Damages to residual stand in commercial thinnings

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Swedish University of Agricultural Sciences
Master Thesis no. 127
Southern Swedish Forest Research Centre
Alnarp 2008

ABSTRACT

Recently more and more attention is paid to the quality of thinning operations and not only thinning efficiency. In order to produce a valuable final crop at the end of the rotation period injuries to the residual stand should be avoided. Thinnings of low quality may not favor the growth of the remaining trees and the timber value at final fellings may be diminished. Wounds imposed in thinning operations are most often reported to deteriorate the timber quality by the incidence of stain or wood decay.

The study aimed at investigating the relationship between thinning damages and stand characteristics such as basal area after thinning, dominant height, age at breast height, spacing and tree species. Strip-road width, distance between strip roads and forwarder types were also included. The study is based on an inventory project carried out at SCA Skog AB in northern Sweden. Damage levels in relation to stand parameters were measured in 100 randomly chosen thinned stands in five forest districts. Data collection was based on circular sample plots.

The average level of damaged trees was 5,8 %. Large variation in the number of damaged trees was found among all stands measured. No clear pattern with regard to respective forest districts could be seen. In regression analysis the group of stands dominated by Norway spruce or lodgepole pine were found to be positively correlated with the damage levels. Thinning during the winter period, i.e. December-March were found to be negatively correlated with the damage levels. Spacing after thinning was nearly-significant and also negatively correlated with the number of damaged trees. The analysis of damaged trees showed that trees with stem damages as the dominant damage type amounted to 55,7 % while trees with butt damages as the dominant damage type amouted to 44,3 %. Additionally, 61,1 % of the damaged trees were found within 5 m from the strip-road edge.

An overview of the litterature concerning thinning damages was done in relation to the obtained results. Additionally, possible improvements towards the reduction of thinning damages were discussed.

ACKNOWLEDGEMENTS

The thesis is based on a project carried out at SCA Skog AB and I would like to thank in the first place Professor Pelle Gemmel who gave me this great opportunity. I acknowledge him for his helpfulness during data collection as well as while putting my findings on the paper.

I express my gratitude to my supervisors at SCA Skog. I thank Tomas Johansson for his support with formulating the queationnaire and understanding the technical aspects of thinning operations. My special thanks should also go to Magnus Andersson who was most helpful with methodology of data collection as well as further result compillation.

I highly acknowledge Associate Professor Per Magnus Ekö and Nils Fahlvik, PhD who were my supervisors at SLU in Alnarp. I kindly thank Professor Per Magnus Ekö for his support and motivation while writing my thesis. Additionally, I appreciate his teaching effort during my studies in Alnarp. The knowledge that I gained found a practical application. I am greatly indebted to Nils Fahlvik for his help with result calculations and proof-reading without which this study would not have taken its proper scientific form. Nils Fahlvik deserves special thanks as he made a great effort helping me while simultaneously being engaged with his own scientific projects abroad.

Last but not least, my thanks should go to Associate Professor Eric Agestam at SLU in Alnarp who was my examiner. I acknowledge him for his comments and corrections which helped my study take its final form.

CONTENTS

Introduction

At a certain stage of stand development a number of trees is removed in order to create a more favourable growth conditions for the remaining trees. Reducing the competition for resources such as water, nutrients, light and space among the remaining trees may contribute to a more valuable final crop. There are multiple desireable effects of thinning of which the most important ones are to enhance diameter growth, improve timber quality of the stand, avoid self-thinning and obtain some income early in the rotation period (Andersson, 1911; Wahlgren, 1914; Juhlin Dannfelt, 1954; Fries, 1961; Anon., 1969; Söderström, 1980). According to the Swedish Forest Association's Technical Forestry Vocabulary (Anon., 1994), thinning is defined as a stand improvement under extraction of wood. In this study thinning will be regarded as a removal of trees from a stand in order to improve the performance of the remaining trees and to generate a net income (commercial thinning).

Nowadays more and more attention is paid to the quality of thinning. The quality of the remaining trees after thinning constitutes an important factor for the future value of the stand. A very efficient and well-planned thinning generating a good net income at a certain point of rotation period may at the same time considerably reduce the income from final felling due to damages to the final-crop trees. Damages imposed by machines may considerably deteriorate the timber quality, cause losses in production or facilitate various fungal infections. Wounds on the remaining trees in thinnings are reported to deteriorate the timber quality by the incidence of stain or wood decay (Vasiliauskas, 2001). The infection of wounds by fungi may lead to serious wood degradation. Following wood infection, the decay in many trees species usually invades the central portion of the stem and a typical heartrot is formed that expands well above and below the wounds (Pawsey and Gladman, 1965; Shigo, 1966; El Atta and Hayes, 1987). Swedish studies have shown that even when roots of spruce are damaged, the resulting decay may enter the stem and affect 1-4 m of its length (Hagner et al., 1964; Nilsson and Hyppel, 1968). Andersson (1985) found that the growth losses for single trees due to stem or root damages can amount to between 5 and 40 %. Since logging injuries usually occure on the lower part of the trunk, wound decay in a tree affects the most valuable timber (Wallis and Morrison, 1975). The value of injured and decayed spruce trunks may be reduced by 30 % compared with sound trunks of identical size (Hasek, 1965; Hakkila and Laiho, 1967). Depending on the frequency and severity of damages in stands of spruce, the financial revenues at final harvest may decrease by 7-20 % because of wound decay (Fanta, 1958; Hilscher, 1964; Steyrer, 1992).

