	351	12.5	64
B	4	R	1270	243.5	4595	0.053	1.8	446	10.3	61
B	6	R	1073	147.1	3385	0.043	1.5	323	8.7	61
B	7	R	534	142.1	(*	(*	1.5	328	7.9	59
B	8	R	441	106.9	1647	0.065	1.6	259	6.5	57
B	9	R	800	145.4	2760	0.053	1.8	260	10.2	54
C	6	R	660	151.9	2660	0.057	1.5	330	8.1	48
C	8	R	414	109.6	1664	0.066	2.5	250	6.5	66
C	14	R	1151	180.0	3837	0.047	1.5	477	8.8	66
A	10	S	1129	242.4	3443	0.070	1.8	229	14.0	75
A	12	S	1200	294.4	3457	0.085	2.1	257	13.2	78
A	19	S	1074	150.5	3630	0.041	2.0	315	11.9	71
A	26	S	883	114.5	2817	0.041	1.7	283	9.5	71
B	1	S	958	169.1	3542	0.048	2.2	236	13.3	88
B	5	S	1157	168.7	3557	0.047	2.2	314	11.2	81
B	10	S	856	123.7	2589	0.048	2.1	233	11.3	77
B	11	S	627	64.4	1653	0.039	3.1	193	8.5	97
C	4	S	687	151.8	2634	0.058	2.7	299	9.1	73
C	15	S	573	134.2	2250	0.060	3.2	250	7.9	75
A	1	O	1025	134.4	2788	0.048	3.0	200	12.1	100
A	6	O	1143	175.3	3164	0.055	2.1	214	14.0	87
A	11	O	1000	207.5	3243	0.064	1.7	286	10.6	85
C	9	O	750	176.4	2633	0.067	1.2	417	6.4	52
C	11	O	630	147.8	2500	0.059	2.2	230	10.3	78
C	12	O	550	128.9	2160	0.060	2.1	250	8.1	100
C	16	O	950	179.0	3588	0.050	2.3	238	12.2	100
C	17	O	408	115.1	1711	0.067	3.3	197	9.3	100
Mean	Treatment	R	933	169	3070 (*	0.057 (*	1.5	361	8.4	56
		S	914	161	2957	0.054	2.3	361	11.0	79
		O	807	158	2723	0.059	2.2	254	10.4	88

(* Stm-file lost from harvester's computer. This plot is not included in computing mean values for number and volume of logs processed for treatment S.

basis of the future tree stand are more clustered in the plot were spruces were not considered while harvesting. The figures reveal that the treatment where spruces are retained is distinctly superior to the treatment where spruces are not considered for the future growth of spruce sapling.

3.2 Time Consumption and Productivity of Cutting

Tree-level time consumption models that predict time consumption of individual work elements are presented in Table 9. The models give realistic estimates compared to the mean value of the original data (Table 8). Positioning-to-cut (t_{pos}), felling (t_{fell}) and processing (t_{proc}) are dependent

Table 6. Number and share of undamaged, damaged and destroyed spruce saplings after harvesting of overstorey birches (I = spruce is not damaged, II = spruce is damaged but vital enough to grow and III = spruce is destroyed).

Stand	Harvesting treatment	Plots n	Original no. of spruces n/ha (st.dev.)	Undamaged spruces n/ha (st.dev.)	Undamaged % (st.dev.)	Damaged %	Destroyed %
A	R	6	3225 (175)	1625 (350)	50 (8.4)	27	23
	S	4	3250 (141)	1125 (417)	35 (12.9)	21	44
B	R	6	1810 (468)	1148 (234)	65 (10.1)	11	24
	S	4	1813 (323)	846 (209)	47 (12.1)	17	36
C	R	3	1531 (248)	1130 (139)	75 (12.8)	11	14
	S	2	1647 (102)	949 (175)	57 (7.8)	18	25
All	R	15	2320 (833)	1335 (355)	61 (13.5)	18	21
	S	10	2355 (800)	978 (306)	44 (13.9)	19	37

Table 7. Estimates of the fixed and random parameters for the model predicting the share of undamaged trees when spruces are retained or not considered while harvesting (Eq. 3). Standard error of the parameter estimate is presented in parenthesis.

Model/ parameter	Dependent variable $N_{spruce\_undamaged(\%)}$ (3)
Fixed	
Intercept	86.3 (5.80)
N_{trees}	–0.0298 (0.006)
N_{spruce}	–0.00614 (0.002)
R	16.7 (2.91)
Random	
Variance of stand effect	0.00 (0.00)
Residual variance	43.1 (14.0)

on the properties of the removed birch (V_{stem}), surrounding trees (V_{stand}, N_{trees}) and treatment.

