Residual Stand Damage Following Cut-to-length Harvesting Operations with a Farm Tractor in Two Conifer Stands

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The objectives of this study was to record residual stand damage during harvesting operations and evaluate the influence of factors such as distance of the tree from the strip road, machine parts, operational phase, on the occurrence of tree wounds. The machine was a farm tractor equipped with a crane mounted on the front axle and a single grip harvester head. The study was carried out in two stands located in Southeast Sweden. Stand 1 was a 30-year-old Norway spruce (*Picea abies* L.) plantation on an afforested pasture while stand 2 was a 90-year-old mixed stand of Norway spruce, Scots pine (*Pinus sylvestris* L.), birch (*Betula pendula* Roth) and aspen (*Populus tremula* L.). The mean damage percentage was 6.3 % for the first stand and 6.5 % for the second stand. Sixty-five percent of the wounds were less than 50 cm^2, with 91 % of the damage occurring on the stem and 9 % of the damage on or below the root collar. Sixty-six percent of the wounds produced by the stem under processing or by the harvesting head while only 10 % of the wounds were produced by the tractor wheel. Damaged trees were distributed evenly in the crane reach zone. Significant differences were found between rut depths after one, two, four and six passes of the tractor in stand 1.

Keywords farm-tractors, harvesting, logging, stand-damage
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1 Introduction

Mechanisation of forest operations in Sweden started during the late 1950s as a response to increasing labour costs, cheap energy supply, and the demands for an improved production economy with the introduction of farm tractors for hauling of manually felled trees (Andersson 1992). Introduction of tractors into the forest stand had an adverse impact on the state and productivity of the remaining stand due to soil compaction and residual tree damage. Reduced tree growth and deteriorated timber quality are often results of damage occurring during the harvesting operation (Fröding 1992). During the 1960s, farm tractors were replaced in large scale forest operations by specialised forest machines (forwarders) adapted to the hard forest work and environment. In small scale forest operations, though, farm tractors are still of great importance since they, after minor or major changes, can become an adequate base machine for a number of implements like grapple-loader trailers and tree processing units facilitating work in the forest (Gullberg 1995, A better agricultural tractor... 1990).

The development of the single-grip harvester in the middle of 1980s was a significant step towards the mechanisation of the thinning operations. These machines required less space and caused less damage to the remaining stand, compared with two-grip harvesters, but were expensive to afford for small scale operations. Improvements in crane technology and the decrease of the weight of the harvesting head allowed them to be placed on lighter and smaller machines like the farm tractor. In large-scale forest operations, where larger wood volumes are available, specialised machines are faster and more economical than farm tractors with forestry attachments (Heinrich 1993). Farm tractors equipped with single-grip harvesters have been studied concerning time consumption and productivity in thinning operations (Gullberg and Johansson 1992, Johansson 1996, Ryynänen 1992 and 1994). They were found to be appropriate for first thinning operations where the trees have small dimensions. In these studies the amount of damage after the felling operations is also assessed but the factors causing the damage are not identified since the results are based on damage inventories after the thinning operation.

Several studies have examined stand damage with a variety of logging systems using a variety of experimental designs. Most studies estimate extent of damage, on sample plots randomly located in the stand (Bettinger and Kellogg 1993), on sample plots located on transects running through the stand (Sidle and Laurent 1986) or on sample plots located along major skid trails (Cline et al. 1991) after that the harvesting operation is complete. The above studies offer uncertainties concerning the cause of damage and at the same time the extent of damage may be underestimated since small dimension wounds or wounds situated high on the stem may not be recorded.

The objectives of this study were:

(i) to record residual stand damage during actual harvesting conditions with an agricultural tractor equipped with a single-grip harvester head and,

(ii) to evaluate the influencing factors such as distance of the tree from the strip road, machine parts, operational phase, on the occurrence of tree wounds.

2 Materials and Methods

2.1 The Stands

The study was carried out in two stands located in Southeast Sweden near Skövde (58°30' N, 13°25' E). The operations took place during a two weeks period in early autumn 1995 on snow-free ground. Soils in both stands were well graded podzols. Terrain conditions were assessed according to a scale of five levels (Terrain classification... 1992), from very good (very good ground condition, very even ground surface, slope less than 7°) to very poor (very poor ground condition, very uneven ground surface, slope more than 26°).

Stand 1 was a 30-year-old Norway spruce (*Picea abies*) plantation on an afforested pasture (Table 1). The strip road system (net of roads in the thinning area along which the machine moves) was planned in advance by a forester. The distance between the strip roads was 19.2 m while strip road width was 3.4 m.

