Bulletin of the *Transilvania* University of Braşov • Vol. 3 (52) - 2010
Series II: Forestry • Wood Industry • Agricultural Food Engineering

ESTIMATING THE LEVEL OF TREES DAMAGES AND FINANCIAL LOSSES BY LOGGING

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Abstract: *The presented results paper can be divided into two groups - the number of injuries according to the affected tree sections (root, buttress, trunk), and according to size intervals (in cm*^{2}*). A survey of injuries after harvester's work was carried out for the age classes 3 (41-60 ys), 4 (61-80 ys) and 5 (81-100 ys). In age class 3-1.50% of the trees left in the stand were damaged, i.e. 19.3 trees/ha. In age class 4, the percentage of injured trees increased by 0.83% up to 2.38% (23.7 trees/ha) and in age class 5 to 2.25% (13.0 trees/ha). Without taking the age classes into consideration, the root buttresses were damaged to the highest degree (18.9 injuries/ha). The damage of the root system amounted to 9.0 injuries/ha.*

Key words: *harvester technology, stand damage, logging.*

1. Introduction

The production costs of logging and hauling activities are constantly growing. To lower these costs, which is a top priority, new technologies are demanded or the existing ones are modified. Cost cutting is considered by most foresters to be the main task. But most of them do not realise that the injuries to trees caused by logging and hauling operations mean a much more expensive problem in future than the present decrease in costs. Due to these injuries trees are threatened by fungous infections. The extent of this threat depends on the size and position of the injuries as well as on the given tree species. The injuries also negatively affect the increment of certain trees.

Damage to tree species and regeneration are among the most stressed drawbacks related to logging and hauling activities in forest management, i.e. in our experimental measurements focusing on the deployment of harvester technologies. Despite the fact that the extent of damage caused to forest stands in the course of deploying harvesters and forwarders is lowest when compared with traditional technologies, we cannot achieve work results with zero damage [4], [11]. Analyses of damage to forest stands have been conducted since the early 1990s [4], [5], [9].

Technological conditions and factors for detailed analyses based on the number code elaborated in co-operation with MZLU

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in Brno was an integral part of the realised experimental examination [3].

Conducted studies fail to provide financial quantification of secondary damage to trees which may be incurred in the course of time due to spreading decay in the injured tree, due to decreased increment and other factors. Such financial quantification is therefore empirically assessed as part of this study.

2. Materials and Methods

The main objective was to analyse the damage caused by the deployed harvester technology, Timberjack 1070 and Timberjack 810B forwarder (see parameters in Table 1) in the Kraslice Forest Management Unit. This study was carried out under the research project "Renewal of the Ecosystem of the Ore Mountains". The results of the analysis show the extent of the tree damage in stands where this technology is used. During collecting the data, the age class of the trees, the injured tree section, and the reasons for the injuries, such as felling, handling the felled trees, storing the timber assortments onto skidding lines, their loading, and last but not least, the influence of other forestry mechanisation used in the area of logging and hauling activities, were taken into consideration. Important, and also taken into consideration, was the number of injuries of different sizes.

Technical parameters Table 1

Selected parameters	Timberjack 1070	Timberjack 810B
Weight [kg]	13800	19000
Length [mm]	6600	7960
Width [mm]	2780	2520
Height [mm]	3620	3720
Clearance [mm]	575	595
Power [kW]	123 kW/2200 [rpm.]	80.5 kW/2400 [rpm.]
Front tire	700 x 22.5	600 x 22.5
Rear tire	600 x 30.5	600 x 22.5
Speed [km]	0 -25	0 - 25
Crane radius [mm]	10000	6500

It was intended to show that the damage rate caused by harvester technologies is not too high. The use of these technologies in logging is increasing along with the tendency to reduce production costs, especially labour costs. The long developing trend of harvester technologies, as was shown by independent researches, could, when properly used, decrease the impact on the forest ecosystem; it means no exposure to wood-destroying fungi and therefore no destabilisation of growth due to these fungi. Thus the damage is minimized, the number of trees affected by decay is kept at minimum, and the quality of wood is not lowered.

