Tree Damage in Single-Grip Harvester Thinning Operations

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ABSTRACT

Tree damage in a one-grip harvester operation was assessed by observing the number of contacts with standing trees and damage resulting from these contacts. The processing phase for a single tree was called a cycle. On average, 19.3% (14.5 - 25.4%) of cycles involved contacts with standing trees. One third of the contact trees were removed during harvesting. Of the struck trees left standing, 28.2 % were damaged. The probability of contact damage was 1.5 times higher in the summer than in other seasons. Mean damage percentage in the study stands was 3.4 (range 0.0 - 8.6%).

Contacts with standing trees were explained by machine operator, stem volume of processed tree and the number of trees on the working area. The probability of damage resulting from contact was explained by harvesting season and size of processed tree. A model was developed to predict tree damage. The model consisted of a contact model and a damage model formulated using logistic regression. The tree damage model and the productivity models can be used, for example, in comparing different thinning regimes in model stands.

The operator had considerable influence on both the harvesting quality and productivity, and there was a large variation between machine operators. High productivity and a good silvicultural result were highly correlated.

Keywords: *tree damage, thinnings, one-grip harvester, logistic regression, single-grip harvester, Picea abies.*

INTRODUCTION

In 1997, the mechanization rate in thinnings in Finland was 77%, an increase of 9% from the previous year [22]. Thinnings are carried out using one-grip harvesters and forwarders. The silvicultural result of thinning includes number, distribution and quality of remaining and removed trees, area of strip roads and amount and quality of tree and soil damage. Forest owners recognize the importance of achieving a good thinning result, and fear of incurring thinning damage can reduce the owner's interest in thinning. Forest owners consider that a good silvicultural result is the most important criterion to be placed on harvesting machinery in the future [13]. Good silvicultural thinning results also play an important role in the certification processes of forest companies.

The amount of tree damage with a one-grip harvester in thinnings has been acceptable on average, but there has been much variation between studied stands. In a large-scale study in Sweden the average damage percentage (percentage of damaged trees over of the number of residual trees after thinning) with a one-grip harvester and forwarder was 5.9 [6]. In Finland the damage percentage in routine inventories between 1993 - 1996 has been around four [8]. These damage numbers are low when compared with damage found after mechanized thinning in North-America. Damage percentages greater than 20 have been reported there when using feller-bunchers and skidders [15, 17].

Damage inventories based on comprehensive data are expensive. They are, however, necessary when information on amount of tree and soil damage caused by different harvesting methods is required. Damage inventories are mostly made post-harvest. The researcher knows the company, machine, operator and season of operation when collecting and processing the damage data. What he does not know is the way the operator has worked, the cause of damage and many other factors affecting damage rates. When classifying the phase of work during which the damage occurred, the result is dependent upon the researcher's experience. In machine work, there are many interdependencies among working technique, productivity and damage. Isolating these interactions with post-harvesting inventories is impossible.

Systematic line plot samples have been the most common tree damage study method in Scandinavia. In the United States three sampling methods for measuring tree damage were compared. Circular sample plots from systematic measuring lines were found to be the best way to study tree damage [19].

There is also another approach to tree damage study. Tree damage can be monitored during the harvester operation. In this case knowledge on the actual causes of damage can be obtained. Monitoring also offers possibilities for modelling the tree damage process. Figure 1 presents a diagram the tree damage process in one-grip harvester operation.