In all these work elements, a change in the cutting method has a distinct effect on the time consumption. For instance, while felling takes between 3 and 7 seconds, the impact of spruce understorey is roughly 1 second/tree. The model also separates forked and broken stems into separate category from normal straight stems. The processing of forked or broken stems increase time consumption by around 15–25 s/tree (Fig. 2).

Positioning-to-cut, felling and processing are all more dependent on the properties of the tree than the properties of the surrounding stand. The total time consumption of these three tree dependent work phases ($t_{tree} = t_{pos} + t_{fell} + t_{proc}$) can be calculated by summing up Eqs. 4, 5 and 6 or alternatively by Eq. 7. The interaction of the volume of removed tree, volume and intensity of surrounding trees (m^3/ha, stems/ha), cutting method and whether the tree is forked or not, is illustrated in Fig. 2.

Plot-level models predict the time consumption elements of the cutting process at working location (plot)-level (Table 11). The models give realistic values compared to the mean values of the original data presented in Table 10. Predicting variables are general stand-level predictors such as the mean size of removed trees (V_{stem}) or the number of trees per hectare (N_{trees}). Model 7 is similar to Model 8 but the former predicts the time consumption of actual cutting for an individual tree (s/tree) while the latter predicts the time consumption per volume of logs produced (s/m^3).

Time consumption of moving, clearing and moving tops, logs and branches (s/m^3) are dependent on mean stem size, number of trees per hectare, and the presence and composition of the understorey. Time consumption of the whole cutting process can be estimated by summing up all work elements (Eqs. 8, 9, 10 and 11 (or 12)) or alternatively with Model 13.

The interaction of the mean volume and number of the removed trees, the presence of understorey spruces and the cutting method is illustrated in Fig. 3 (Eq. 13). Since the equation gives the time consumption of cutting in seconds per m^3, the inverse of that number has to be multiplied by 3600s to give the result in volumes per effective hour.

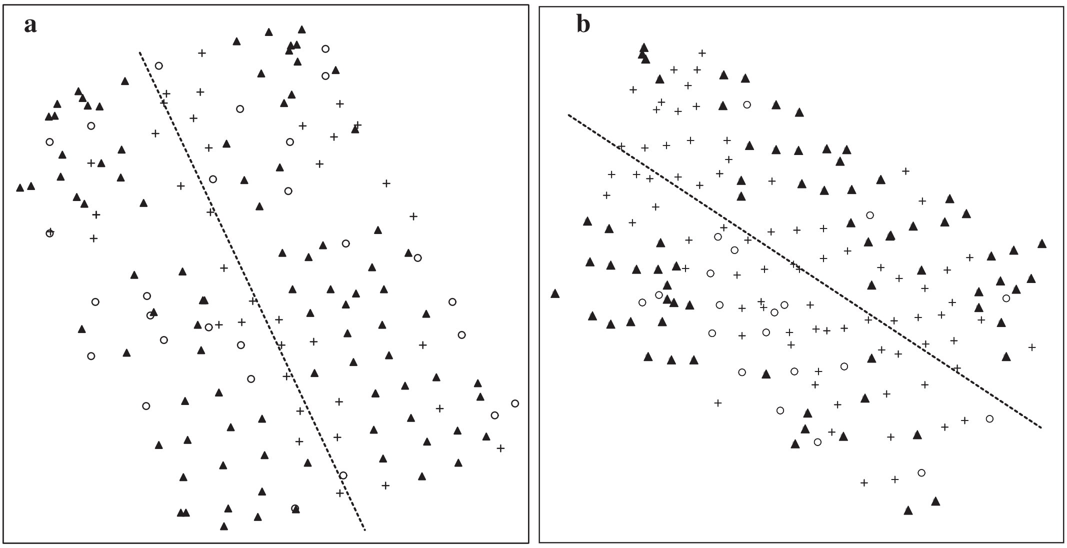

Fig 1. Spatial variation of the undamaged, damaged and destroyed spruce saplings in stand B where spruces are retained (a, plot 6) or not considered (b, plot 1) while harvesting. Interpretation of symbols: ▲ = undamaged, ○ = damaged, + = destroyed.

3.3 Forwarding

Time consumption of loading calculated from the original data is presented in Table 12 and the models predicting loading are presented in Table 13. Time consumption of loading (s/m^3) is dependent on the volume of overstorey (m^3/ha) and the presence and retaining of undergrowth spruces.

Time consumption of driving can be calculated by the result of average speed and driving distance. The average speed of driving empty was 1.3 m/s and that of driving loaded was 1.1m/s. Time consumption of unloading was not dependent on the treatment, number of trees or mean tree size. Consequently, the mean values presented in Table 14 can be used as an estimate to predict the time consumption of unloading.