A mathematical-statistical analysis was used to assess the damage in the whole area investigated. It can be assumed that the highest rate of damage can be found directly on the skidding lines where the machines (harvester and forwarder) move. Therefore the damage was recorded and measured alongside the whole lengths of the skidding lines. But also all other types of damage in the operating area were recorded at the same time. All tree injuries were divided by tree sections (roots, buttress, stem), as well as by size intervals: 0-10 cm^2, 11-50 cm^2, 51-200 cm^2, 201-500 cm^2, and 501-1000 cm^2. A registration of other natural, technical and technological conditions and factors for detailed analyses based on the number code elaborated in co-operation with MZLU in Brno was an integral part of the realised experimental examination [3].

Conducted studies fail to provide financial quantification of secondary damage to trees which may be incurred in the course of time due to spreading decay in the injured tree, due to decreased increment and other factors. Such financial quantification is therefore empirically assessed as part of this study.

3. Results and Discussion

3.1. Quantification of Damage to Trees

The results presented in this paper can be divided into two groups:

1. The number of injuries according to the affected tree sections (root, buttress, trunk), and according to size intervals (in cm^2).
2. The number of injured trees (Tables 2, 3, and 4).

Number and percentage of injuries - age class 3 Table 2

Size interval	**Tree section**						**Number of injuries**	**Per-cent of injuries**
[cm^2]	Root		Buttress		Trunk			
	[No./ha]	[%]	[No./ha]	[%]	[No./ha]	[%]	[No./ha]	[%]
0-10	0.5	1.9	0.1	0.4	0.5	1.9	1.1	4.2
11-50	2.3	8.8	1.6	6.1	0.9	3.4	4.8	18.3
51-200	4.4	16.8	5.0	19.1	1.1	4.2	10.5	40.1
201-500	1.6	6.1	4.1	15.6	0.3	1.1	6.0	22.9
501-1000	0.3	1.1	3.2	12.2	0.3	1.1	3.8	14.5
Total	9.1	34.7	14.0	53.4	3.0	11.8	26.2	100
Number of injured trees				Percent of injured trees				
[trees/ha]				[%]				
19.3				1.50				

Number and percentage of injuries - age class 4 Table 3

Size interval	**Tree section**						**Number of injuries**	**Per-cent of injuries**
[cm^2]	Root		Buttress		Trunk			
	[No./ha]	[%]	[No./ha]	[%]	[No./ha]	[%]	[No./ha)]	[%]
0-10	0	0	0.2	0.6	0.3	1.0	0.5	1.6
11-50	2.8	9.0	2.7	8.7	1.0	3.2	6.5	20.8
51-200	5.4	17.3	7.4	23.7	1.0	3.2	13.8	44.2
201-500	1.3	4.2	5.6	17.9	0.6	1.9	7.5	24.0
501-1000	0.1	0.3	2.4	7.7	0.4	1.3	2.9	9.3
Total	9.6	30.8	18.3	58.7	3.3	10.6	31.2	100
Number of injured trees				Percent of injured trees				
[trees/ha]				[%]				
23.7				2.38				

A survey of injuries after harvester's work was carried out for age classes 3, 4 and 5. Even though it was not possible to verify a zero hypothesis for a single age class (Table 5), due to an insufficient number of measurements (44 stands), some differences were found. Harvester technologies using Timberjack 1070 and Timberjack 810B injured in a single age class from 1.50% to 2.38% of the trees left in the stands. In age class 3, 1.50% of the trees left in the stand were damaged, i.e. 19.3 trees/ha. In age class 4, the percentage of injured trees increased by 0.83% up to 2.38% (23.7 trees/ha) and in age class 5 to 2.25% (13.0 trees/ha). The lowest percentage of injured trees in age class 3 was due to not too well developed buttresses. The buttresses of trees in age class 4 were more often injured by machines travelling along the skidding lines, by ground skidding, or by wrong piling of logs against or between trees on skidding lines. Trees were injured by the hydraulic jib of a forwarder.

