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Effect of Day or Night and Cumulative Shift Time on the Frequency of Tree Damage during CTL Harvesting in Various Stand Conditions

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Abstract: Thinning is one of the most important tools of forest management, although thinning operations require the use of machines which ultimately cause damage to the remaining stand. The level of damage largely depends on the human factor, and a tired, less focused operator will create more injuries in the forest. With this in mind, the objectives of this research were to find out whether the probability of tree damage caused by an operator is also affected by: (1) the part of the day (dawn/day/dusk/night), and (2) the cumulative shift time. The research was carried out in pure pine stands of different ages, density and thinning intensities. Sample plots were selected that had an increasing number of trees per hectare and growing thinning intensities were applied. The same Komatsu 931.1 harvester was used for the thinning operations in each stand. In all the age classes combined, 5.41% of the remaining trees were wounded. There was a significant influence of the part of the day on the percentage of damaged trees, which was positively correlated with the cumulative shift time. Stand conditions, such as age class and stand density, as well as thinning characteristics—thinning intensity, number of harvested trees and productivity—have different effects on the distribution of damage intensity and on probability. The results may improve the planning of operators' work shifts in forests of various ages and densities, allowing harvester productivity to be maintained while at the same time inflicting the lowest possible level of damage.

Keywords: optimisation of thinning operation; day shift; night shift; twilight zone; ergonomics; Scots pine (*Pinus sylvestris* L.)

1. Introduction

Modern machines have changed forest operations in the last few decades, increasing productivity rates when compared to manual harvesting. In fact, in the last decade, cut-to-length (CTL) technology has replaced manual wood harvesting in many European countries [1]. This increase in the use of harvesting equipment has come about due to a shortage of labor and the need to lower the cost of wood production. Indeed, recent studies have shown a large reduction in the forestry workforce as a result of low wages [2], a poor professional image [3], strenuous working conditions [4,5], high accident rates [5], and a high prevalence of occupational illnesses [6]. On the other hand, the mechanization of forest operations can greatly increase labor productivity [7], thereby helping to satisfy, in a more efficient way, the growing worldwide demand for wood, wood products and energy from biomass [8].

The mechanization process has inevitably been followed by organizational changes. Mechanized harvesting operations are capital-demanding, with operations and maintenance costs exerting more pressure on forest entrepreneurs [9,10]. In order to reduce the impact of high equipment costs on a "per unit of production" basis, and to increase overall profits, some logging companies have implemented extended working hours [11,12]. It has also been observed that, nowadays, operators work more hours (10 h) and there are two shifts (2 × 10 h) instead of three (3 × 8 h shifts). The extension of working hours has been suggested as a means to achieve bigger profits, reduce equipment obsolescence and increase operational efficiency and competitiveness in the market [9,12]. Additional advantages of an extended, even 24 h, working time (split into shifts) include better control of the harvest cost in short periods [13], a reduction in transport costs and greater machine safety [14]. During autumn and winter, when the days are very short, harvester operators usually start working at dawn, completing their shifts at dusk or later in the night [15]. Additionally, due to shift extensions expanding to a darker time of the day, harvester and forwarder manufacturers have equipped machines with lights. However, working at night affects the sleep patterns of operators, leading to combined problems of circadian tiredness, weariness and a reduction in alertness as a result of work monotony [9]. Previous studies have tried to examine the effect of modified work schedules [9,11,12] and working at different times of the day [16] on operator productivity, as well as the economics of extended shifts and twenty-four seven harvesting [17].

Despite these organizational changes and the technological advances, damage to the remaining stand is a side effect of thinning operations in commercial forests and, in some cases, also in protected forests [18]. Tree damage can be inflicted during tree felling and skidding or forwarding. Individual damage may also occur during the transportation of wood from the forest. Damage to the remaining trees has a measurable and practical meaning since it can affect the growth of trees [19] and, eventually, worsen stem quality [20]. Healed wounds that are still present inside the tree adversely affect the mechanical properties of the wood [21], potentially lowering the future income derived from the timber. Previous studies have examined the impact of various factors such as the tree species, stand age, type of thinning and thinning intensity on the damage frequency, severity and wound location on the tree [22–26]. The relationship between the operator's experience and the level of tree damage was indicated by Sirén [27], where it was observed that operators with more experience create less damage. However, the same author [27] reported that the season of the year can have a larger impact on damage frequency than operator experience. In particular, more damaged trees with larger wounds were observed after logging in summer than in other months [28]. Other factors that affect the probability of tree damage include the strip road's configuration [29], the amount and extent of road curvature [30], and the distance between strip roads [31–34]. Increasing the distances between strip roads leads to a higher probability of tree damage [35], as does the length of tree assortments, with longer processed logs causing more damage [7,23,24,35–38].