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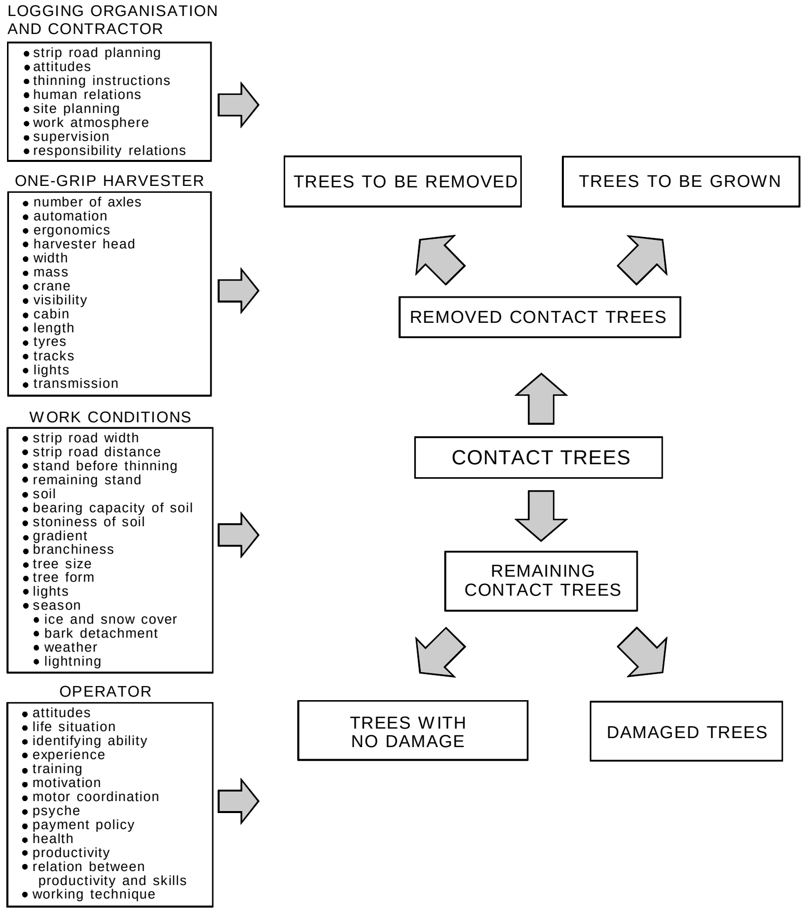

Figure 1. Elements influencing tree damage in a one-grip harvester operation.

The aim of the present study was to model the tree damage process in thinning with a one-grip harvester. Also work productivity, factors affecting work productivity and associations between productivity and tree damage were studied. Factors affecting productivity are not extensively discussed, however, in this paper.

MATERIALS AND METHODS

Field study

In the field study, harvester operations were monitored by three researchers: one attended to time study functions with particular attention being paid to tree location (distance from the strip road), grip angle and processing location; another monitored a harvester's movements (base machine and multi-function unit) in meters and, with regard to the processing of individual trees, the available space and the number of trees so that each tree's individual working conditions were assessed. The method for estimating the available space and the number of trees on the working area is presented in Figure 2.

The third researcher monitored contacts with standing trees and recorded the observed number of contacts, location of any contacted tree and point of contact, work stage in progress at the time of contact, object (machine part, tree) causing contact, reason for contact and severity of contact.

Only contacts caused by the stem, thick branches or machine were taken into account. In order to be taken into account, contacts must involve the stem, root collar or root system (less than 1 m from the root collar). Contacts with trees located on the strip road were not included. All contacted trees were numbered and labelled. At the end of the monitoring period diameter at breast height, type and extent of possible damage, distance of damage from root collar and distance between tree and strip road were recorded for all labelled trees. Damage was classified as superficial, when only bark was removed. Where wood fibres were damaged, this constituted deep damage.