A considerable number of studies have been carried out in order to investigate various aspects of damages in thinnings. In Sweden, the research has mainly focused on spruce monocultures in the southern part of the country (Johansson et al. 2002, Wallentin 2007). Wallentin (2007) conducted a comprehensive study concerning thinning injuries in even-aged spruce monocultures. The author found that the damage levels were higher in late as compared with early thinnings mainly due to significantly higher root injuries following late thinnings. Additionally, the injury level was significantly higher amongst trees adjacent to strip roads compared to trees in the interrior of the stand, also stem injuries in late thinnings were significantly negatively correlated to the width of the strip roads. Previously unthinned stands with high initial stem numbers and large basal areas were at higher risk of injury in the thinning operations; thinning during winter reduced the amount of root injuries in early thinnings (Wallentin, 2007). It is, however, assumed that the observed aspects of damage occurrence are also relevant for the conditions in northern Sweden. Froehlich (1976) found that the level of damages in thinnings is dependent on tree species, tree dimensions, stand density and the character of root systems. Norway spruce for instance has a horizontal root system with many roots in the upper soil layer and a relatively thin bark which makes it susceptible to damages in thinnings (Koch and Thongjiem, 1989). Scots pine in contrast is considered to be more resistant due to its relatively thick bark and taproot system. Furthermore, the susceptibility of bark to injuries is conditioned by the time in which thinning is done. During late autumn bark strength is 1,5 times higher than during spring season (Wästerlund, 1986). Also, damage to roots and trunks is less severe during winter thinnings since the ground is frozen and bark strongly attached to the trunk (Hannelius and Lillandt, 1970; Kärkkäinen, 1969, 1973; Ohain, 1974; Grinchenko, 1984; Kallio, 1984). Winter injuries are usually smaller and less deep than those made in summer (Kärkkäinen, 1973; Isomäki and Kallio, 1974; Kovbasa, 1996).

Damages on the remaining trees can be divided into various types with regard to their structure and location. If the damage is superficial and only the bark layer is injured then it is termed as bark-stripping whereas additional breach in the wood structure of the trunk is defined as timber damage (Fröding, 1983). Taking into account the location on an individual tree, damages on roots and stems are distinguished. In a study carried out in thinned, young-growth true fir (*Abies concolor* and *Abies magnifica*) stands in California, basal wounds (those in contact with the ground) were found to be more susceptible to infection and to have more decay than those located above the ground line, additionally gouge wounds had more decay than smooth ones (Aho et al., 1983). What is more, observed (partially healed) and original (measured directly after thinning) wound size and age were the most important characteristics related to the amount of decay. (Aho et al., 1983). Taking into account the fact that much of the value (both quantity and quality) in a tree is in the butt log, basal damages are of considerable importance. Andersson (1984) and Fröding (1987) found that root and stem damages arise mainly as a result of skidding. Machine tyres are the most important cause of root damages while the machine body, load and crane cause stem damages (Andersson 1984, Sirén 1987). It has been found than most trees wounded due to forest operations are situated close to the extraction racks (Marchenko, 1964; Huse, 1978; Bettinger and Kellogg, 1993; Kovbasa 1996; Athanassiadis, 1997). In Finnland Hannelius and Lillandt (1970) found 81 per cent of the injured trees 1m from the extraction racks and Siren (1982) reported that only 10 per cent of wounded stems were found more than 5m from the centre of the extraction rack.

The level of damages increases considerably with an increasing degree of mechanisation (Andersson, 1985; Fröding, 1985). The most dominant system used in Sweden today is the fully-mechanised system with forwarders and harvesters. The level of damages on the remaining trees is primarily dependent on the following factors: machine size and equipment, skidding intensity, machine driver's competence and strip-road width (Fries, 1976). Apart from damages imposed to the standing trees and their roots, soil compaction may arise due to high skidding intensity or moist ground conditions. Fröding (1982)

found that 35 % of thinning damages can be assigned to this category. It is rather a specific pressure of machines on the ground than their weight which influences damage levels. By using a large tyres or caterpillars pressure can be reduced and consequently fewer damages imposed (Fries, 1976; Björkhem et al, 1974). Also, equal distribution of weight and all-wheal drive can reduce damage levels (Marklund and Ala-Ilomäki, 1987) It is, however, not only the machine type that are decisive for the level of damages. Sirén (1987) found that the machine driver is the most important factor. Their experience, awareness and carefullness are crucial in damage reduction especially in rising degree of machine use. Furthermore, drivers' skills and attitude to their machine and work influence the levels of damages (Froehlich, 1976).
Periodical follow-ups of thinning operations are carried out in order to investigate their quality and overall result. It is essential for large forest-based companies that thinnings positively influence the growth of remaining trees and do not deteriorate timber quality.

This study focuses on the levels of thinning damages imposed on remaining trees as the main quality criteria. Data presented in the study is based on an inventory project carried out at SCA Skog AB during the summer season 2007. The inventory was carried out in order to investigate the quality of the perfomed thinning operations within all five SCA forest districts (Jämtland, Medelpad, Norrbotten, Västerbotten och Ångermanland). The inventory included different aspects of thinning quality. In this study only the data that concerns the level of damages on remaining trees is included. It is investigated if there is a relation between number of damaged trees and stand structures such as basal area after thinning, dominant height, age at breast height, spacing and tree species. Additionally, it is researched if the number of damaged trees is correlated with strip-road width, distance between strip roads and forwarder types used in thinnings.