4 Discussion

The study material comprises 33 harvesting plots in three different long-term study areas in western Finland. The material offered a unique possibility to investigate this phenomenon in a strictly controlled environment. The material constitutes a large variation in terms of the number of trees per hectare of birch overstorey. In all study plots, the spruce understorey was planted but it is quite obvious that the study results can be applied to similar types of forest where spruce undergrowth grows naturally.

All study plots were cut by the same harvester and driver. This is both advantageous and disadvantageous. When the machine and driver are the same, we can eliminate the effect that is caused by these factors, but on the other hand, the generalisation of harvesting productivity can be restricted. However, we cannot be sure that all experienced operators would have similar differences in the productivity and quality of harvesting sites.

Using video clips and a new tool to facilitate the analysis of the video material increased the reliability in separating time elements from each other. This method was advantageous, especially when analysing harvester work in stands with a

Table 8. Time consumption of the work elements in cutting of individual birch trees by tree (s/tree), different harvesting treatments (calculated from the original data).

Time consumption, s/stem	R (N=1086)		S (N=698)		O (N=556)	
	Mean	*St.dev.*	Mean	*St.dev.*	Mean	*St.dev.*
Positioning-to-cut(t_{pos})	7.8	3.5	6.7	2.8	6.5	2.2
Felling (t_{fell})	4.5	2.6	3.3	1.7	3.2	1.7
Processing of stem(t_{proc})	15.6	10.9	15.8	11.5	15.7	12.3
Total (t_{tree})	27.9	12.4	25.8	12.7	25.4	13.5

Table 9. Mixed tree-level time consumption models (Eqs. 4–7) (s/tree). Standard error of the parameter estimate is presented in parenthesis.

Model/ parameter	Dependent variable t_{pos} (4)	t_{fell} (5)	t_{proc} (6)	t_{tree} (7)
Fixed				
Intercept	6.24	0.703	6.43	13.0
	(0.145)	(0.526)	(1.72)	(2.04)
V_{stem}	0.00269	0.00410	0.0327	0.0383
	(0.001)	(0.001)	(0.003)	(0.004)
lnV_{stem}		0.199	0.824	1.15
		(0.093)	(0.398)	(0.461)
N_{trees}		0.00118	–0.00594	–0.00390
		(0.000)	(0.001)	(0.001)
V_{stand}			0.0232	0.0176
			(0.005)	(0.007)
R	1.15	1.03	3.78	6.21
	(0.168)	(0.214)	(1.61)	(1.90)
F			11.1	11.2
			(0.960)	(1.11)
$lnV_{stem}*R$			–0.605	–0.653
			(0.336)	(0.394)
$lnV_{stem}*F$			0.0285	0.030
			(0.004)	(0.004)
Random				
Variance of	0.0903	0.287	0.377	0.943
stand*plot effect	(0.0568)	(0.0872)	(0.306)	(0.498)
Residual	9.22	3.99	53.5	71.1
variance	(0.271)	(0.117)	(1.58)	(2.09)

high number of undergrowth spruces with minor visibility. In the tree-level analysis, it was essential to be able to check and edit the matching of cutting cycle and stem data from harvester computer at a later stage.

In the modelling of the time consumption of the work phases, the mixed linear modelling technique was applied. Cutting of trees is in most cases dependent on both the characteristics of the tree that is processed and the surrounding trees. The technique utilised can be used to identify the role of the individual tree, surrounding trees (working location or plot effect) and the differences between the study stands and can therefore be regarded an appropriate method for similar work studies. At tree-level, variance of interaction of stand and plot effect were quite low compared to residual variance, which means that the characteristics of individual stems and surrounding trees can predict differences in tree-levels quite well. At the plot-level, random variances caused by the stand are quite high. Factors that may have an