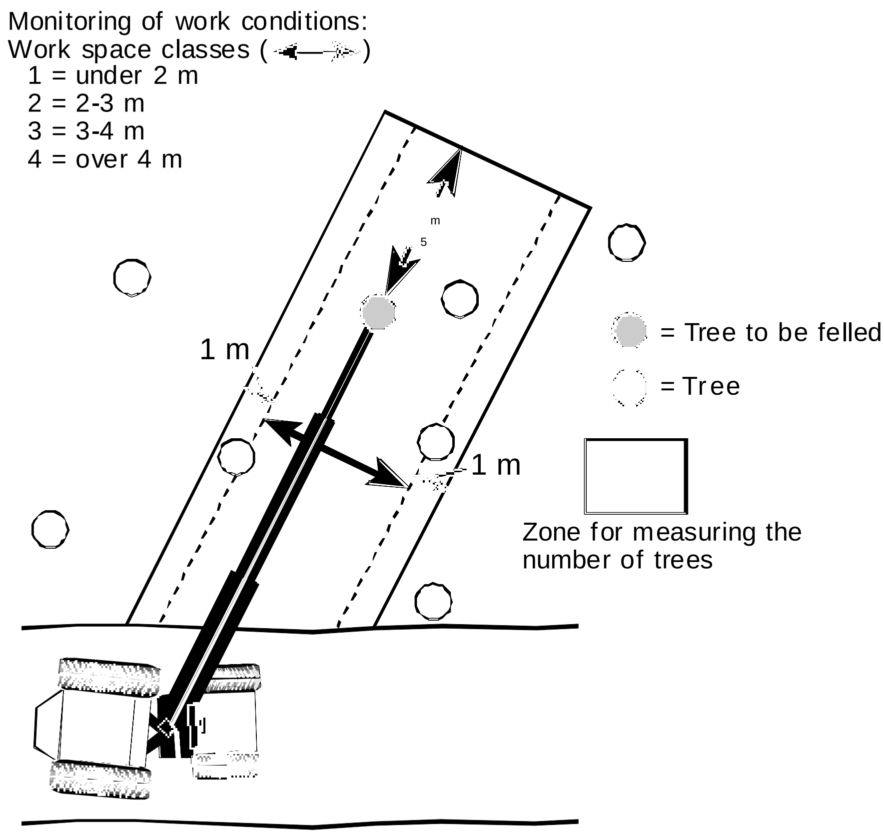

Figure 2. The method of estimating the available space and number of trees on a machine's working area.

Research Material

The research material was collected from 15 monitored stands and involved a total of 8192 stems with a total volume of 1085 m^3, of which 586 m^3 was cut in winter, 288 m^3 in spring or autumn and 211 m^3 when sap was flowing (April – May). The stands were first and second thinnings. Thinning was done as low thinning; smaller trees and trees with lower quality were removed. The initial growing stock in the stands studied averaged 1169 stems/ha while the corresponding figure after thinning was 634 stems/ha. The average size of removed trees was 135 dm^3 and 73.9 m^3/ha was removed in total. The stands were dominated by Norway spruce (*Picea abies*).

The machine studied was a Valmet 901 one-grip harvester equipped with a Valmet 942 harvester head. The machine was working on the strip roads. Distance between strip roads was 20 m. Pulpwood was cut to 5 m lengths. The stands studied were located on easy terrain with no steep slopes.

Four operators were included in the study. Two (operators A and D) were very experienced operators. Operators B and C were not so experienced, and their skills can be regarded as moderate.

Modelling

When predicting tree damage, the number of work stages in operating the harvester and the working conditions must be known. Details of the contacts to standing trees and of the factors affecting the number of contacts are also needed. The effects of different kinds of contacts and also the influence of factors such as harvesting season on damage occurrence from contacts must also be known.

A "Tree Damage model" was built to predict tree damage using a logistic regression model and MS Excel software to predict contact and damage. Logit analysis was carried out with SAS software. Contact models were built for the work cycle and also for different work phases. Damage models describe the results of contacts and the factors affecting them. All contacts were handled together; the results of contacts can be regarded as independent of the operator. The damage model was based on observations from 1049 contacts.

In addition to the contact and damage models, the Tree Damage model includes a submodel for the removal of damaged trees, a submodel for two contacts and two damages to the same tree and submodels for damage location and damage type. The diagram the Tree Damage model is presented in Figure 3.