Climate change is advancing and forest management practices are being adjusted in order to contribute to mitigation goals [8,39]. There is a general preference that wood harvesting with technologically advanced machinery takes place during the wintertime rather than the growing season due to the limited impact on the residual stand, in terms of soil compaction and rutting [40] and nutrient removal. At temperatures below or near freezing, the likelihood of both bark removal and damage frequency due to the operation of a nearby machine is lower [41]. However, in recent years, there has been growing concern regarding the possible ways in which climate change may impact the harvesting period [42]. Winters without frost, as well as a heavier rainfall in autumn, will inevitably affect forest operations in Central Europe by shortening the period in which mechanized operations can be carried out. This comes at a time of growing wood demand [43]. New investments in Finland, for instance, will increase the demand for pulpwood, placing greater importance on thinning as a mode of supplying pulpwood. However, the amount of tree damage in Finland has recently increased and tree damage at the roots and stem has emerged as the most significant single factor contributing to the deterioration of logging quality [44].

The objectives of the research were to find out if there is an impact from: (1) the type of shift (dawn/day/dusk/night), and (2) the cumulative shift time on the probability of tree damage in pure pine stands of different ages, density and thinning intensities. In this context, it was hypothesized that increasing time into the shift may affect the level of damage towards the end of the working period. Furthermore, it was hypothesized that working in the dark (at dusk, night or dawn) may cause a higher level of damage.

2. Materials and Methods

2.1. Study Area

Pure Scots pine (*Pinus sylvestris* L.) stands were selected for the study in Northwest Poland (E 15°50′–16°0′, N 53°10′–53°13′). All the stands were of a similar site quality index, and soil conditions were optimal for pine. The selected stands within the same age class (AC) had a growing number of trees. Silvicultural treatments were prescribed according to the current management plan (Table 1).

The sample plots were classified according to age class and tree density per hectare (DC). In total, 53 sample plots were selected: (1) AC3: 41–60 years old = 15 stands, (2) AC4: 61–80 years old = 18 stands, and (3) AC5: 81–100 years old = 20 stands. Furthermore, the sample plots were grouped into DCs according to the number of trees per hectare: (1) DCA included stands with less than 600 trees ha^{-1}, (2) DCB included stands ranging from 601 to 900 trees ha^{-1}, and (3) DCC had more than 901 trees ha^{-1}.

In each AC, sample plots were selected that had an increasing number of trees per hectare: 563–1603, 323–868 and 476–836 trees ha^{-1}, in AC3, AC4 and AC5, respectively. Moreover, in each AC, an increasing number of trees per hectare were selected for harvesting: 130–853, 80–315 and 108–282, in AC3, AC4 and AC5, respectively, with the relevant increasing thinning intensity: 35–84, 21–77 and 34–88 m^3 ha^{-1}.

Sample plots in the shape of a rectangle with an area of 0.3 ha (30 m × 100 m) were marked in the AC3 stands, with an area of 0.4 ha (40 m × 100 m) in the AC4 stands, and an area of 0.5 ha (50 m × 100 m) in the AC5 stands. Maintaining a constant width of 100 m in each sample plot allowed for the application of an identical arrangement of strip roads (they were different only in length). Bigger sample plots were selected in older stands (characterized by a lower number of trees) in order to have a similar number of trees available for thinning operations.

All the trees in the sample plots were assigned a number; this identification number was marked in paint on each tree. The diameter at breast height (dbh) of all the trees was measured using an electronic caliper with an accuracy of 0.1 cm.

Table 1. Stand and thinning characteristics.

AC3								AC4								AC5							
SP	Stand		Thinning					SP	Stand		Thinning					SP	Stand		Thinning				
	NT	DBH	ET	DT	TI	PR	PD		NT	DBH	ET	DT	TI	PR	PD		NT	DBH	ET	DT	TI	PR	PD
1	563	26	127	7	53	22	D	16	323	33	98	15	51	32	D	34	476	28	78	12	34	25	N
2	703	23	120	20	35	25	D	17	460	28	68	7	35	27	D	35	518	28	182	28	88	26	D
3	863	19	240	7	45	16	N	18	513	26	73	12	34	24	D	36	534	26	68	16	37	23	D
4	917	20	210	33	57	22	D	19	540	26	95	5	39	28	N	37	564	28	156	20	72	28	D
5	957	20	380	43	62	18	D	20	560	26	58	20	27	23	D	38	594	26	156	18	61	25	N
6	1043	20	323	70	38	16	ND	21	570	25	135	15	36	19	DN	39	594	27	142	26	56	23	N
7	1070	20	330	23	73	18	ND	22	593	25	110	17	38	18	N	40	596	27	172	30	65	26	D
8	1083	19	327	40	57	16	D	23	625	24	130	22	44	22	D	41	618	25	122	22	49	22	N
9	1097	20	380	37	53	15	D	24	660	21	130	10	26	18	D	42	632	24	156	52	55	23	D
10	1123	20	350	50	60	17	D	25	663	29	158	17	44	25	D	43	634	25	162	8	53	22	N
11	1153	19	380	67	72	17	DN	26	663	25	200	27	50	18	N	44	640	25	90	18	46	22	DN
12	1270	19	480	57	71	16	N	27	683	24	215	37	55	23	N	45	644	26	138	38	57	18	D
13	1297	17	457	43	66	15	D	28	695	26	195	15	65	26	D	46	648	26	190	34	67	23	D
14	1403	18	447	80	64	15	N	29	708	24	270	42	27	26	D	47	674	22	160	40	77	24	D
15	1603	15	557	67	55	12	D	30	708	21	165	20	77	17	D	48	682	25	188	32	59	24	N
								31	748	24	300	27	78	24	ND	49	708	22	224	18	47	19	D
								32	768	24	245	27	61	21	N	50	720	22	164	28	57	22	D
								33	868	22	278	42	56	20	D	51	756	22	202	42	68	19	ND
																52	758	24	136	28	50	21	DN
																53	836	24	220	52	53	19	D

AC: age class; SP: sample plot number; NT: number of trees before thinning [n ha^{-1}]; DBH: average diameter at breast height [cm]; ET: number of extracted trees [n ha^{-1}]; DT: number of damaged trees [n ha^{-1}]; TI: thinning intensity [m^3 ha^{-1}]; PR: productivity rate [m^3 h^{-1}]; PD: part of the day (ND—dawn, D—day, DN—dusk, N—night).