Materials and methods

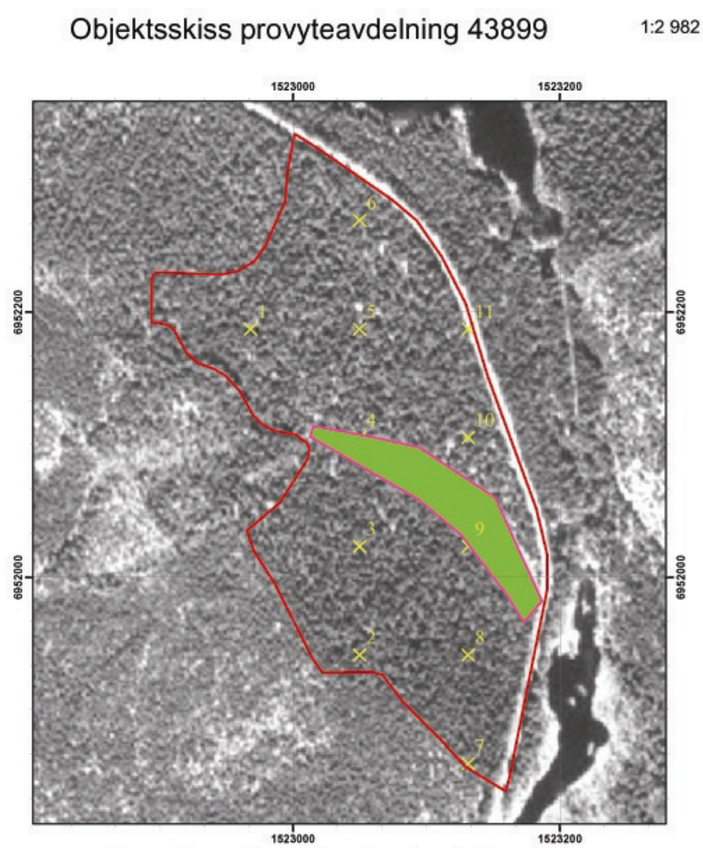
The inventory data used in this study was collected during a follow-up project of thinned stands carried out at SCA Skog AB in northern Sweden in all five SCA forest districts (Jämtland, Medelpad, Norrbotten, Västerrbotten and Ångermanland). The invetory included 100 thinned stands, with 20 stands selected within each district. The inventory was carried out at two different stages with regard to the period in which stands were thinned. During the first stage 10 stands from each SCA forest district thinned in the period from January until April 2007 were inventoried. During the second stage the inventory was followed in another 10 stands in each SCA forest district thinned in the period from May until November 2007. The stands were randomly selected among all stands that had been thinned during respective period. Stand selection was done from a list of units to which one stand or a group of stands are assigned. In most cases for units to which more than one object was attributed, the largest object was chosen. In five cases more than one stand from a single unit was chosen for the inventory since the amount of thinned stands during the second inventory stage was relatively small. It was essential that a total of 10 stands per each district were measured.

Data representing the state after thinning for all stands are presented in Table 1.Out of 100 stands inventoried 63 stands were Scots pine (*Pinus sylvestris*)-dominant, 14 stands were lodgepole pine (*Pinus contorta*)-dominant, 2 stands were Norway spruce (*Picea abies*)-dominant. A single-species stand was defined as a stand in which more than 70% of the total stem number belongs to a single tree species.

Table 1. Mean, min and max values for different stand parameters for the inventoried stands

Stand parameters	Mean	Min	Max
Basal area after thinning [m^2/ha]	18,1	11,6	29,1
Number of stems after thinning [st/ha]	758	441	1222
Dominant height [m]	16,1	12,1	20,6
Age at breast height [years]	40,0	20,2	84,4

The measurements were carried out on randomly selected sample plots. For each object a map with a schematic plot layout and coordinates was created using an application to SkogsGIS called ‘Slumpa provytor ver 0.7’ (Fig. 1). If possible, any set-aside areas located within the stand were marked with a polygon in the map. The number of sample plots and the distance between them was correlated with stand area (Table 2). A GPS-receiver was used to locate the centre of the sample plots, based on the coordinates from the map.



FID	Shape	Karta	Avdnr	Provyteld	X_rt90	Y_rt90
0	Punkt	111111	111111	1	6952188	1522968
1	Punkt	111111	111111	2	6951942	1523050
2	Punkt	111111	111111	3	6952024	1523050
3	Punkt	111111	111111	4	6952106	1523050
4	Punkt	111111	111111	5	6952188	1523050
5	Punkt	111111	111111	6	6952270	1523050
6	Punkt	111111	111111	7	6951860	1523132
7	Punkt	111111	111111	8	6951942	1523132
8	Punkt	111111	111111	9	6952024	1523132
9	Punkt	111111	111111	10	6952106	1523132
10	Punkt	111111	111111	11	6952188	1523132

Figure 1. Example of a map with sample plot layout, coordinates and set-aside area (green field).

Table 2. Relationship between stand area, number of plots and the spacing between them.

Area (ha)	No of plots	Spacing (m)
≤2	6	≤60
4	8	70
6	10	80
8	12	80
10	14	80
12	15	90
14	16	90
16	17	100
18	18	100
≥20	19	≥100

Circular sample plots with a radius of 7,98 m (200 m^2) were used. Sample plots located on impediments, openings, close to stand borders and in unthinned parts of the stand were mirrored. Mirroring was done at a right angle or reverse to the walking direction towards a plot. Mirroring distance depended on the distance between sample plots (mirroring up to half of the distance between sample plots in order not to establish plots too close to each other). In some cases mirroring was not possible due to large unthinned areas, narrow stand patches or large openings and in those cases the sample plots were skipped. Location of a plot on a strip-road did not result in mirroring.

Only trees with a diameter at breast height greater than 7 cm were considered at the measurements on each plot. The values for the different stand parameters on stand level were calculated as the average from plots.

Diameter at breast height was measured with a calliper (Digitech Professional). The tree species distribution was calculated based on the registered trees.

The dominant height was measured as the average height of the two largest trees, according to the diameter at breast height. The tree heights were measured with a Vertex IV hypsometer. One of the dominante trees on each plot was cored at breast height and the number of annual rings was registered in the calliper.

The number of damaged trees was counted at each sample plot. A damaged tree was defined as a tree with a damage larger or equal to 15 cm^2 and no distinction was made whether it was a bark-stripping or timber damage. The calliper was used to calculate the percentage of damaged trees in relation to the total number of trees with a diameter > 7 cm registered at each plot. During the first inventory stage only the number of damaged trees was measured while a more detailed analysis followed during the second inventory stage. At the second measurment damages were divided in terms of the distance from the strip road as well as the location of the damage on the trees. It was registered whether a damaged tree was located within a distance of 5 m from the edge of a strip road (zone 1) or further than 5 m from the edge of the strip road (zone 2). Trees with damages located up to 70 cm from the ground were included into the category butt damages while trees with damages located higher than 70 cm from the ground were included into category stem damages. Due to problems related to the calliper software it was not posible to register trees damaged both on stem and butt and therefore such trees were registered as either trees damaged on stem or butt with regard to damage extent. Since the number of trees damaged both on stem and butt was small it is therefore judged not to have a significant impact on the result.

Two measurements of strip-road width and distance between strip roads were taken at each sample plot. A straight line from sample plot centre to the nearest strip-road edge was drawn using a conventional thread meter (Fig. 2).