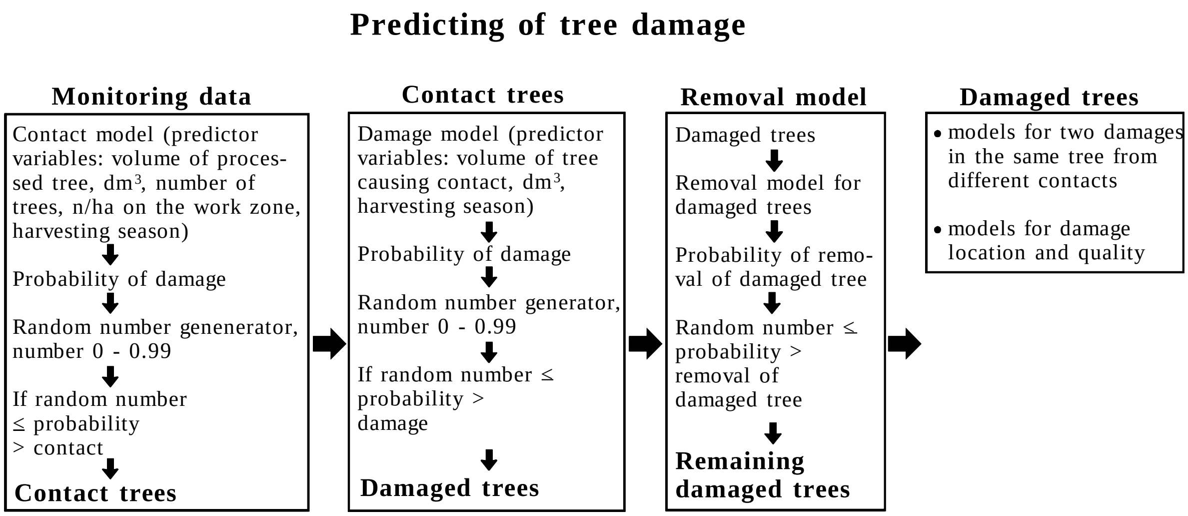

Figure 3. Diagram of the Tree Damage model.

RESULTS

Productivity

Direct productivity comparisons among operators were not possible because of the differences in stand characteristics. However, considerable differences in productivity were observed. Figure 4 shows the influence of stem size on effective time taken. Table 1 lists the equations developed to predict effective time as a function of stem volume. The average productivity was 11.0 m^3/E_0 (E_0 = effective time, includes no delay times).

The productivity of operator A was 16.4 m^3/E_0, that of operator B was 8.8 m^3/E_0, operator C 9.8 m^3/E_0 and operator D 12.3 m^3/E_0.

When operators process trees at the strip road, more branches are available for protecting both soil and roots. For trees taken to the strip road for processing, the effective time consumption was only slightly higher than with trees processed near the stump.

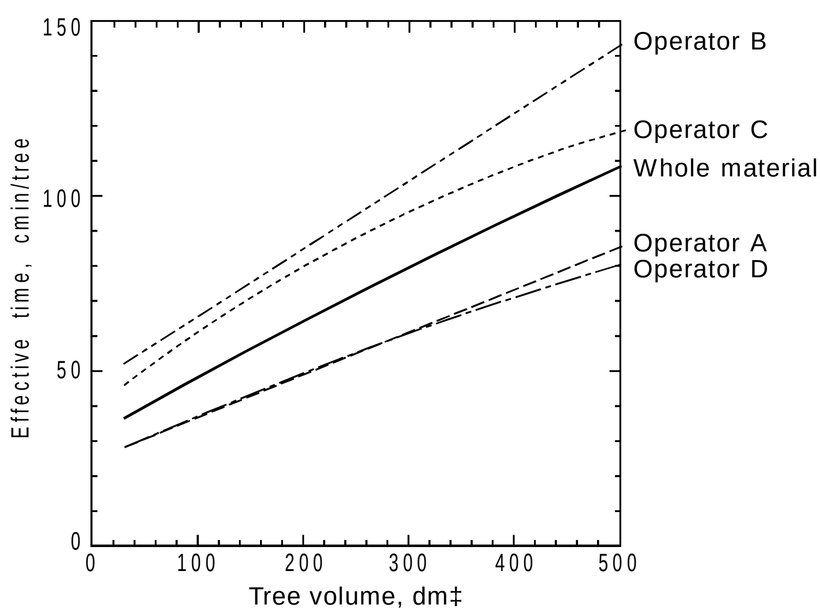

Figure 4. The influence of stem size on effective time consumption with spruce by operator.