2.2. Characteristics of the Forest Operation

The thinning operations on all of the sample plots were carried out within 15 days from late November to early December. The length of the day (from dawn to dusk) in the specific latitude decreased from 8 h and 14 min to 7 h and 45 min during the study period. The thinning operations were carried out during the daytime (without artificial lighting provided by the harvester) and at night (with lighting), and during the transitional periods of dawn and dusk (with or without lighting) described in the ergonomic literature as twilight zones [45,46]. The two operators worked on randomly selected sample plots. They were aged 39 and 44, both with 7 years' experience. A Komatsu 931.1 harvester with a powerful 193 kW (stroke volume: 7.4 l) engine was used for the thinning operations. The machine was equipped with a CRH 22 boom, with a reach of 9.8 m, and a Komatsu 365 head. When necessary, sufficient artificial machine light was used: according to the manufacturer, the machine was equipped with more than 30 lux in the entire work area and at least 30 lux at the head.

The same pattern of strip roads was followed in all the sample plots, with a maximum width of up to 4 m and a distance between them of 20 m (from axis to axis). On all the sample plots, the same types of assortments were harvested: 2.85, 2.50 and 2.45 m; long saw logs, pulp wood and industrial wood, respectively.

2.3. Measurement of Damage

After the thinning operations, all of the remaining trees were inspected according to the method described by Meng [47]. All of the trees identified as having any damage were marked with green paint (to avoid being counted twice). Only damage to the phloem or wood fibers was taken into account. In the case of bark damage (without exposing the phloem surface), it was assumed that it fulfilled its protective function by preventing exposure of the phloem, therefore it was not taken as a wound. As the focus of the research was the frequency of tree damage, all the analyzed trees in each sample plot were assigned to one of two basic groups: trees with damage (possibly with multiple wounds), and trees without damage. However, in the case of two or more wounds on one tree, this was still recorded as one tree with damage.

2.4. Statistical Analysis

The analysis of covariance (ANCOVA) provided during the formulation of a linear regression model was performed in order to examine the effect of the experimental variables on the frequency of damaged trees. The normal distribution of the data was checked using the Shapiro–Wilk test [48], while the homogeneity of variances was verified using Levene's test. Pearson's correlation was also determined in order to measure the dependence of the characteristics.

The chosen dependent variable (occurrence of a damaged tree) had a binomial character (1 = yes, 2 = no) that could fit better to nonlinear regression models [49]. The correlation and interaction plots were used to identify the most important interactions [50] which were later included in the model. To reduce the number of the estimated parameters of the model, the backward stepwise procedure was performed in which the Akaike Information Criterion (AIC) was applied [36,51]. Out of the set of candidate models, the one with the lowest AIC was chosen. Analysis of the data sets was provided using the logistic model, which has also been applied in other studies [49,52,53]. The fixed simple logistic model can be written as:

$$\eta = \text{logit}P = \log\frac{P}{1-P} = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_n x_n \tag{1}$$

where P denotes the probability of damaging a tree, β_0 denotes the border (threshold) between two categories (0-category: damaged tree; 1-category: not damaged tree), $\beta_1, \beta_2, \ldots, \beta_n$ are unknown regression parameters and $x_1, x_2, \ldots, x_n$ are the known covariates. On the right side of Equation (1), the chosen interactions from $\beta_{kl} x_k x_l$ (k, p chosen from $1, \ldots, n$) were added. To estimate the significance of the parameters included in the model, an analysis of deviance was carried out using the Wald test. Additionally, the Z test was used to estimate the significance of the nonlinear regression coefficient. Finally, P was calculated from model (1), which, after transformation, is expressed as Equation (2):

$$P = \frac{exp(\text{logit}P)}{1 + exp(\text{logit}P)} \tag{2}$$

where P is between 0 and 1. Statistical inference was performed at a significance level of $\alpha = 0.05$. R software ver. 3.6.3 and R packages stats, ordinal and ggplot2 were used for the calculations [54].

3. Results

During the study, a total of 15,794 trees were examined. During thinning, 4254 trees were cut and 625 of the remaining trees were damaged. Throughout the whole experiment, 1816 m^3 of merchantable timber (without bark) was harvested. Harvesting was carried out by two operators who, after thinning, generated a similar level of damage: 6.24% by operator A and 4.62% by operator B (Table 2).

Table 2. Frequency of damaged trees with respect to operator.