Stand 2 was a 90-year-old mixed stand of Scots pine (*Pinus sylvestris*), Norway spruce (*Picea abies*), birch (*Betula pendula*) and aspen (*Populus tremula*). This stand was a clear-cut stand, but only the smallest trees (< 28 cm diameter in breast height) were harvested in this study. Stand data are shown in Table 1.

Before the start of the study the diameters of all trees in both stands were measured and marked on the stems.

Table 1. Stand data.

	Stand 1	Stand 2
Basal area (m/ha)	23.25	24.3
Species mix (pine, spruce, deciduous), in tenths	0, 10, 0	3, 6, 1
No of trees per hectare prior to (after) thinning	2120 (1179)	940 (374)
Mean cut tree diameter (cm)	12.9±3.8 (SD)	16.5±5.4 (SD)
Mean cut tree volume (m^3)	0.096	0.194
Ground conditions	Very good	Very good
Surface structure	Very even	Medium class. Some area of the stand worse than medium class
Slope	Less than 7°	Less than 7°

2.2 The Harvester

The harvester was a CASE 5120 tractor with a crane (Mowi EGS 465) attached to the front. The crane reach was 5.9 m. The harvester head (GM 728R PAN) was able of handling stems up to 28 cm dbh (diameter at breast height). The tractor was 225 cm wide and had a mass of 7750 kg. The operator had one month experience with this machine, but he had operated forwarders for six years, a Logma processor for three years, and an FMG single-grip harvester for one year. Further information on the machine, a detailed production study and an ergonomic assessment is reported by Johansson (1997).

2.3 Harvesting Systems

In stand 1 the harvester operator selected trees to thin within crane reach as he progressed through the stand on strip roads (crane zone). Trees that could not be reached by the harvester (middle zone-trees) were manually felled towards the nearest strip road. After harvesting the crane zone-trees the machine was driven along the strip roads again to process the middle zone-trees. These trees were taken from the top, and then adjusted so they could be processed from the butt. In the crane zone 574 trees were harvested and in the middle zone 219 trees were harvested.

In stand 2 no strip road network was used. The machine operated in the stand winding between remaining trees. The smaller trees were harvested by the harvester while the larger trees were to be harvested manually at a later date (two stage felling).

2.4 Damaged Trees

Damage to the remaining trees was recorded during the harvesting operation. Only wounds that occurred in connection to the tractors work were noted. Wounds that occurred during manual felling were not recorded. Trees that had ripped-off bark and exposed sapwood were regarded as damaged and several characteristics concerning the wounds and the trees were collected; size of the wound (maximum length and maximum width were measured), location of the wound, distance of the damaged tree from the strip road edge, and diameter of the damaged tree.

The wound sizes were grouped in six classes: 0–20 cm^2, 20–50 cm^2, 50–100 cm^2, 100–200 cm^2, 200–300 cm^2, and 300– cm^2. Location of the wounds was identified for three regions:

1. root collar and roots within horizontal distance of 0.7 m from stem surface at root collar height
2. from root collar up to 1.5 m above root collar and,
3. rest of the stem.

The wounds were also categorised according to the part of the machine causing the wound (crane, felling head, chassis, tree under processing, wheels), and the operational phase during which damage occurred (move to the next location, select and cut the tree, process the tree). "Move to the next location" begins when the harvester starts to move and ends when the harvester stops moving to perform a task. "Select and cut the tree" begins when the boom starts to move and ends when the tree has been felled. "Processing" begins when the tree has been felled and ends when the felling head has dropped the tree top and the boom starts to move to the next tree or the harvester moves to a new location.

2.5 Rut Depth

Rut depths of wheel trails free from residue cover were measured in both stands by placing a rigid pole across the full width of the wheel trail and measuring the distance from the pole (placed on the top of the forest floor) to the soil surface in the centre of each wheel trail. Rut depth in stand 1 was measured after one, two, four and six passes. Measurements were taken on unequal distances due to residue occurrence. Rut depth in stand 2, was measured in places where the two front wheels of the harvester were stationed while the machine was felling, delimbing, cross cutting and bunching and in places where the machine just passed without stopping.

The one-sample Kolmogorov-Smirnov test was used to test the hypothesis that the observations in the rut depth data sets are normally distributed. The Student's t-test was used to determine whether the differences between the rut depths were statistically significant ($p < 0.05$).

3 Results

In stand 1, 6.3 % of the remaining trees or 64 spruce trees were damaged (74 wounds). Processing the manually felled middle zone-trees damaged 18 trees (23 wounds) and harvesting the crane zone-trees damaged 46 trees (51 wounds).

In stand 2, 6.5 % of the remaining trees or 30 trees, of which 5 were pines, 7 were birches and 18 were spruces, were damaged (38 wounds).