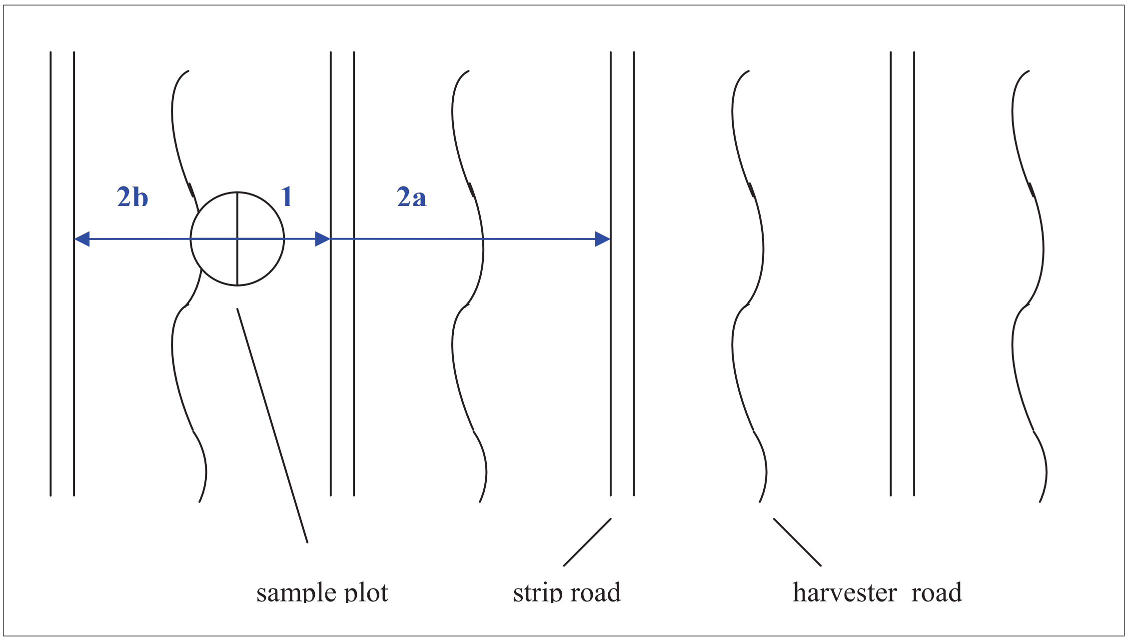


Figure 2. Drawing a straight line from sample plot centre to the nearest strip-road edge (1). Second strip-road edge was found by either following the original line (2a) or in the opposite direction (2b).

From the defined point at the strip-road edge a distance of 10m alongside strip-road track was marked using a self-retracting pocket tape. Strip-road width was calculated as the sum of two meaurements taken to the middle of the strip-road track between two trees which location was nearest to the strip-road edge (Fig. 3).

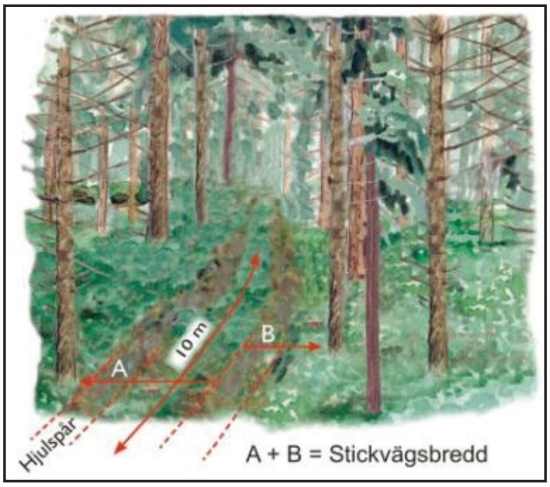


Figure 3. Measurement of strip-road width. (Adapted from 'Så här ska Du gallra', SCA Skog AB)

Strip-road width was measured at each plot twice (two adjacent strip roads) and the average value was calculated. In some cases strip-road measurement was skipped due to plot location, for instance in parts of the stand where only one strip road was laid or where strip road pattern was not clear and finding a parallel strip road was difficult.

Strip-road distance was measured twice at each sample plot. The line drawn from the sample plot centre to the nearest strip-road edge was also used to define a point from which distance to adjacent strip road was measured (Fig. 2). The measurement was taken between the centres of two adjacent strip roads. Two values of strip-road distance at each plot were registered in the calliper and the average value was calculated. In cases where it was not possible to measure the strip-road distance twice, the measurement was skipped. A conventional thread meter was used for the measurement.

Terrain conditions of each stand were estimated as either difficult or normal. No specific scale or parameters were used in this judgement. It was a subjective assessment and the main attention was paid to elevation and the amount of rocky outcrop.

A regression model was used to analyse the influence of the measured stand parameters on the damage level. Since the proportions of damaged trees did not follow a normal distribution the arcsin transformed value of damage level was used:

$p' = \arcsin\sqrt{p}$ where p is the proportion of damaged trees

First the relationship between damage level and each of the stand parameters was studied in order to decide which of the parameters that should be included in the regression model (Fig. 4 and Table 3). Only spacing was found to be significantly correlated with the level of damages and the variable was included in the model. In addition, strip-road width and strip-road distance were included in the model since they were considered to be relevant for explaining the level of damages. Six indicator variables were also used, describing the age of the thinned stands, thinning season, tree species, machine size and the terrain conditions. The variables included in the final model are presented in Table 4.