In the case of age class 3, trunks of trees were less often injured thanks to protection provided by branches situated lower on the trunk. The extent of injuries in age class 5 compared with that of age class 4 decreased due to a greater spacing of trees and a thicker bark.

Number and percentage of injuries - age class 5 Table 4

Size interval	**Tree section**						**Number of injuries**	**Per-cent of injuries**
[cm^2]	Root		Buttress		Trunk			
	[No./ha]	[%]	[No./ha]	[%]	[No./ha]	[%]	[No./ha)]	[%]
0-10	0	0	0.1	0.6	0.2	1.2	0.3	1.8
11-50	0.5	3.1	1.2	7.4	1.5	9.2	3.2	19.9
51-200	1.1	6.7	4.2	25.8	1.8	11.0	7.1	43.6
201-500	0.8	4.9	2.7	16.6	0.5	3.1	4.0	24.5
501-1000	0.1	0.6	1.3	8.0	0.3	1.8	1.7	10.4
Total	2.5	15.3	9.5	58.3	4.3	26.4	16.3	100
Number of injured trees			Percent of injured trees					
[trees/ha]			[%]					
13.0			2.25					

Table 5

Scattering analysis of damaged trees and bark injuries on 1 ha regardless of age class

Source	**Sum of squares**	**Degrees of freedom**	**Mean square**	***F*-ratio**	***p*-value**
Scattering analysis of damaged trees					
Age class	159.38	2	79.69	0.1685	0.8455
Within groups	19391.3	41	472.96		
Total	19550.7	43	-	-	-
Scattering analysis of injuries					
Age class	631.94	2	315.97	0.3635	0.6978
Within groups	35632.0	41	869.22		
Total	36269.9	43	-	-	-

The total number of injuries was higher than the number of injured trees. The ratio between the number of injured trees and the total number of injuries amounted to 75.6%, 81.0% and 85.4% in age classes 3, 4 and 5 respectively. This was because there were two or more injuries per tree. The number of injuries per tree increased with the increase of stand density. The risk of decay rises with the number of injuries, which leads to secondary commercial losses. The injuries were recorded in accordance to their distribution in the respective tree sections:

- root up to a distance of 1 m from the tree,
- buttress,
- trunk, regardless of the injury position.

It is not possible to specify the tree sections with specific units because their metrical span is changing within age, natural conditions and the species. Therefore the damage was assessed specifically for each injured tree.

Injuries in tree sections can not be regarded from a quantitative point of view. There is a different degree of risk of fungous infection followed by spreading of decay throughout a tree, depending on the place of injury (root, buttress or stem).

Considerable differences between respective tree sections with respect to the number of injuries are evident in 1. These differences were validated by the scattering analysis - the hypothesis of mean value equality was generated with high reliability (Table 6). A detailed assessment of the differences between the sections was proved by Scheffe's method for multiple comparing (Table 7). Differences between roots and buttresses, and between trunks and buttresses were statistically significant (at the significance level 0.05). On the contrary, no significant difference was found between roots and trunks.

Without taking the age classes into consideration, root buttresses were damaged to the highest degree (18.9 injuries/ha). The damage of the root system amounted to 9.0 injuries/ha. The lowest number of injuries was found on the trunks - they amounted to 5.8 injuries/ha. The number of trunk injuries may be limited by minimizing the interaction between a machine and a tree. This goal is reached when the width of the skidding lines is between 3.5 and 4 m [10] and there are few obstacles on the skidding line. Obstacles increase the risk of skewing the machine and damaging the trunk by uprights, cabs or other components. Another danger for trunk injury is a non-guided way of downfall in case of the operator's lack of experience or whencutting