				Frequency of Damaged Trees (%)				
					Interval for Mean			
Operators	**N**	**Mean**	**Std. Deviation**	**Std. Error**	**Lower Bound**	**Upper Bound**	**Minimum**	**Maximum**
A	22	6.24	2.45	0.52	5.15	7.32	1.60	10.92
B	31	4.62	2.15	0.39	3.38	5.65	1.12	8.37

3.1. The Impact of Age Classes

In all the stands (all age classes), on average, 5.41% of the remaining trees were wounded (Table 3). The highest damage frequency was found in AC5 (5.77%), followed by AC3 (5.59%) and AC4 (4.51%), although these differences were not statistically significant ($F = 2.039$, $df = 2$, $p = 0.1360$).

Table 3. Frequency of damaged trees with respect to age class (AC).

				Frequency of Damaged Trees (%)				
					Interval for Mean			
Age Class	**N**	**Mean**	**Std. Deviation**	**Std. Error**	**Lower Bound**	**Upper Bound**	**Minimum**	**Maximum**
AC3	15	5.59	2.53	0.65	4.18	6.99	1.12	9.72
AC4	18	4.51	2.29	0.53	3.38	5.65	1.12	9.59
AC5	20	5.77	2.33	0.52	4.68	6.86	1.69	10.92
Total	53	5.29	2.40	0.32	4.63	5.95	1.12	10.92

The dependent variable (percentage of damaged trees) fulfilled the normality criterion ($p = 0.6361$) and both classification variables, AC ($p = 0.0934$) and DC ($p = 0.0861$), fulfilled the homogeneity of variances criterion.

The ANCOVA results were used to present the regression lines with their confidence intervals in the graphs (Figures 1 and 2). The mean frequency of damaged trees (black curves) is positively correlated with the cumulative shift time (Figure 1a), thinning intensity (TI (Figure 1c)) and the number of harvested trees (Figure 1d). The reverse trend can be observed only in the case of productivity (Figure 1b). However, this trend is not statistically significant ($p = 0.2698$) in contrast to TI ($p = 0.0003$) and the number of harvested trees ($p = 0.0004$).

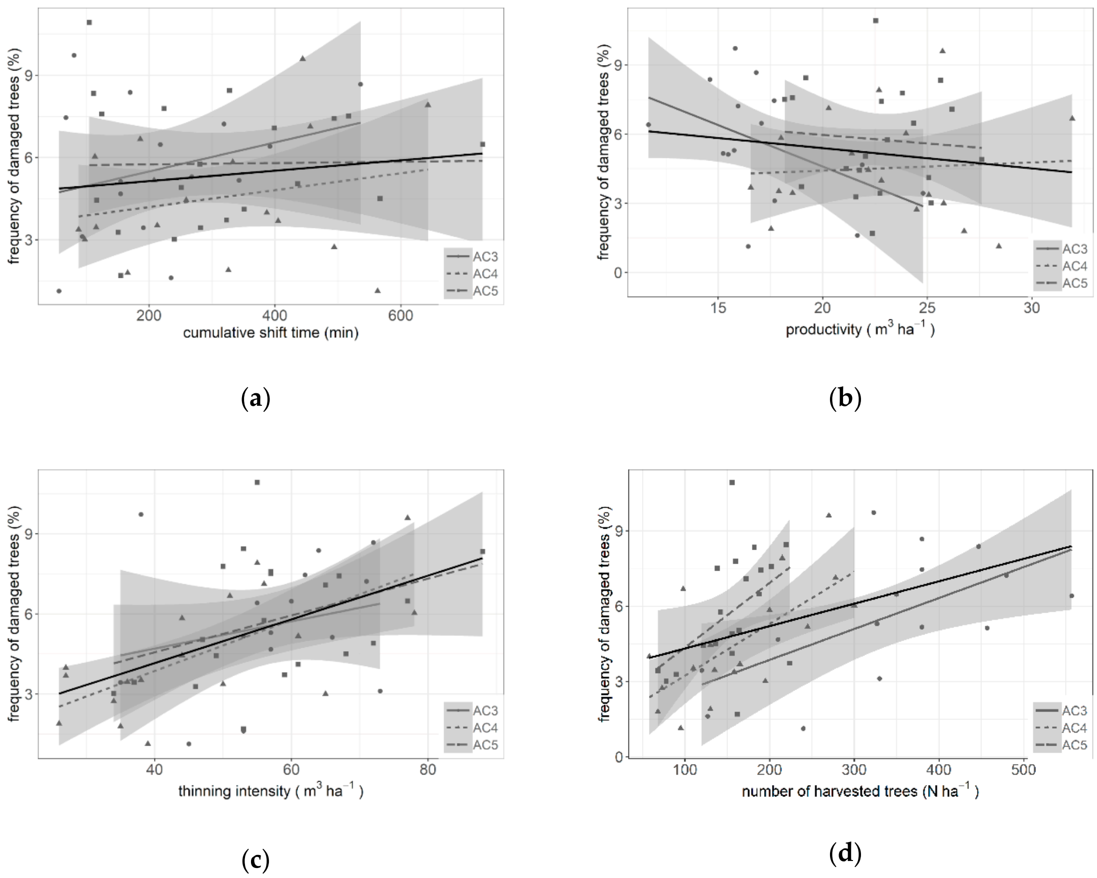

Figure 1. Frequency of damaged trees in age classes (AC) as a function of: (**a**) cumulative shift time; (**b**) productivity; (**c**) number of harvested trees; (**d**) number of extracted trees. Black curves represent mean values for all cases.