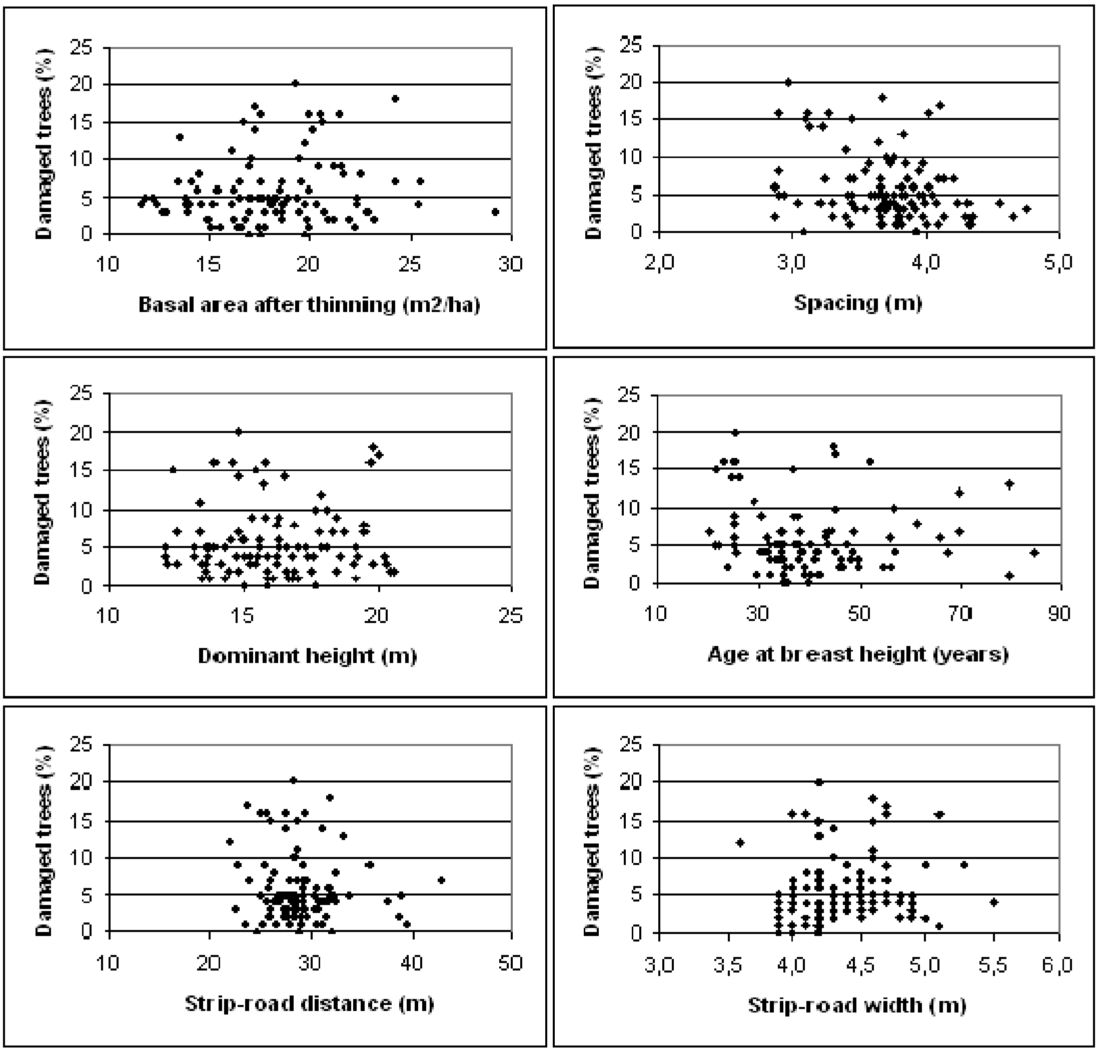


Figure 4. Relationship between the proportion of damaged trees and stand parameters

Table 3. Correlation matrix. The upper value describes the correlation between the two variables. A value of 0 means that there is no linear correlation between the two variables. A value of 1 or -1 means that there is an exact positive respectively negative linear correlation between the two variables. The lower value is the p-value for the estimation. The variable Damage refers to the transformed value of damage level

	Damage	Basal area after thinning	Spacing	Dominant height	Age at breast height	Strip road distance	Strip road width
Damage	1	0,106	-0,286	0,035	-0,045	-0,075	0,174
		0,304	0,005	0,737	0,662	0,463	0,089
Basal area after thinning	0,106	1	-0,191	0,584	-0,129	0,100	-0,029
	0,304		0,061	<,0001	0,208	0,329	0,781
Spacing	-0,286	-0,191	1	0,467	0,554	0,039	0,190
	0,005	0,061		<,0001	<,0001	0,705	0,063
Dominant height	0,035	0,584	0,467	1	0,481	0,029	-0,017
	0,737	<,0001	<,0001		<,0001	0,776	0,868
Age at breast height	-0,045	-0,129	0,554	0,481	1	-0,014	-0,077
	0,662	0,208	<,0001	<,0001		0,890	0,452
Strip road distance	-0,075	0,100	0,039	0,029	-0,014	1	0,124
	0,463	0,329	0,705	0,776	0,890		0,228
Strip road width	0,174	-0,029	0,190	-0,017	-0,077	0,124	1
	0,089	0,781	0,063	0,868	0,452	0,228	

Table 4. Description of variables included in the regression model.

Variable	Unit	Description
SPACING	m	Average spacing of the remaining trees
EARLY	-	Indicator variable for stand phase. EARLY=1 if stand age < 40 years, otherwise EARLY=0
WINTER	-	Indicatorvariable for thinning season. WINTER=1 if thinned during the period December-March, otherwise WINTER=0
PINE	-	Indicator variable for tree species. PINE=1 if Scots pine stem number > 70 %, otherwise PINE=0
THINBARK	-	Indicator variable for tree species. THINBARK=1 if Norway spruce or lodgepole pine stem number > 70 %, otherwise THINBARK=0
DIFFTERR	-	Indicator variable for terrain conditions. DIFFTERR=1 if terrain conditions difficult, otherwise DIFFTERR=0
ROADDIST	m	Distance between strip roads measured
ROADWIDTH	m	Strip-road width measured
LARGEFWRD	-	Indicator variable for forwarder size. LARGEFWRD=1 if forwarder size is S-large, otherwise LARGEFWRD=0 Forwarder types were grouped according to SCA classification. Forwarder weight and skidding capacity were used. Three forwarder groups were distinguished: S-large, M-medium and L-small.

The following regression model was choosen:

$$y_i = ß_0 + ß_i * x_i + e_i$$

where y_i is a dependent variable, $ß_0$ is a constant , $ß_i$ a vector of coefficients for the independent variables x_i and e_i is a random variation.