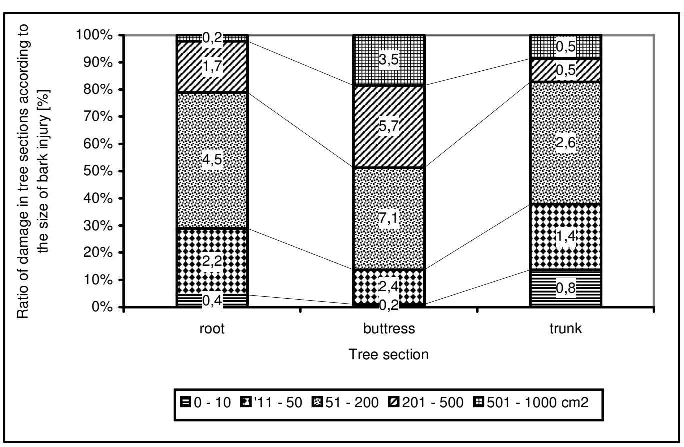

Fig. 1. *Ratio of damage in tree sections according to the size of bark injury*

Scattering analysis of injuries in different tree parts Table 6

Source	Sum of squares	Degrees of freedom	Mean square	*F*-ratio	*p*-value
Tree section	4060.42	2	2030.21	11.82	0.00002
Within groups	22162.94	129	171.81		
Total	26223.36	131	-	-	-

Multiple comparing of injuries in tree sections Table 7

Section	Count	Mean	Homogeneous group
Trunk	44	5.91	x
Root		8.95	x
Buttress		18.89	x

overgrown trees which cannot be transferred by a logging head.

The last analysis concerned five intervals specifying the area of injury: 0-10 cm^2, 11-50 cm^2, 51-200 cm^2, 201-500 cm^2, and 501-1000 cm^2. The hypothesis of equality of mean values of the number of injuries in individual intervals (Table 8) was verified. Then the differences between all interval pairs were assessed with Scheffe's method for multiple comparing (Table 9) at the significance level 0.05.

In the case of the root sections, the smallest number of injuries occurred in the interval group 501-1000 cm^2, 0-10 cm^2, 201-500 cm^2, and 11-50 cm^2. The differences between these intervals were statistically indistinguishable (they formed a so called homogenous group). On the other hand, the injury rate in the interval 51-200 cm^2 was significantly higher than in the remaining intervals.

In the case of the buttress sections, the smallest number of injuries occurred in the interval group 0-10 cm^2 and 11-50 cm^2, and the greatest number in the interval groups 201-500 cm^2 and 51-200 cm^2. *In the case of the trunk sections,* the smallest number of injuries occurred in the interval groups 201-500 cm^2, 501-1000 cm^2, 0-10 cm^2 and 11-50 cm^2, and the greatest in the interval 51-200 cm^2.

Table 8

Scattering analysis of the damages according to injury size within the tree part

Source	Sum of squares	Degrees of freedom	Mean square	*F*-ratio	*p*-value
Scattering analysis of root injuries					
Size interval	541.32	4	135.33	13.30	0
Within groups	2187.35	215	10.17		
Total	2728.67	219	-	-	-
Scattering analysis of buttress injuries					
Size interval	1316.64	4	329.15	13.11	0
Within groups	5399.67	215	25.11		
Total	6716.31	219	-	-	-
Scattering analysis of trunk injuries					
Size interval	136.55	4	34.13	6.22	0.0001
Within groups	1180.52	215	5.49		
Total	1317.07	219	-	-	-

Multiple comparing of injuries of different size Table 9

S.	Interval [cm^2]	Count	Mean	Homogeneous group
Root	501-1000	44	0.19	x
	0-10		0.38	x
	201-500		1.65	x
	11-50		2.18	x
	51-200		4.54	x
Buttress	0-10	44	0.16	x
	11-50		2.42	xx
	501-1000		3.50	x
	201-500		5.68	xx
	51-200		7.13	x
Trunk	201-500	44	0.53	x
	501-1000		0.55	x
	0-10		0.80	x
	11-50		1.40	xx
	51-200		2.62	x