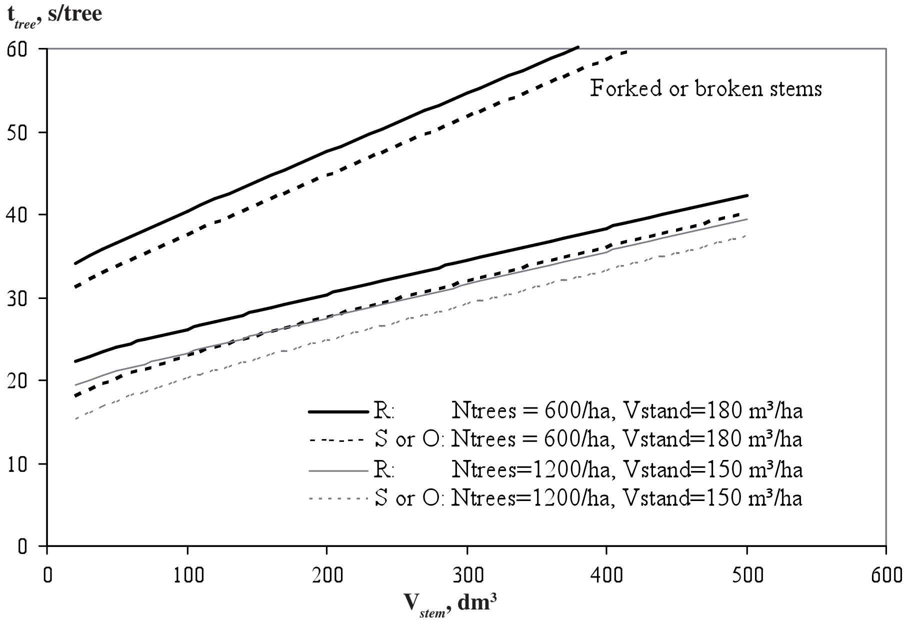

Fig. 2. Illustration of Eq. 7 that describes the tree-level time consumption depending on the volume of removed tree (V_{stem}), volume (V_{stand}) and density (N_{trees}) of surrounding trees, treatment and whether the tree is forked or not. R = understorey is retained, S = understorey is not considered, O = understorey is not present.

Table 10. Time consumption of the work elements in cutting birches (s/m^3), different harvesting treatments as calculated from the original data.

Time consumption, s/m^3	S (N=15) Mean	S (N=15) *St.dev.*	R (N=10) Mean	R (N=10) *St.dev.*	O (N=8) Mean	O (N=8) *St.dev.*
Positioning-to-cut (t_{pos})	46.3	12.2	43.3	12.5	35.3	9.5
Felling (t_{fell})	27.0	8.9	20.9	3.4	17.6	4.4
Processing of stem (t_{proc})	95.0	14.1	95.6	10.8	87.5	9.2
Total (t_{trees})	16..3	30.2	159.8	24.0	140.3	19.6
Moving harvester (t_{mov})	23.0	6.2	15.5	6.5	11.8	2.8
Clearing(t_{clear})	6.7	3.5	9.5	3.4	2.9	1.5
Moving logs. tops & branches ($t_{arrange}$)	4.7	2.8	5.0	1.9	3.6	2.5
Cutting in total (t_{cut})	202.7	37.3	189.9	29.5	158.7	21.3

impact at the stand-level are the number of forked or broken stems, crookedness, general working conditions (temperature, depth of snow, etc.) or the approach taken by the machine operator.

The cutting treatment selected, whether the undergrowth spruces were considered or not, had a distinct impact on productivity, but the difference was somewhat lower than originally assumed. The denser the original stand, the bigger the difference between the cutting methods. The retention of undergrowth spruces decreases the productivity of cutting in managed stands (600 stems/ha) by 6–9 per cent and in unmanaged stands (1200 stems/ha) by 11–17 per cent compared with clear cutting, when the understorey was not considered. Compared to the case where

Table 11. Mixed plot-level time consumption models of cutting process (s/m^3) (Eqs. 8–13). Standard error of the parameter estimate is presented in parenthesis.

Model parameter	Dependent variable					
	t_{trees} (8)	t_{mov} (9)	t_{clear} (10)	$t_{arrange}$ (11)	$t_{arrange}$ (12)	t_{cut} (13)
Fixed						
Intercept	345	62.2	7.65	8.23	9.91	424
	(33.4)	(11.7)	(2.13)	(2.05)	(2.60)	(43.0)
V_{mean}	–1.64	–0.272	–0.0182	–0.165	–0.0236	–1.91
	(0.424)	(0.149)	(0.010)	(0.008)	(0.008)	(0.546)
V_{mean}^2	0.00306	0.000491				0.00343
	(0.001)	(0.004)				(0.001)
N_{trees}		–0.020			–0.00297	
		(0.0046)			(0.002)	
$L_{saplings}$			0.661		0.333	
			(0.130)		(0.085)	
R			–2.33			
			(1.01)			
O				–2.59		
				(0.845)		
$R{*}N_{trees}$	0.0205	0.0135				0.0122
	(0.011)	(0.002)				(0.015)
$S{*}N_{trees}$	0.00163	0.00398				–0.0133
	(0.012)	(0.002)				(0.016)
$O{*}N_{trees}$	–0.00648	0				–0.0360
	(0.013)					(0.017)
Random						
Variance of	25.6	2.01	0.609	5.44	3.85	67.5
stand effect	(46.6)	(3.69)	(1.68)	(5.94)	(4.24)	(94.2)
Residual	118.0	14.7	6.53	3.49	2.99	194.1
variance	(33.6)	(4.13)	(1.80)	(0.933)	(0.814)	(54.9)