The parameters were estimated using the stastistical program SAS version 9.1.

Results

The average amount of damaged trees in all 100 stands inventoried was 5,8 %. For the first inventory stage the number of damaged trees averaged 5,4 % while for the second it was 6,2 %. It is difficult to find a clear difference or a pattern while comparing both inventory stages with regard to forest districts (Fig. 5). The mean value of damaged trees in Scots pine-, lodgepole pine-, and Norway spruce-dominant stands was 4,9 %, 11,1 % and 4,5 % respectively. The average level of damages in mixed stands equalled 5,1 %.

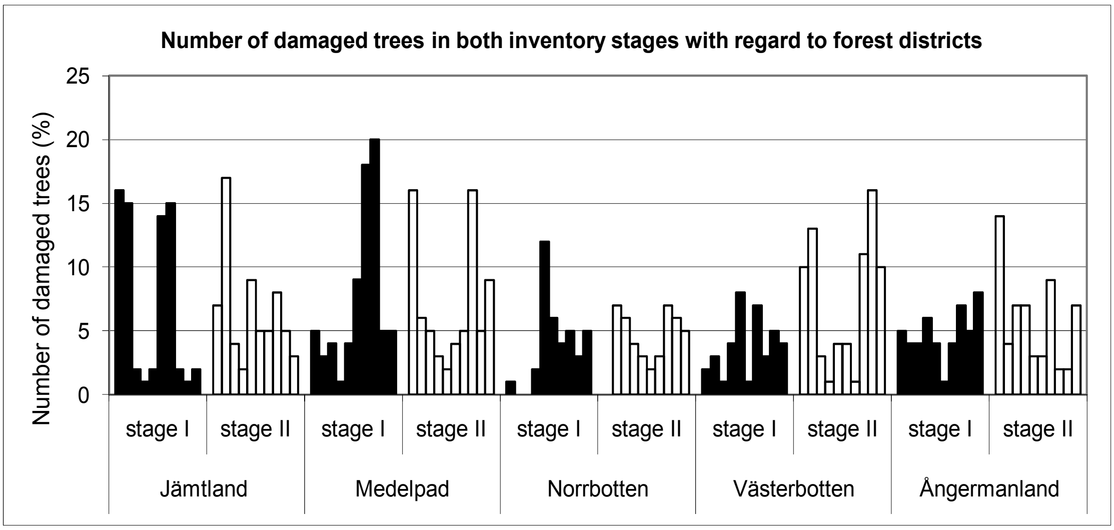


Figure 5. Number of damaged trees in both inventory stages with regard to forest districts.

The regression model was significant (p<0.0001) and R-square value equalled 0,3558 which indicates that 35,58% of the variance of damage levels can be explained by the model. A comparison between observed and predicted values indicated unbiased predictions (Fig. 6). The only statistically significant parameters in the regression model were the indicator variables THINBARK, WINTER and ROADWIDTH (Table 5). SPACING was found to be nearly-significant (p=0.0560) and negatively correlated to the level of damages (Table 5).

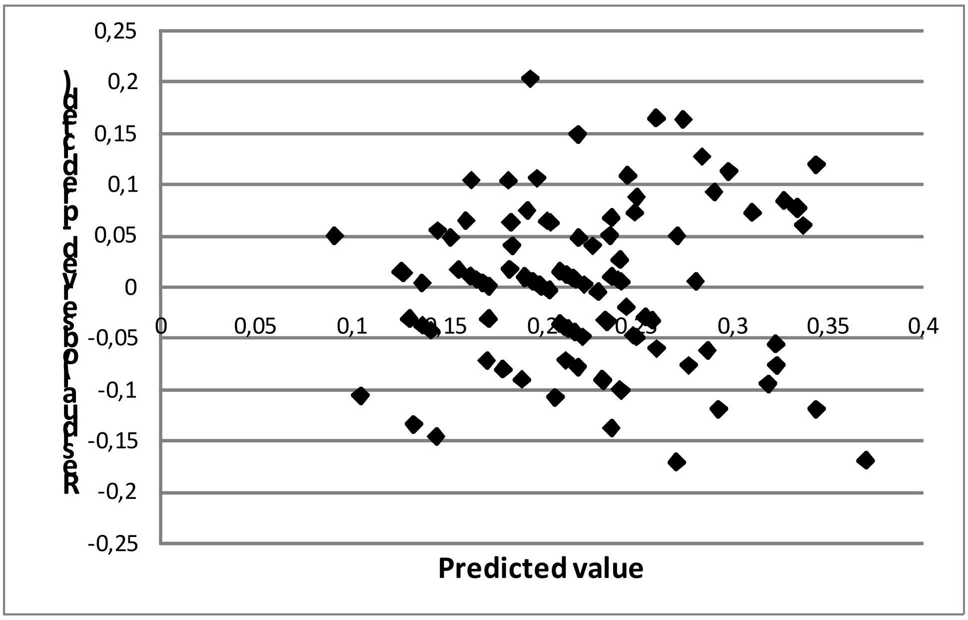


Figure 6. Residuals for the regression model. Dependent variable is the arcsine transformed value of damage level.

Table 5. Regression of proportion of damaged trees on parameters describing the stand and the thinning

Dependent variable: arcsin√p where p=proportion of damaged trees

Variable	Coeff.	t-value	p-value
Intercept	0.31581	2.12	0.0366
SPACING	-0.05727	-1.94	0.0560
EARLY	-0.03561	-1.75	0.0841
WINTER	-0.06879	-2.99	0.0037
PINE	-0.000625	-0.03	0.9777
THINBARK	0.07147	2.24	0.0277
DIFFTERR	0.01783	0.71	0.4826
ROADDIST	-0.00433	-1.66	0.1013
ROADWIDTH	0.05625	2.11	0.0380
LARGEFWRD	0.03112	1.66	0.1014
Number of observations	100		

For the stands inventoried at the second stage it was found that more trees were damaged on stem (higher than 70 cm from the ground) than on the butt (up to 70 cm from the ground). Stem-damaged trees amounted to 55,7 % while butt-damaged trees to 44,3 %.