Table 1. Predictive equations for effective time/tree as a function of tree volume for four operators studied.

Operator	Equation	r^2
A	$y^1 = 25.100 + 0.119 * x^1$	0.626
B	$y = 47.569 + 0.189 * x$	0.417
C	$y = 40.313 + 0.222 * x - 0.00014 * x^2$	0.337
D	$y = 25.767 + 0.130 * x - 0.00005 * x^2$	0.387
All operators combined	$y = 32.480 + 0.169 * x - 0.00004 * x^2$	0.362

[1]x = volume per stem (dl) y = effective time (c min/tree)

Number of contacts and damage to standing trees

The study material comprised 8192 stems. A total of 1579 working cycles (19.3%) resulted in contacts to trees. Frequencies of work cycles (work cycle = all the work elements for processing a single tree) resulting in contacts and corresponding percentages per operator are presented in Table 2.

The number of contacts does not directly reflect how demanding a particular work situation is, or how skilled the operator is, because when operating in cramped conditions an operator can fell a tree towards another tree which he knows will soon be removed. This being the case, contacted trees - which operators later felled - were classified as either "trees removed for silvicultural reasons" and "trees removed because of contact damage". All remaining contacted trees were examined for possible damage and such damage was measured and found to be distributed as presented in Table 3.

Table 2. Number of processed trees and contacts.

Operator	Stems processed, N	Number of work cycles resulting in contacts	%	Contact with two trees per work cycle	%
A	1664	269	16.2	9	0.5
B	2911	740	25.4	75	2.6
C	465	112	24.1	11	2.4
D	3152	458	14.5	25	0.8
Total	8192	1579	19.3	120	1.5

Table 3. Numbers of removed contact trees, their distribution by silvicultural classes and damage occurrence in remaining contact trees.

Operator	Contacts	Removed trees for silvicultural reasons	Removed trees because of contact damage	Remaining trees with contact damage	%	Superficial damage %	Deep damage %
A	278	83	6	45	23.8	69	31
B	815	242	39	181	33.9	86	14
C	123	30	9	38	45.2	95	5
D	483	194	19	41	15.2	95	5
All	1699	549	73	304	28.3	86	14

The mean damage percentage (percentage of the damaged trees from the number of remaining trees) in the monitored stands was 3.4 varying between 0.0 and 8.6%. The number of damaged stems/ha was 22.0 varying between 0.0 and 60.9. The mean damage percentage by operator A was 2.2, by B, 4.9%, by C, 6.6% and by operator D, 1.4%.

Type and location of damage

Of all damage, 92.4% was to the stem and 7.6% to root collars. The average surface area of damage was 54 cm^2, with superficial damage averaging 49 cm^2 and deep damage 81 cm^2. The average area of the wintertime damage was 39 cm^2, while damage in the sap period averaged 78 cm^2 and damage in the spring and autumn averaged 55 cm^2. The length-width ratio for damage averaged 6.8.

The average contact point was at a height of 450 cm from the root collar, while the average distance between the harvester and contacted trees was 720 cm. The average height of damage in stems was 275 cm above the root collar. On average, the damaged trees were 595 cm from the strip road centre.