3.2. The Impact of Density Classes

In contrast to the AC, the damaged tree frequency was highest in DCC (6.47%), followed by DCB (5.44%) and DCC (4.10% (Table 4)). These differences were statistically significant (F = 3.935, df = 2, p = 0.026).

Table 4. Descriptive statistics for the frequency of damaged trees in density classes (DCs).

		Frequency of Damaged Trees (%)						
					Interval for Mean			
Stand	**N**	**Mean**	**Std. Deviation**	**Std. Error**	**Lower Bound**	**Upper Bound**	**Minimum**	**Maximum**
DCA	15	4.10	2.09	0.54	2.94	5.26	1.12	8.33
DCB	26	5.44	2.51	0.49	4.42	6.45	1.12	10.92
DCC	12	6.47	1.91	0.55	5.26	7.68	3.11	9.72
Total	53	5.29	2.40	0.33	4.63	5.95	1.12	10.92

The mean frequency of damaged trees (black curves) in the DC were distributed with the same tendency as in the AC. In particular, the frequency of damage was positively correlated with the cumulative shift time (Figure 2a), TI (Figure 2c) and the number of harvested trees (Figure 2d), and negatively correlated in the case of productivity (Figure 2b). A significant positive dependence was observed for the number of harvested trees (Figure 2d, p = 0.0010) and TI (Figure 2c, p = 0.0001).

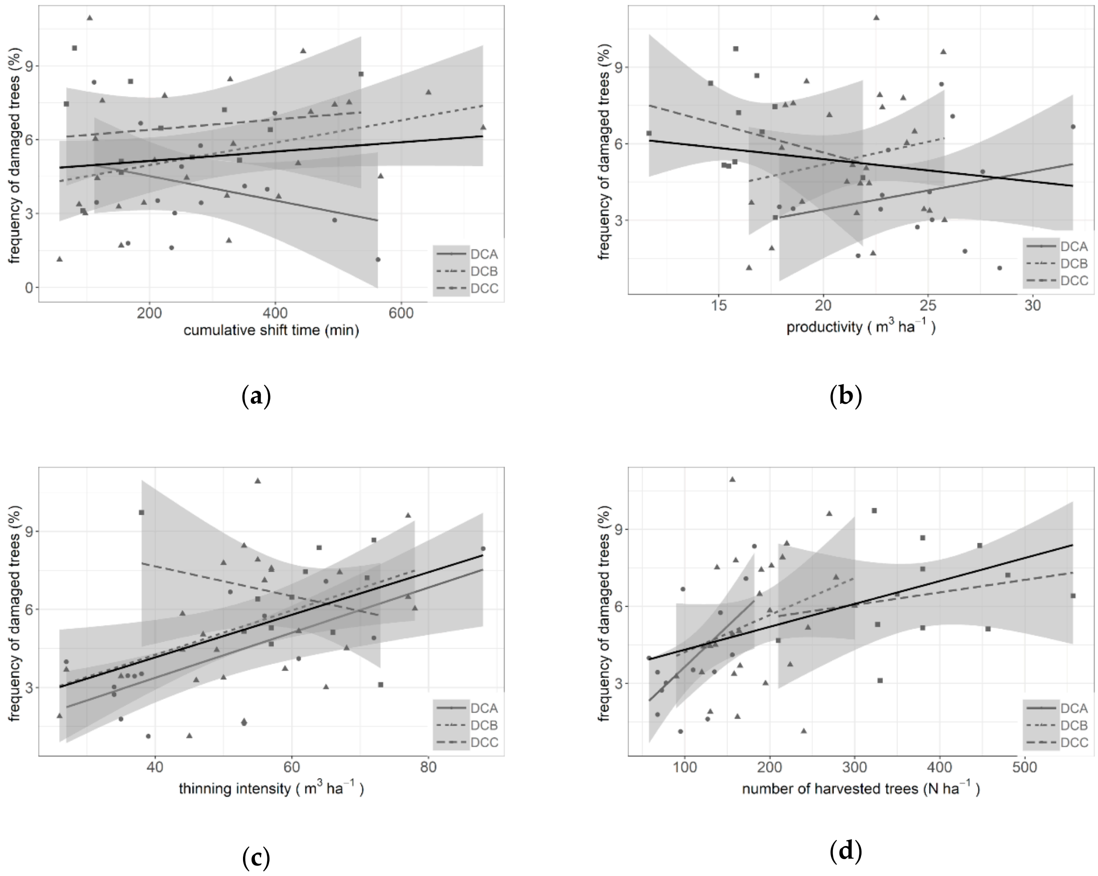

Figure 2. Percentage of damaged trees in density classes (DC) as a function of: (**a**) cumulative shift time; (**b**) productivity; (**c**) number of harvested trees; (**d**) number of extracted trees. Black curves represent mean values for all data.