On average 33,3 % of the damaged trees were registered as stem damages within zone 1, 27,8 % as butt damages within zone 1, 23,4 % as stem damages within zone 2 and 15,5 % as butt damages in zone 2. Large variation in the distribution pattern of trees damaged on stem and butt in both zones was found (Fig. 7).

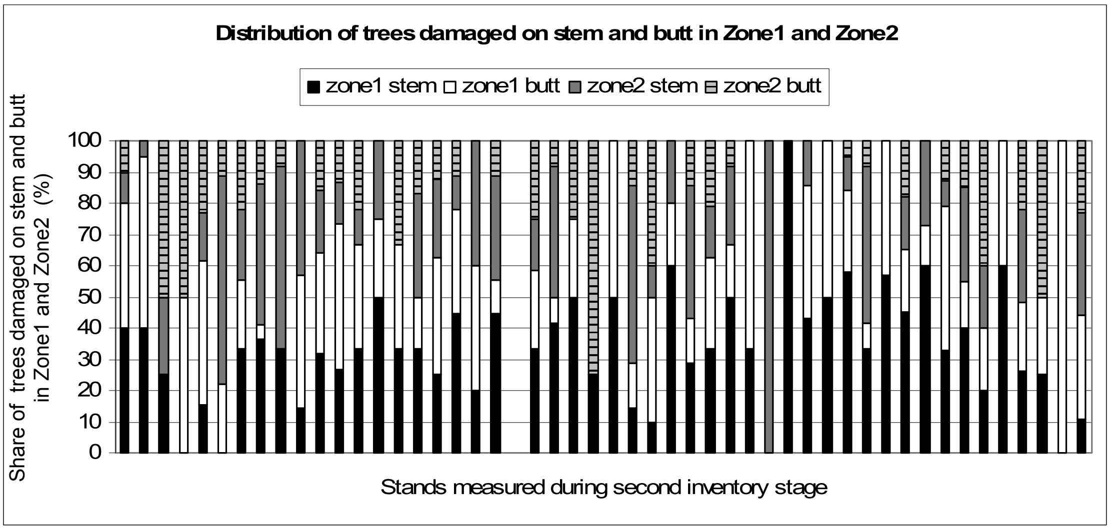


Figure 7. Distribution of trees damaged on stem and butt in zone1 and zone2.

Among stands inventoried at the second stage there were 32 Scots pine-dominant, 8 lodgepole pine-dominant and 10 mixed. Share of stem-damaged trees as compared with butt-damaged trees was found larger for all three above-mentioned stand types, however the difference is not pronounced (Table 6). Share of stem-damaged trees in Scots pine-dominant stands was almost equal to butt-damaged trees in zone 1 while the difference was more pronounced in zone 2. In two other categories the difference between the share of stem- and butt-damaged trees was larger in zone 1 as compared with zone 2 (Table 6).

Table 6. Share of damaged trees with regard to stand types and damage location.

Stand type	Share of damaged trees (%)					
	Total stem	Total butt	zone 1		zone 2	
			stem	butt	stem	butt
Scots pine-dominant	54,7	45,3	30,8	28,5	23,9	16,8
lodgepole pine-dominant	58,0	42,0	38,9	28,6	19,1	13,4
mixed	58,9	41,1	41,7	29,3	17,2	11,8

Discussion

In the current Swedish Forest Act there is a general advice that deliberate damages on remaining trees cannot be accepted (Bäcke, J. 1998). According to the Swedish Forest Agency's recommendation, the maximum level of damaged trees after thinning should not be higher than 5 % (Bäcke, J. 1998). Damage is defined as a stem or root damage larger or equal to 15 cm^2. In Sweden, investigators have reported the percentage of trees wounded by cut-to-length-thinning in stands of Scots pine and Norway spruce at 5–9 % (Froding 1992, Johansson 1996, Lageson 1997) and 13–17 % (Jaghagen and Lageson 1996). In the present study the average number of damaged trees equalled 5,8 %. Large variation in damage levels within and between forest districts was found.

The only statistically significant parameters in the regression model were THINBARK, ROADWIDTH and WINTER. THINBARK and ROADWIDTH were found to be positively , while WINTER negatively correlated to the number of damaged trees. SPACING was found to be nearly-significant and also negatively correlated to the damage levels. The susceptibility of thin-barked tree species to thinning injuries was confirmed in a number of studies investigating the damage to residual stand. Heitzman and Grell (2002) found that certain tree species are particularly susceptible to logging damage and associated stem decay. In western forests of the United States, vulnerable species include the relatively thin-barked western hemlock (*Tsuga heterophylla*) and the true firs (*Abies concolor* and *Abies magnifica*), which are both thin-barked and not highly resistant to infection and decay entering through scars (Hunt and Krueger 1962, Wallis and Morrison 1975, Filip et al. 1995). In this study it was found that the group of stands dominated by Norway spruce or lodgepole pine proved to be more susceptible to thinning damages than Scots pine which is more resistant due to a relatively thick bark. Additionally, lodgepole pine is thought to be the most vulnerable species of all three investigated since the bark stripping may occur also when the large crowns of harvested trees rubs against the remaining trees. Very high density of lodgepole pine stands is also perceived as an obstacle at thinnings since the visibility is reduced.

Opposite to what could be expected the level of damage was found to be positively correlated to strip-road width in this study. This result cannot be easily explained but there might be a relationship between road width and other factors that might influence the risk of damages like for example the driving conditions.