The injury ratio for respective tree sections is shown in Figure 1. The smallest injuries (up to 10 cm^2) were the least frequent ones. Their number amounted to 1.4/ha. Injuries of this size occurring on trees with thicker bark did not affect the wood fibre and were not regarded as injuries. The number of injuries 11-50 cm^2 in size was 6.0/ha (regardless the age class). The highest number, i.e. 14.2 injuries/ha, occurred in the group of injuries 51-200 cm^2 in size. In this case, the number of injuries was significantly higher, and the probability of fungal infection and decay was very high. The numbers of injuries for the size intervals 201-500 cm^2 and 501-1000 cm^2 were 7.9/ha and 4.3/ha respectively. Injuries in these two intervals may have been caused by an intensive overdrive over the same buttress or root not protected by slash.

Injuries of these sizes are not exceptional at the exits from the analysed areas or on the truck landing border. Injuries in these places are mainly due to hydraulic jibs or handling with cut-outs.

3.2. Empirical Assessment of Financial Losses on the Damaged Trees

Logging and hauling activities of any technology cause a certain degree of damage which is reflected in the production functions of the forest ecosystem and therefore in the financial aspect of forest management. In order to prevent these losses it is necessary to be aware of their extent and to take into consideration possible preventative or remedial measures which may ultimately be more costly than leaving the damage to its natural regeneration.

Financial losses incurred by damaged trees after the implemented logging may be calculated from the following relation (1):

$$Z_D = (Z_1 + Z_2) \cdot V_s . \left(1 + \frac{\Delta V_p}{V_s}\right) \cdot (1 + k_n) \cdot (1 - k_{vp}) \cdot k_h \cdot k_p \cdot c_D \cdot \left(1 - \frac{c_p}{c_D}\right) \text{ [CZK/ha]},$$

Z_1 - number of injuries on the existing trees caused by felling and processing the trees (units/ha);

Z_2 - number of injuries in the existing trees caused by hauling timber (units/ha);

V_s - mean volume of the existing forest stand (m^3/tree);

ΔV_p - difference between the expected mean volume at time of the following harvesting measure and the present mean volume, i.e. $\Delta V_p = V_p - V_s$;

V_p - expected mean volume in time of the following measure, see Figure 1 (m^3/tree);

k_n - risk coefficient of possible fungal attack (–), $k_n \in \langle 0.1\text{-}1 \rangle$;

k_{vp} - coefficient of multiple damage to a tree, see Table 2 (–);

k_h - coefficient of qualitative loss upon fungal attack to the tree, see Table 3 (–);

k_p - coefficient of increment reduction (–), $k_p \in \langle 0.5\text{-}0.99 \rangle$;

c_D - mean financial yield from a healthy trunk (CZK/ m^3);

c_p - mean financial yield from a decay-infested trunk (CZK/ m^3).

• *Expected mean volume in period of the following harvesting measure* (V_p)

The value specification is based on yield tables which are part of the Regulation No. 84/1996 Coll. of the Ministry of Agriculture on Forestry Planning. The expected spruce volume is conditioned by the absolute yield class and the age of the given forest stand (Figure 2).

• *Risk coefficient of fungal attack to the trees* (k_n)

The coefficient is specified by the size of injury and the risk of possible infection. Grammel (1988) asserts the risk of infection attack from 0 to 44%, with respect to the size of the injury. According to Isomäki (1979) in Horek (1991), peeling of spruce bark exceeding 100 cm^2 represents 40% risk of red rot attack. Damage of 200 cm^2 which extends to wood itself represents 100% certainty of infection.