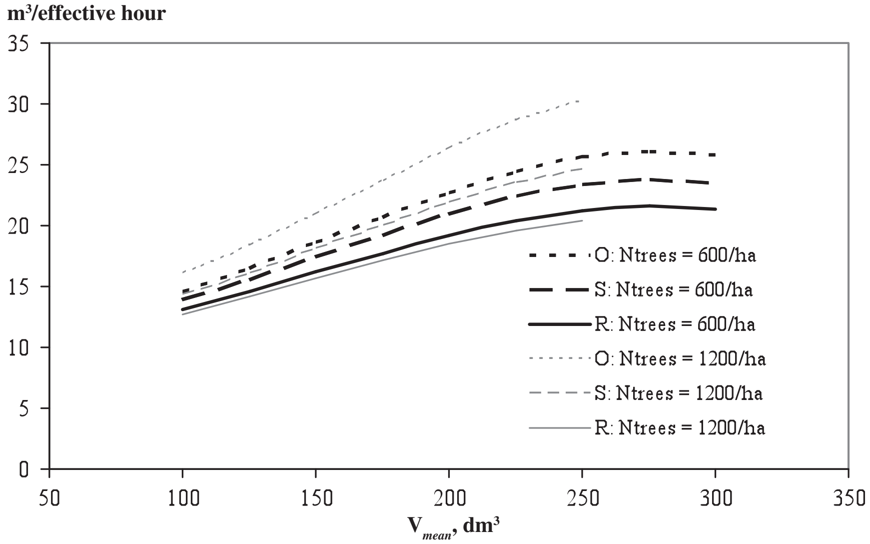

Fig. 3. Illustration of Eq. 13 that describes the interaction of the mean volume (V_{mean}) and number of the removed trees (N_{trees}) and the treatment on the productivity of cutting . R = understorey is retained, S = understorey is not considered, O = understorey is not present.

Table 12. Time consumption of the work elements in loading (s/m^3), different harvesting treatments as calculated from the original data.

Time consumption, s/m^3	R (N=15)		S (N=10)		O (N=8)	
	Mean	St.dev.	Mean	St.dev.	Mean	St.dev.
Reaching the pile	31.4	10.3	24.8	5.8	23.0	3.9
Lifting the grapple load	41.8	11.8	36.0	5.5	31.9	3.6
Actual loading (t_{load_a})	73.2	21.8	60.9	11.2	54.8	7.1
Handling logs on the ground	4.3	3.0	1.6	1.6	1.0	0.7
Handling logs in the bunk	10.5	4.9	10.7	5.7	7.7	1.1
Relifting of the fallen logs	2.7	2.6	2.8	1.7	1.8	2.1
Misc. loading activities (t_{load_m})	17.4	7.3	15.0	6.6	10.5	3.2
Moving while loading (t_{load_drwl})	12.4	3.5	8.6	1.8	7.4	1.9
Loading in total (t_{load})	103.0	27.8	84.5	16.0	72.7	9.0

Table 13. Mixed time consumption models of loading (Eqs. 14–17) (s/m^3). Standard error of the parameter estimate is presented in parenthesis.

Model parameter	Dependent variable $t_{load\ a}$ (14)	$t_{load\ m}$ (15)	t_{drwl} (16)	t_{load} (17)
Fixed				
Intercept	54.5	10.2	13.5	79.3
	(10.2)	(4.57)	(2.16)	(13.8)
$R^* V_{stand}$	0.104	0.0421	–0.00957	0.130
	(0.049)	(0.027)	(0.013)	(0.069)
$S^* V_{stand}$	0.00718	0.0174	–0.0294	–0.009
	(0.047)	(0.026)	(0.012)	(0.066)
Random				
Variance of stand effect	126	6.89	1.80	207
	(141)	(11.0)	(2.69)	(233)
Residual variance	106	33.3	7.19	208
	(31.9)	(9.98)	(2.16)	(62.5)

Table 14. Time consumption of unloading by work elements (s/m^3).

Work element	Mean,	St. dev.
Moving the empty grapple loader into the bunk	13.3	1.6
Lifting the grapple load onto the landing pile	17.9	1.6
Sorting and handling the logs in the bunk	0.5	1.0
Sorting and handling the logs on the landing pile	2.6	1.9
Lifting of logs fallen while loading	1.8	1.3
Total	36.3	3.3

no understorey was present, the decrease in productivity was 10–17 per cent and 21–30 per cent respectively (Figs. 3 and 4). In addition, the vitality and actual growth of understorey spruces are better in well-thinned birch stands than in dense ones (Heikurainen 1985, Mård 1996, Hilli et al. 2003, Niemistö and Poutiainen 2004). Regeneration via undergrowth spruces seems to be a more feasible management pattern in well-managed birch stands compared with unmanaged stands.