Thinning period was found to be an important factor and correlated with the damage levels. Stands thinned during the winter season, i.e. in the period from December until March were found to have a lower average level of damage compared to stands thinned during other time of the year. . The winter season which is profound in northern Sweden seems to be more favourable for tree resistance to thinning damages. During late autumn bark strength is 1,5 times higher than during spring season (Wästerlund, 1986). Also, damage to roots and trunks is less severe during winter thinnings since the ground is frozen and bark strongly attached to the trunk (Hannelius and Lillandt, 1970; Kärkkäinen, 1969, 1973; Ohain, 1974; Grinchenko, 1984; Kallio, 1984). Winter injuries are usually smaller and less deep than those made in summer (Kärkkäinen, 1973; Isomäki and Kallio, 1974; Kovbasa, 1996). Spacing after thinning was found to be nearly-significant and negatively correlated to the damage levels in this study. Wallentin (2007) found that stands with high initial stem numbers and large basal areas were at higher risk of injury in the thinning operations. Other studies report that in both softwoods and hardwoods pre- and post-harvest densities influence the level of stand damage, with higher densities contributing to more wounding (McLaughlin and Pulkki, 1992; Howard, 1996; Hassler et al., 1999). It is resonable to suggest that the number of stems before thinning and the thinning grade should be important factors to explain the level of damages. These factors could, however, were not analysed in this study due to lack of data.

Earlier studies have reported that 80-90 % of all thinning damages with cut-to-length systems are imposed to stems (Sirén, 1981; Fröding, 1992; Jaghagen and Lageson, 1996; Athanassiadis, 1997; Lageson, 1997). However, Wallentin (2007) found much smaller contribution of stem injuries: ≤ 40 % and ca. 70 % in late thinnings and early thinnings, respectively. The difference between the above-mentioned studies and this by Wallentin (2007) can be partially explained by the fact that they were based mainly on Scots pine-dominant stands while the latter was done in Norway spruce monocultures (Scots pine has less exposed roots and thicker bark than Norway spruce). In the present study stem-damaged trees were found to be more frequent than butt-damaged trees, however, the difference was not pronounced: 55,7 % and 44,3 % respectively. It might have been expected that the share of stem-damaged trees could be larger as the majority of stands measured were Scots pine-dominant. A majority of butt damages are caused by transportation of timber and more precisely forwarder wheels that injure trees adjacent to the strip roads. Scots pine has a taproot system and a relatively thick bark which makes it more resistant to butt damages and therefore butt damages could be expected to constitute a much smaller share as compared with lodgepole pine-dominant and mixed stand. It is however, difficult to find a clear pattern in respect to tree species since the share of stem-damaged trees was larger than the share of butt-damaged trees for Scots pine-dominant, lodgepole pine-dominant and mixed stands and the difference was not pronounced.

The analysis of damage location showed that 61,1 % of damaged trees were found in zone 1 (within 5 m from the strip-road edge). Other studies, however, report an even higher injury level in the vicinity of strip roads. Bettinger and Kellogg (1993) have found that 72 % of the total scar area (surface area of scars on residual trees) was within 3,1 m from a logging trail when a cut-to-length harvesting system was used in a commercial thinning operation. In Finnland Hannelius and Lillandt (1970) found 81 % of the injured trees 1 m from the extraction tracks and Sirén (1982) reported that only 10 % of wounded stems were found more than 5 m from the centre of the extraction track. The probable reason behind relatively lower injury level in the vicinity of the strip roads in this study might be explained by the thinning technique. In northern Sweden it is common that harvester roads are laid out between strip roads. Harvesters operating between strip roads might impose more damages to the interior of the stand simultaneously decreasing the damage share adjacent to the strip roads.

The share of stem- and butt-damaged trees in zone 1 was found to be almost equal. It is presumed that skidding injuries imposed by forwarder wheels (probable factor of butt damages) were of similar grade to injuries imposed by forwarder body or harvester crane during strip road establishment (probable reason of stem damages). In zone 2, however, the discrepancy between the stem and butt damages seemed to be greater. It is supposed that the majority of damages in zone 2 were imposed by the harvester crane.

”The best commerical logging will damage at least some residual trees during all forms of partial cutting, no matter how carefully done. Yet recommendations show there is much that one can do to limit damage by proper road and trail layout, proper training and supervision of crews, appropriate equipment and diligence” (Nyland, 1989). Investigation of damages imposed in thinning operations may be conducted through the analysis of stand internal characteristics (tree species, terrain conditions, amount of undergrowth) or more external factors such as types of machines used, type of thinning, strip-road system and machine drivers’ experience. In this study aspects of both internal and external factors were brought up however the main focus was on stand characteristics. Based on the results of this study special attention should be paid to stands dominated by thin-barked species like lodgepole pine. Moreover, thinning should be carried out in the winter in order to reduce the damages. It is difficult, however, to carry out thinnings only during the winter season as the industry demands an even timber supply over the whole year. Terrain conditions did not prove to be significantly correlated with the damage levels and were based on subjective judgement. Nonetheless, it is reckoned that the probability of damaging residual trees is higher in stands with difficult terrain as the working conditions are more demanding. Perhaps the establishment of wider strip roads could diminish the level of injuries. With the increased distance between trees growing on strip-road edge, the probability of skidding damage could be minimized. Size of machines used in thinnings is currently under discussion and is deemed to be of significant importance in reducing damage levels (Nyland, 1989). One of the examples of innovations towards the reduction of injury levels and improved efficiency was the introduction of so-called “Sluten Upparbetning” in Sweden (Hallonborg et al. 1999). The method is applicable for first and second thinning with trees not exceeding 18 m of height. Trees are harvested standing onto the strip road where they are felled and processed directly on the machine load. Apart from the influence of machine types used in thinnings many studies emphasize also the role of machine drivers in damage reduction. Fröding (1985) argued that increased motivation through better training and a bonus system for low damage levels and follow-ups could improve driver's performance and decrease damage levels. Heitzman and Grell (2002) found that the lack of cut-to-length experience, which is particularly important for processor operators, may also have contributed to the abundance of damaged trees. Based on these findings it is crucial to emphasize the role of machine drivers. Balance between productivity and quality of thinning operations shall be maintained. Increasing machine drivers' skills and awareness might substantially contribute to reduction of damages imposed in thinnings.

Conclusions

1. Thin-barked species, Norway spruce and lodgepole pine, were found to be more susceptible to thinning injuries.
2. By carrying out thinning operations during the winter period, the level of damages can be reduced.
3. More damaged trees were found closer to the strip roads than in the interior of the stand.
4. The share of stem- and butt-damaged trees in the vicinity of the strip roads was found to be almost equal while relatively more stem- than butt-damaged trees were found in the interior of the stand.

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