3.3. Model Development

A stepwise logistic method was used to fit predictive variables in the model. The optimization of the combination of parameters (characterizing the stands and thinning) was carried out using a backward stepwise logistic regression method. However, both the TI and productivity rate were excluded from the model fitting as they did not meet the AIC criterion. The significance of the selected parameters was then verified using the analysis of deviance.

Some parameters, such as the cumulative shift time, part of the day, AC, DC, operator and percentage of harvested trees, were found to have a significant influence on the percentage of damaged trees (Table 5). This was also valid for interactions such as the type of shift × AC, and part of the day × productivity rate. In contrast, the interactions: operator × cumulative shift time, and part of the day × DC were not found to be statistically significant. The operators differed statistically in terms of the damage inflicted, thus the operator variable was considered as fitting in the model (Table 5).

An interaction with statistical significance between part of the day × AC was recorded (Table 5). Based on the model (1), estimators of the probability of tree damage depending on the part of the day in a given AC were obtained (Table 5).

The highest tree damage probabilities at dawn and during the day were in AC5, amounting to 0.0758 and 0.0679, respectively. This trend changed at dusk and during the night where the highest tree damage probabilities were in AC3. It should be noted that at dusk and during the night, some of the lowest tree damage probabilities ranging from 0.0392 to 0.0474 were observed (Table 6).

Table 5. Analysis of deviance with Wald chi-square tests (logistic model).

Factor/Interactions	Df	χ2	*p*-Value
Cumulative shift time	1	6.334	0.0118
Part of the day	3	15.796	0.0013
AC	2	20.113	0.0000
DC	2	27.051	0.0000
Operator	1	31.326	0.0000
Percentage of harvested trees	1	112.894	0.0000
Part of the day × Productivity	4	26.564	0.0000
Part of the day × AC	6	214.839	0.0000
Part of the day × DC	2	3.929	0.1402
Cumulative shift time × DC	2	5.293	0.0709
Cumulative shift time × AC	2	4.112	0.1280

AC: age class; DC: density class.

Table 6. Estimates of damage probability in relation to the part of the day, age class (AC) and density class (DC).

Stand Factor	Class ID	ND	D	DN	N
Age	AC3	0.0637	0.0528	0.0867	0.0608
	AC4	0.0603	0.0430	0.0345	0.0474
	AC5	0.0758	0.0679	0.0392	0.0429
Density	DCA	n.a.	0.0427	0.0345	0.0352
	DCB	0.0689	0.0577	0.0392	0.0450
	DCC	0.0637	0.0578	0.0867	0.0785

ND: dawn, D: day, DN: dusk, N: night.

Damage in AC3 at dusk (0.0867) was statistically different to the other ACs. Furthermore, during the night shift, a higher tree damage probability was observed in AC3 (0.0608) than in the other ACs (Table 6).

In all the types of shift, increasing productivity rates resulted in decreased probabilities of damage. This tendency was more evident for the N, DN, and ND shifts. During the day shift, this tendency was not statistically significant.

The interaction was not statistically significant. The lack of interaction between the time of shift and AC indicates a similar increase in the tree damage probability with the increase of the cumulative shift time (Figure 3).

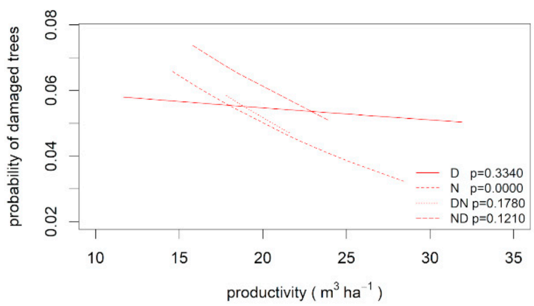

Figure 3. Probability of damage depending on the productivity in different type of shifts (ND—dawn, D—day, DN—dusk, N—night).

The tree damage probability depending on the time of shift showed a rising tendency from the beginning of the shift for AC3 and AC4, and this was significant ($p = 0.0020$ and $p = 0.0098$, respectively). In contrast, a constant probability of tree damage was observed in AC5 regardless of the time of the shift ($p = 0.8500$). A rising tendency was also found from the beginning of the shift for DCB and DCC, but it was significant only for DCB ($p = 0.0000$ (Figure 4)).

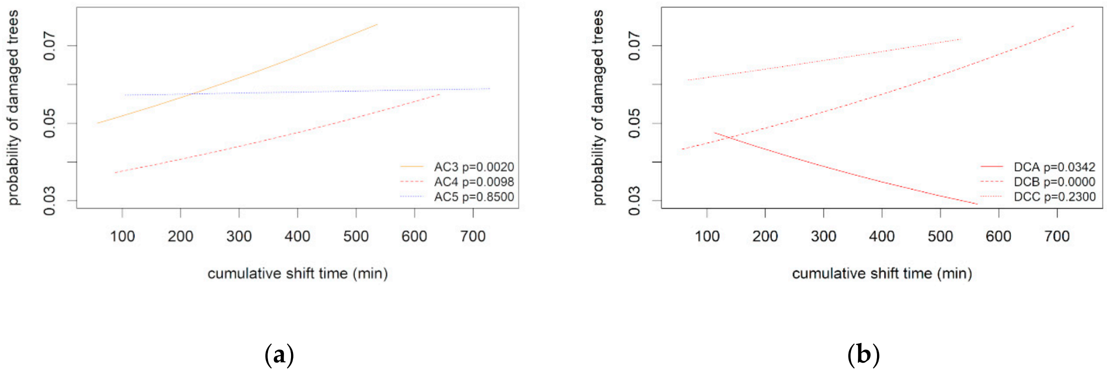

Figure 4. Tree damage probability as a function of the cumulative shift time with respect to: (**a**) age class, and (**b**) density class.