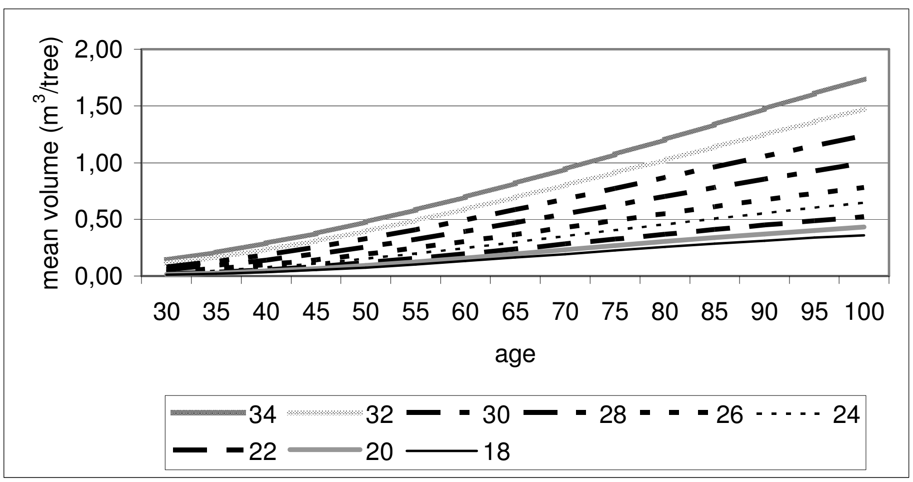

Fig. 2. *Expected mean volume (V_p) depending on age and site quality of stands*

• *Coefficient of multiple damage to the tree* (k_{vp})

The coefficient is defined by the number of injuries in a single tree. The higher number of injuries in a single tree increases the risk of its infection, while the damage to the stand as a whole decreases. The coefficient is specified on the basis of experimental measurements and it is defined for age classes in which middle-powered harvester technologies were deployed (Table 10).

Coefficient of multiple damage to tree (k_{vp}) Table 10

Age class	3	4	5
k_{vp}	0.1 – 0.4	0.1 – 0.3	0.1 – 0.2

• *Coefficient of qualitative loss upon fungal attack to the tree*

The wood quality of trees attacked by fungal infection is depreciated. The speed of fungal attack cannot be clearly defined. The coefficient specifies the speed of the fungal infection spreading through the wood. With respect to the speed of fungal spread, the coefficient value changes with time which elapsed since the harvesting measure in the course of which the tree was damaged (Table 11).

Coefficient of qualitative loss after the fungal attack (k_h) Table 11

Jogging cut period	1	2	3	4	5	6	7	8	9	10
k_h	0.01-0.08	0.02-0.15	0.04-0.26	0.06-0.29	0.07-0.35	0.10-0.41	0.11-0.47	0.12-0.53	0.13-0.58	0.15-0.63

• *Coefficient of increment reduction* (k_p)

The coefficient specifies the quantitative volume loss caused by the damage to the tree. The highest risk of increment reduction, up to 50%, is caused by amputation of the taproot by moving machinery. The coefficient does not encompass the risk of increment reduction caused by pressure of machinery exerted on the soil surface and thus on the tree‘s root system.

4. Conclusions

There is a series of logging and hauling technologies and their modifications for operational cutting. But none of them can be regarded as an ideal one that causes no damage to the forest stands. Not always can we opt for technologies which cause the least amount of damage because they may not be used under the given conditions because of excessive production costs or deficient technical background (vehicle fleet etc.). In spite of that there is a future perspective for harvester technologies, since this assortment method causes less damage than trunk methods, e.g. MP, horse, LKT which injure 22% of trees [11].

An analysis of possible technologies with goal-directed optimised logging and technological parameters or optimised technical parameters can be of remarkable significance in limiting the damage.

Reaching minimum damage in forest stands during the production process does not involve purely the selection of suitablemachinery and logging technologies but it is also necessary to follow the fundamental rules related to TDS engagement in the production process, i.e.:consistent structuring of stands, marking trees intended for cutting, observance of production techniques.

Economic production does not always agree with the ecological point of view. But it must be realised that direct decontamination labour costs, as well as future losses due to fungal infections decrease with an increased use of new harvester technologies.

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