In general, the productivity of cutting birches per effective hour (E_0) is 15–29 m^3 in stands where there are no spruces present, 14–24 m^3 in stands where spruces exist but are not considered and 13–21 m^3 in stands where undergrowth spruces are retained. In forwarding, retaining the undergrowth increases time consumption for loading by 10–30 per cent, whereas the harvesting treatment has no effect on the time for other work phases (driving unloaded, driving loaded, unloading). The total productivity of forwarding decreases by 7–14 per cent when undergrowth is retained (Fig. 4). The productivity of cutting measured and modelled in this study is comparable to previous studies. The models presented by Nurminen et al. (2006) gives the productivity of 11–28 m^3 in clear cutting of birches within the same circumstances as in this study.

In the harvesting treatment where spruces were retained, the time consumption was higher for the most important phases of cutting and loading compared with the method when spruces were not considered. In positioning-to-cut, the difference was around 1 s/tree, in felling around 1 s/tree and in processing of a tree around 0.5–2.0 s/tree (the

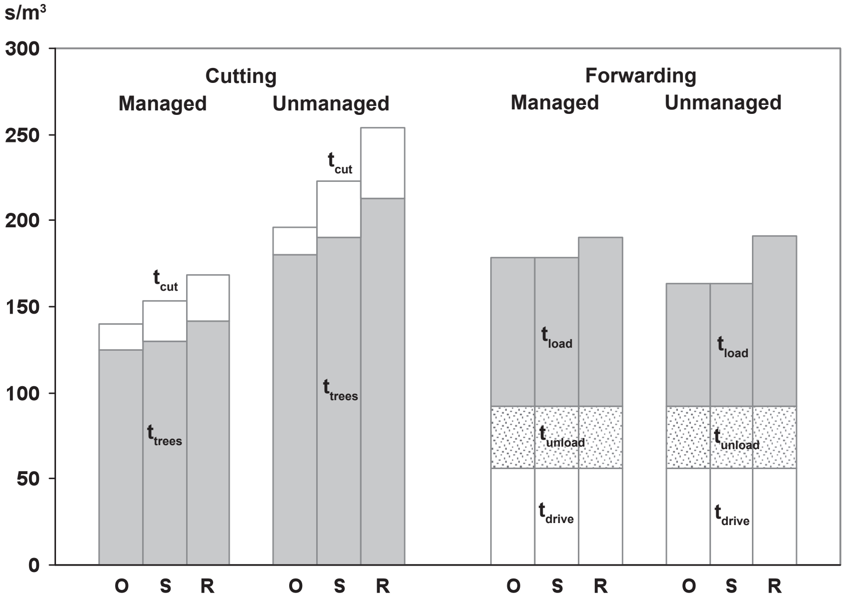

Fig. 4. Time consumption of cutting and forwarding according to treatment of spruce undergrowth in managed (N = 600 stems/ha, V = 180 m^3/ha) and in unmanaged (N = 1200 stems/ha, V = 150 m^3/ha) birch stands. Mean distance to landing pile is 300 m. R = understorey is retained, S = understorey is not considered, O = understorey is not present.

difference decreased with increasing stem size). In total, this difference was approximately 20 s/m^3 in high density stands and 10 s/m^3 in low density stands. The reasons for lower productivity is lower visibility, careful movement of the harvester head, consideration of the felling direction and careful movement of the stem to the processing position. However, there were only minor differences in the productivity between the cases when spruces were not considered and in cases when there were no spruces present.

When spruces were retained, the moving of the harvester took 5–10 s longer per m^3 compared with the method where spruces were not considered. In stands where there were no spruces present, the time consumption of moving was still 4 s shorter per m^3 and in addition the moving of logs, tops and braches took around 2.5 s less per m^3 compared with the stands were there were spruces present. The main reasons for these differences is more careful positioning of log piles on both sides of harvester and a higher number and smaller size of the piles when spruces are retained, and to some extent when the spruces are present but not considered.

In most work phases of cutting, the time consumption (s/tree) increased with increasing stem size and an increasing number of stems and in cases where spruces were retained. The moving of the harvester made a difference. The time consumption (s/m^3) decreased where there was an increase in the number of stems. The clearing of undergrowth which had a negative effect also made a difference. It took around 2 s longer per m^3 when spruces were not considered compared to the other treatments. The time consumption of clearing (s/m^3) was dependent on the density and height of the spruce stand but it also increased in very dense birch stands due to the high number of small non-commercial stems.