Finally, an additive logistic model was built (Table 7) with the following factors/variables: time of shift, operator, type of shift, AC and DC.

Table 7. Relationships between the probability of damage and model variables.

Model: $\text{logit}P = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 + \beta_5 x_5 + \beta_6 x_6 + \beta_7 x_7 + \beta_8 x_8 + \beta_9 x_9 + \beta_{10} x_{10}$

P = Probability of damage
x_1 = Cumulative shift time
x_2 = Operator (1 = Operator A, 0 = Operator B)
x_3 = Part of the day DN (1 = yes, 0 = no)
x_4 = Part of the day N (1 = yes, 0 = no)
x_5 = Part of the day ND (1 = yes, 0 = no)
x_6 = Percentage of harvested trees
x_7 = AC4 (1 = yes, 0 = no)
x_8 = AC5 (1 = yes, 0 = no)
x_9 = DCB (1 = yes, 0 = no)
x_{10} = DCC (1 = yes, 0 = no)

Parameter	Estimate	Std. error	z Statistic	Pr (>|z|)
β_0	−4.9834	0.2115	−23.570	0.0000
β_1	0.0003	0.0002	−1.535	0.1247
β_2	0.3918	0.0596	−6.569	0.0000
β_3	−0.2332	0.1087	2.145	0.0320
β_4	−0.0220	0.0648	0.339	0.7345
β_5	−0.0808	0.1001	0.808	0.4194
β_6	0.0338	0.0051	−6.681	0.0000
β_7	0.6979	0.1863	−3.747	0.0002
β_8	1.0324	0.1825	−5.656	0.0000
β_9	0.1105	0.0794	−1.392	0.1639
β_{10}	1.0425	0.2019	−5.164	0.0000

Note: Goodness-of-fit: AIC = 12,124.40

ND: dawn, DN: dusk, N: night, AC: age class; DC: density class.

4. Discussion

The reported frequency of the trees being damaged in all the age classes and tree density classes combined was 5.29%, and the damage frequency ranged from 1.12% to 10.92% on the study's sample plots, suggesting low damage levels. The reported damage frequency due to thinning operations varies greatly among studies. McNeel and Ballard [55] reported that less than 5% of the residual trees were injured after a thinning operation in a Douglas-fir plantation on flat to rolling terrain (0–17% slope gradient), whereas damage frequencies of 40%, or even more, were reported for harvester-forwarder operations [56,57]. Comparisons among studies should be made with caution following the suggestion of Mederski et al. [34].

Well-performed thinning operations result in the right number and arrangement of trees with the lowest possible number of damaged trees. Thinning operations are subject to restrictions set by a wide variety of factors such as the thinning type, type of equipment used and thinning intensity (TI). Lageson [22] reported no differences in terms of the residual stand damage and frequency between two thinning types. Equipment may vary in a number of ways, such as the machine type used, the combination and the dimensions [58]. In this case, the TI differed widely among stands as a result of their age class from 22 m^3 ha^{-1} to 88 m^3 ha^{-1}. Despite such large differences, the TI did not exert a statistically significant impact on the probability of tree damage on the study plots. With an increased thinning intensity, the risk of damage to remaining trees is reduced, as there are fewer trees in the area being thinned. Additionally, during the initial removal of trees, the trees being felled and processed can damage trees that have also been marked and will be cut later. It should be stressed that the probability of tree damage is not reduced, but the probability of damage to the remaining trees is. Moreover, high-intensity thinning is usually characterized by a large number of trees per hectare. This proves that a relatively large number of trees are often in the bottom layer of the stand with smaller dimensions and with thinner crowns. Such trees may cause less damage to the remaining trees during felling and processing than trees with a crown and stem parameters equal to the remaining stand.

This finding may be linked to the importance of the strip road design [34,59,60]. Some authors have suggested that a higher density of strip (skid) roads increases the vulnerability of trees in terms of damage frequency because of their positions in proximity to machine movement [31,32]. However, similar damage frequency levels were reported after the reduction of the distance between skid roads from 20 m to 10 m [34]. Furthermore, a clear trend towards the increasing probability of newly inflicted bark damage when the distance exceeded 20 m was observed [35].

Another factor contributing to low damage levels in the present study may be the short length of wood assortments, which was indicated in other studies [7,23,24,35,36]. In the present study, short logs were processed (maximum 2.85 m), hence the level of damage was lower in contrast to the greater damage frequency when long timber was extracted [58].

4.1. Part of the Day

The study's second hypothesis—that the type of shift has a limited effect on the tree damage frequency—was verified. During the day (D) shift, productivity rates increased but the probability of damage remained stable (Figure 3). In contrast, during the dawn (ND), dusk (DN) and night (N) shifts, decreased levels of damage were observed with increasing productivity rates. This finding suggests the need for future research on the topic, most preferably with more extensive data taken during the ND, DN, and N shifts compared to those in the present study.