The majority of contacts (68%) and damage (65%) occurred at the felling stage and were caused by trees as they were felled. Delimbing and moving stems are other stages in the processing when contacts are highly likely**.**

The most common reasons for contacts were found to be difficult tree location or "other reason" (used when no particular reason could be observed to apply). For example, when large trees are felled in a dense stand, contacts with standing trees are often impossible to avoid - in such cases the entry was "other reason". The third main reason was operator negligence.

Contact models

Felling and processing accounted for more than 90 % of contacts, and are the most important work phases in contact modelling. The contact model for the work cycle is presented in Table 4.

Operator, size of tree being processed and the number of trees on the work zone were the factors explaining the occurrence of contacts. The probability (p) of a contact can be calculated as follows [9]:

$$p = \frac{e^{\log it(p)}}{1 + e^{\log it(p)}}$$, where e = 2.718.

Damage models

The damage model is presented in Table 5. Size of tree causing the contact explained the most damage occurrence. The harvesting season also affected damage. During the summer, the odds for damage occurrence was 1.7 times greater than in other seasons. For each 100 dm^3 increase in the size of tree causing the contact raises, the odds for damage grow 19%.

DISCUSSION

One of the main problems in forest work study is the great influence of an operator on both machine productivity and on the silvicultural result of harvesting. There are several ways to describe the operator. Test series for measuring the physical and psychological properties of workers have been used in forest work study in Finland [7]. Machine entrepreneurs are working in practical work with expensive machinery and their willingness to participate in this kind of testing is often low. The method also demands the participation of a large number of operators in order to establish relationships between work results and human characteristics. The high costs of field tests limit the number of operators that can be tested.

If the operators cannot be classified with test series, productivity and working practices provide a practical way of describing machine operators. Productivity was the way to describe machine operators in this study. The working condition around every single tree was carefully measured to determine the relationships between machine productivity and work conditions along with tree damage.

Many studies [3, 5, 14] have demonstrated that branch mats have reduced soil damage. The effect of processing side on the effective time consumption for trees taken from outside the strip road was small. In stands with poor bearing capacity it is useful to process trees over the strip road.

The considerable influence of the machine operator on both the productivity and harvesting quality, and the large variation between machine operators can be regarded as the main results of the study. High productivity and good silvicultural result were found to be highly correlated. The average damage percentage, 3.4%, is acceptable. However, the average percentage varied from 1.4 to 6.6 with different operators.

The study showed the great influence of season on damage occurrence. The damage model predicts a 1.7-fold odds on damage occurrence in the summertime compared with other seasons. The power needed to loosen

Table 4. Predictive model for contact (1) and no contact (0) in the work cycle. Base level, operator D.

$$\text{logit}(p) = a + bx_1 + cx_2 + d_1k_1 + d_2k_2 + d_3k_3$$

where

x_1 = size of processed tree, dm³.

x_2 = number of trees, N/ha on the work zone.

k_1 = dummy variable, =1, if operator = A, otherwise 0.

k_2 = dummy variable, =1, if operator = B, otherwise 0.

k_3 = dummy variable, =1, if operator = C, otherwise 0.

a = constant

b, c,…,d_3 = parameter estimates

Observations	Distribution of response variable	N
7973	1	1548
	0	6425

Parameter	Parameter estimate	Std. error	Wald Chi-square	Pr>Chi- square	Odds ratio
a	-2.921	0.0997	858.475	0.0001	
b	0.003	0.0002	259.250	0.0001	1.003
c	0.001	0.0001	112.645	0.0001	1.001
d_1	-0.008	0.0882	0.007	0.9313	0.992
d_2	0.615	0.0692	79.021	0.0001	1.850
d_3	0.495	0.1267	15.246	0.0001	1.640

Goodness of fit

Deviance	Df	p-value
4548.3	4331	0.0106

Table 5. Predictive model for damage (1) and no damage (0) following contact. Base level other season but summer.

$$\text{logit}(p) = a + bx_1 + cv_1$$

where

x_1 = size of tree being processed, dm³.

v_1 = dummy variable, = 1, if season = summer, otherwise 0.