The effect of the cutting method on the productivity and quality of the remaining stands has been studied earlier in spruce stands in Sweden. Lageson (1997) investigated the effect of two different thinning treatments, thinning from above and thinning from below, on the productivity of harvesting. It was noted that a higher thinning ratio (i.e. the relationship between the mean diameter at the breast height of extracted trees to remaining trees) can increase the removal of damaged, suppressed and to some extent strip road trees. Eliasson et al. (1999) compared the productivity of clear cutting to shelterwood cutting in mature spruce stands and found that productivity decreased from 64 m^3 per effective hour in clear-cutting to 54 m^3 and 41 m^3 when shelterwoods with 259 and 381 stems per hectare, respectively, were retained. That equates to between 15 and 36 per cent. Hånell et al. (2000) found a similar ratio in productivity between clear cutting and shelterwood cutting, although they ended up with a slightly lower productivity level than that of Eliasson et al. (1999).

Harvesting treatment where spruces were retained produced a much better structure of the remaining stands than the method where spruces were not considered. In the former method only 14–24 per cent of the original spruces were totally destroyed while in the latter case 25–44 per cent were. One reason for this positive result arose from the tree species of the overstorey. Usually Downy birch stands are very dense when young and thinnings do not heavily result in small and narrow crowns. During cutting these kind of trees do not cause serious damage to the remaining spruce sapling. In studies of shelterwood cutting and shelterwood removal in spruce forests (Westerberg et al. 1996) and pine forests (Westerberg and Berg 1994) it was noted that the proportion of dead or damaged coniferous seedlings after harvesting can be large, up to 65 per cent, but the remaining number of living seedlings has still been sufficient to ensure satisfactory forest regeneration.

In this study it was further noted that the spatial distribution of the remaining spruces was much better in the method where spruces were retained. Even if spruces were not considered, the number of released undamaged spruces per hectare was in some cases at an acceptable level, but they were too clustered to build up a productive future tree stand.

Our study results shows that in this kind of two storey birch-spruce forest, the cutting method where spruces are retained while harvesting is most likely to be seen as a very acceptable and profitable method. It leaves vital spruce saplings to grow which avoids the regeneration costs and other harmful effects of clear cut areas, such as freezing of young spruce plants (Leikola and Rikala 1983) and an increase in the ground water table (Päivänen and Sarkkola 2000). It is quite obvious that more of this type of research where the cutting method is somehow changed from the current practice is needed in the future. Modern forests owners are keener on alternative growing and cutting methods rather than traditional forest practices where clear cutting is followed by planting, weeding, cleaning and thinning. Modern harvesters do not restrict the use of alternative cutting practices, although these methods are to a certain extent subject to a decrease in productivity.

References

Brunberg, T. 1997. Basic productivity norms for single-grip harvesters in thinning. The Forestry Research Institute of Sweden, Uppsala. Redogörelse 8. 18 p. (In Swedish with English summary).

— 2004. Productivity-norm data for forwarders. Skogforsk Redogörelse 3. 12 p. (In Swedish, English summary).

Eliasson, L. 2000. Effects of establishment and thinning of shelterwoods on harvester performance. Journal of Forest Engineering 11(1): 21–27.

— , Bengtsson, J., Cedergren, J. & Lageson, H. 1999. Comparison of single-grip harvester productivity in clear and shelterwood cutting. Journal of Forest Engineering 10(1): 43–48.

Finnish Statistical Yearbook of Forestry. 2008. Finnish Forest Research Institute. 458 p.

Glöde, D. 1999. Single- and double grip harvesters productivity measurements in final cutting of shelterwood. Journal of Forest Engineering 10(2): 63–74.

Gullberg, T. 1997. A deductive time consumption model for loading shortwood. Journal of Forest Engineering 8(1): 35–44.

Hånell, B., Nordfjell, T. & Eliasson, L. 2000. Productivity and costs in shelterwood harvesting. Scandinavian Journal of Forest Research 15: 561–569.

Heikurainen, L. 1985. The influence of birch nurse crop (Betula pubescens) on the growth of spruce (Picea abies) seedling stand on drained peatlands. Silva Fennica 19(1): 81–88. (In Finnish with English summary).

Hilli, A., Päätalo, M.-L., Moilanen, M., Piiroinen, M.-L., Issakainen, J. & Tillman-Sutela, E. 2003. The effect of nurse crop density and fertilization on the height growth of Norway spruce seedlings on drained peatland. Suo (Peat and Mires) 54(2): 69–79. (In Finnish with English summary).