Furthermore, considerably reduced damage probabilities were found during the DN and N shifts (Table 6) in AC4, AC5, DCA and DCB. This result may be attributed to a combination of the strip road network design and the provision of adequate lighting. It seems that this combination may warrant a better quality of CTL harvesting in older stands or in stands with a tree density lower than 900 trees ha^{-1}. In AC3 and DCC, which were characterized by higher tree densities, the operator had more difficulty in carrying out his work due to the greater use of artificial light. In addition, light intensity was lowered due to the large number of standing trees reducing the operator's visibility.

In this research, artificial lighting was constantly in use for sample plots during the night and partly for sample plots at dawn (when the operator used artificial lighting which was eventually switched off during the shift), and at dusk (when the operator started the shift without artificial lighting and switched it on during the shift). The results obtained indicate that the greatest probability of damage occurred in the dense (DCC) young stand (AC3) at dusk (Table 6). This seems to confirm the observations of Nicholls et al. [9] that as well as dim light, operators found that shadowing and glare inhibited visibility and the precision of machine positioning, thereby reducing productivity. Operators working in poor light lacked confidence and became unwilling to attempt difficult terrain during the night. Owens [45] observed a similar relationship when analyzing fatal road accidents, where among all the accidents in transition time (during the twilight zone), 70% of them occurred in the evening twilight zone (dusk).

However, it may raise doubts that there are such significant differences only at dusk. In the case of dawn, no such differences were observed. Perhaps the explanation for this phenomenon is the significantly different type of human vision during photopic (daylight), mesopic (dusk) and scotopic (night) conditions. Mesopic vision is an intermediate stage between seeing in normal lighting conditions, called photopic vision, and the perception of the image only in gray colors, when there is very little light, called scotopic vision [61]. Therefore, mesopic is a state of impaired operation of the human (operator's) eye, which can certainly cause an increased level of damage in dense (young) stands and the failure of the operator to notice (skip) trees marked for felling. A solution to this problem could be the continuous use of artificial light or the automatic turning on of lamps using a light sensor.

4.2. Cumulative Shift Time

From an ergonomic point of view, the mechanization of forest operations has contributed to workplace improvement. Machine operators can work in an ergonomically fitted cabin [62,63], often without the need for the manual lifting of equipment and objects. However, more demands, especially of a cognitive nature [64], have emerged following the paradigm shift from "doing to thinking" [65]. This raises the question as to whether cumulative cognitive fatigue may lead to increased damage levels the way muscular fatigue does [66], and if it may act as a source of error and accidents [67].

A higher tree damage probability was found in AC3 and AC4 as the operating hours into the shift increased compared to the older stand of AC5. A similar finding was recorded for the higher density stands DCB and DCC compared to DCA. These findings confirmed the first hypothesis and could be attributed to the accumulated fatigue of the operator during work in the higher tree densities observed in younger forest stands. The data suggest that this trend remains valid for AC5, possibly due to the more favorable stand conditions for the harvester operator, who had more space to reach, fell and process the trees to the required assortments [9].

When the operator is feeling tired, it is advisable that he takes a break. Shorter duration breaks of 10 min taken every 90 min may be combined with longer, 30–40 min breaks taken every 4 h, as suggested by Kirk [68]. During these breaks, the operator is expected to get out of the cabin and stretch, thereby alleviating the monotony of the task [68].

4.3. Operators

The two operators who participated in the present study had similar work experience, but they differed in terms of the level of tree damage caused. According to Malinen et al. [44], after the initial learning phase of up to 15 years of experience, some parameters, such as the average productivity, are expected to increase slowly. This suggests a need to examine the development of operator skills across longer time periods. A closer look at the differences between the operators showed that the level of damage was practically the same.

The damaged tree frequency range (1.12–10.92%) was close to that reported by Sirén (1.4–6.6%) [27]. According to Sirén [27], the most important factor determining the level of damage may be the skill and motivation of the harvester operators. The latter factor is difficult to assess and may vary to a considerable extent [60,69–71].

Extended shift hours may cause greater operator fatigue which may lead not only to machine damage and safety concerns, but also to higher tree damage levels [9]. Thus, the significantly different levels of damage caused by the operators in this study justify the inclusion of the operator variable in the logistic model.

5. Conclusions

In the future, extended shifts are expected to become more common in mechanized CTL harvesting. The results obtained indicate that the part of the day and cumulative shift time have an impact on the frequency of damaged trees in the remaining stand. Both results have practical implications for mechanized thinning operations.

In the presented research, it was proven that more damage could be observed when light conditions were less favorable or in artificial light, especially at dusk and in younger, or more dense stands. This information may be used during the planning of harvesting operations by programming activities according to age class, stand density and thinning intensity.

Based on the results from the study, it is suggested that the operator has short breaks when a higher probability of damage is expected: in the dusk and towards the end of the shift. In this context, one point that could be further examined is the design of extended shift patterns. More information would assist the optimum allocation of the number and the duration of breaks during the shift, with the aim of improving operator focus and thus lowering the probability of tree damage.

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