a = constant

b, c = parameter estimates

Observations	Distribution of response variable	N
1049	1	285
	0	764

Parameter	Parameter estimate	Std. error	Wald Chi-square	Pr>Chi- square	Odds ratio
a	-1.496	0.1242	145.154	0.0001	
b	0.002	0.0004	21.236	0.0001	1.002
c	0.562	0.1617	12.072	0.0005	1.754

Goodness of fit

Deviance	Df	p-value
196.6	149	0.0055

root bark of pine and spruce was 40 N/cm^2 in the summer and 60 - 80 N/cm^2 in the autumn [23]. These study results support each other.

Most tree damage inventories are made post-harvest. However, there have been some studies before this present study using a monitoring approach. Tree damage in loading forwarder was studied in Sweden for example, where the frequency of contacts with standing trees was related to the number of trees on the work area. Almost 80% of the contacts occured during loading. Of 195 contacts recorded in the study 16% resulted in damage [16].

Contacts and damage in thinning of a dense first thinning spruce stand with small 7 - 8 tonne one- and two-grip harvesters were studied in Finland [21]. Stem size of removed trees was 60 dm^3. The share of work cycles resulting in contact was 13.8% with the two-grip harvester and 1.1 % with the one-grip harvester. A total of 74 contacts were recorded, 42% of which resulted in damage. Harvesting was done in wintertime. “Trees being processed” and “machine crane” caused most of the contacts. The smaller size of removed trees may explain the difference in the number of contacts compared with the present study.

In thinning with a farm tractor-based one-grip harvester, two thirds of the damage was caused during felling and processing. More than 90% of damage was superficial, and 65% of the damage was smaller than 50 cm^2 in extent [1].

In post-harvest inventories the information on reasons for and causes of damage are estimates. In one-grip harvester operations, 90% of damage was estimated to occur in processing and less than 10% in felling [6]. In the present study more than 60% of damage was incurred during felling of trees. However, the line between felling and processing is vague.

The contact and damage models of the study were formulated using logistic regression. Use of logistic regression models in forest work science studies in Finland has been small. However, in forest economics research, logistic models are widely used [10, 12, 18, 20].

In North-America, damage frequency after mechanized harvesting is often high. In that case it is often reasonable to predict damage probabilities for single trees. Logistic regression models for predicting damage have been widely used [2, 4, 15, 17]. The modelled methods have been different tree-length harvesting methods.

In thinning of hardwood stands with a feller-buncher and grapple skidder, the predictors for damage occurrence were treatment, distance from tree to the skid trail, tree species and diameter [17]. The smallest probability for damage was with small trees far away from skid trails.

A damage model operating in conjunction with an interactive machine simulation program that can model harvesting performance was developed in North-America [2]. The damage probability for a single tree was explained by harvesting method and treatment, initial stand basal area, tree species, diameter and distance from skid trail. That damage model has a similar structure to the model presented in this study. However, that model [2], as well as other damage models presented in North-America, are based on post-harvest damage inventories. Also the damage patterns for tree length harvesting methods differs a lot from that of one-grip harvester operations.

The damage model presented in this study is based on real time monitoring of the damage process, and the model gives information on the influence of harvesting season on level of damage. The main problem in damage model estimation is the large variation between operators and even between stands harvested by the same operator. However, the mean damage level found in this study is near to the level found in large-scale routine inventories in Finland. The model can be used for estimating damage after different treatments and for clarifying the effect of harvesting season on damage occurrence. Together with the calculation model for estimating the economic consequences of damage [11] and combined with direct harvesting costs, the tree damage model can be used for calculation of total economy of different harvesting methods.

Due to the high variation in the harvesting quality, both the continuing supervision of the silvicultural thinning result and the training of machine operators are absolutely necessary. Thinning spruce stands when sap is flowing is inadvisable due to the high risk of tree damage, and decay following damage. Generally it is possible to obtain a good silvicultural thinning result with one-grip harvester operation.

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