Hynynen, J., Niemistö, P., Viherä-Aarnio, A., Brunner, A., Hein, S. & Velling, P. 2010. Silviculture of birch (Betula pendula Roth & Betula pubescens Ehrh.) in northern Europe. Forestry 83(1): 103–119.

Kärhä, K., Rönkkö, E. & Gumse, S.-I. 2004. Productivity and cutting costs of thinning harvesters. International Journal of Forest Engineering 15(2): 43–56.

Kuitto, P.J., Keskinen, S., Lindroos, J., Oijala, T., Rajamäki, J., Räsänen, T. & Terävä, J. 1994. Puutavaran koneellinen hakkuu ja metsäkuljetus. Mechanized cutting and forest haulage. Metsäteho Report 410. 38 p. (In Finnish with English summary).

Lageson, H. 1997. Effects of thinning type on the harvester productivity and on the residual stand. Journal of Forest Engineering 8(2): 7–14.

Leikola, M. & Rikala, R. 1983. The influence of the nurse crop on stand temperature conditions and the development of Norway spruce seedlings. Folia Forestalia 559. 33 p. (In Finnish with English summary).

Mård, H. 1996. The influence of a birch shelter (Betula spp.) on the growth of young stands of Picea abies. Scandinavian Journal of Forest Research 11(4): 343–350.

McNeel, J.F. & Rutherford, D. 1994. Modelling harvester-forwarder system performance in a selection harvest. Journal of Forest Engineering 6(1): 7–14.

Mielikäinen, K. & Valkonen, S. 1995. Kaksijaksoisen kuusi–koivu-sekametsän kasvu. Folia Forestalia – Metsätieteen aikakausikirja 1995(2): 81–97. (In Finnish).

Moilanen, M. & Saksa, T. 1998 (eds.). Alikasvokset metsänuudistamisessa – Varjosta valoon. Pihlajasarja 3. 123 s. ISBN 952-5118-18-5. (In Finnish).

Niemistö, P. 1991. Growing density and thinning models for Betula pubescens stands on peatland in northern Finland. Folia Forestalia 782. 36 p. (In Finnish with English summary).

— & Poutiainen, E. 2004. Hieskoivikon käsittelyn vaikutus kuusialikasvoksen kehitykseen Keski- ja Pohjois-Pohjanmaan viljavilla ojitusalueilla. Metsätieteen aikakauskirja 4/2004: 441–459. (In Finnish).

Nurminen, T., Korpunen, H. & Uusitalo, J. 2006. Time consumption and analyses of the mechanized cut-to-length system. Silva Fennica 40(2): 335–363.

Ovaskainen, H., Uusitalo, J. & Väätäinen, K. 2004. Characteristics and significance of harvester operators' working technique in thinnings. International Journal of Forest Engineering 15(2): 67–77.

— , Uusitalo, J. & Sassi, T. 2006. Effect of edge trees on harvester positioning in thinning. Forest Science 52(6): 659–669.

Päätalo, M.-L., Hilli, A., Moilanen, M. & Tillman-Sutela, E. 2003. Impact of birch nurse crop density and height equalization of Norway spruce understorey on spruce seedlings' height growth on a drained peatland. Suo (Peat and Mires) 54(3): 105–115. (In Finnish with English summary).

Päivänen, J. & Sarkkola, S. 2000. The effect of thinning and ditch network maintenance on the water table level in Scots pine stand on peat soil. Suo (Peat and Mires) 51(3): 131–138.

Seppälä, K. & Keltikangas, M. 1978. Occurrence of understorey seedlings in drained Betula pubescens stands in Ostrobothnia. Suo 29(1): 11–16. (In Finnish with English summary).

Väätäinen, K., Ala-Fossi, A., Nuutinen, Y. & Röser, D. 2006. The effect of single grip harvester's log bunching on forwarder efficiency. Baltic Forestry 12(1): 64–69.

Valkonen, S. & Valsta, L. 2001. Productivity and economics of mixed two-storied spruce and birch stands in Southern Finland simulated with empirical models. Forest Ecology And Management 140(2–3): 133–149.

Verkasalo, E. 1997. Quality of European white birch for veneer and plywood. Finnish Forest Research Institute Report 632. 483 p. (In Finnish with English summary).

Westerberg, D. & Berg, S. 1994. Felling of standards: trial method for determining productivity, costs and damage to advance growth. The Forestry Research Institute of Sweden. Redogörelse 10. 26 p. (In Swedish with English summary).

— , Sikström, U., Hofsten, H. von & Gustafsson, L. 1996. Shelterwood systems. In: Frumiere, G. (ed.). Research and Development Conference 1996. The Forestry Research Institute of Sweden, Report 1. p 112–133. (In Swedish with English summary).

Total of 32 references