Wounds smaller than 20 cm^2 were the most frequent in stand while in stand 2 wounds in the 20–50 cm^2 class were more common (Table 2). 79% of the total amount of wounds in both stands covered less than 13 % of the damaged tree circumference (Table 2). The wounds were concentrated in the tree region from the stump up to 1.5 m over stump. This was common for both stands and all three harvesting regimes (Table 2). The phase that caused most wounds was the processing phase mainly due to trees under processing by the harvester (Table 3). Damaged trees were distributed more or less evenly in the stand (Fig. 1).

The observations in the rut depth data sets were found to be normally distributed. Rut formation is clearly influenced by the number of trips in stand 1 (Table 4). Significant differences

Table 2. Wound frequency (%) into wound size classes (WS), damage circumference classes (DCC) and location on the stem.

	Regime: Stand 1 Crane zone (%)	Stand 1 Middle zone (%)	Stand 2 (%)	Total (%)
WS ≤ 20 cm^2	40	48	24	36
20 < WS ≤ 50 cm^2	24	21	39	29
50 < WS ≤ 100 cm^2	20	9	16	16
100 < WS ≤ 200 cm^2	10	18	8	11
200 < WS ≤ 300 cm^2	2	–	8	4
WS > 300 cm^2	4	4	5	4
DCC ≤ 13 %	76	70	89	79
13 < DCC ≤ 25 %	18	26	8	17
DCC > 25 %	6	4	3	4
Root collar and root	8	4	13	9
Stem –1.5 m	86	83	74	81
1,5 m–	6	13	13	10

Table 3. Distribution (%) of the wounds to machine parts and operational phases.

	Regime: Stand 1 Crane zone (%)	Stand 1 Middle zone (%)	Stand 2 (%)	Total (%)
Machine part				
Wheels	8	4	13	9
Chassis	–	–	–	–
Crane	10	4	3	6
Felling head	11	17	26	18
Tree	63	75	47	60
Other	8	–	11	7
Operational phase				
Moving	8	4	16	10
Crane in/out	18	17	16	17
Processing	66	79	58	66
Unknown	8	–	10	7

Table 4. Mean Rut Depth (MRD) cm ± (SD.)

Stand 1 Passes	MRD (±SD)	No. of observations	Stand 2	MRD (±SD)	No. of observations
Pass1	*3.9A ± (2.08)	28	Stand Point	5.7D ± (1.09)	15
Pass2	4 A ± (3.8)	13	Move Point	4.7E ± (0.96)	15
Pass4	6.02B ± (1.3)	16			
Pass6	7.3C ± (1.83)	12			

*Rut depths followed by the same letter are not statistically different (a = 0.05)

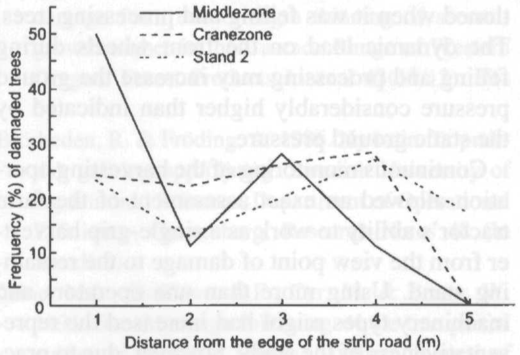

Fig. 1. Distribution of the damaged trees according to their distance from the edge of the strip road (%). (Middlezone and cranezone refer to Stand 1)

were found between rut depths created by the tractor after different number of trips on residue-free parts of the road. The only non-significant difference was found between the rut depth after one and two passes of the harvester.

Significant difference was found in stand 2 between the rut depth measured on road sections where the front wheels of the tractor where situated when it was felling and processing trees and the rut depth measured on road sections where the machine was just passing (Table 4). Both road sections were residue-free.

4 Discussion

The continuous observation of the farm tractor during the harvesting operations gave the opportunity not only to assess the amount of tractor damage to the residual trees but also to categorise the damage by cause. Nevertheless, some damage may have escaped observation in stand 1 because of poor visibility due to high initial density and distance between the observer and the machine needed for safety reasons, but also to avoid disturbing the operator.

A consensus is lacking over the size and type of wounds researchers record during a damage inventory. Bettinger and Kellogg (1993) group the wounds into three classes; minor (up to 30 in^2), significant (30–100 in^2) and major (over 100 in^2). Lageson (1996) uses three size classes as recommended by Björheden and Fröding (1986): up to 20 cm^2, 20–100 cm^2 and over 100 cm^2 but faces difficulties in detecting wounds smaller than 20 cm^2 especially if they are located high up on the stem. Eriksen (1990) considers only wounds larger than 15 cm^2 in his study. The choice to disregard small wounds appears logical since severity of decay is greater for larger wounds (Hunt and Krueger 1962 , Yde-Andersen 1976).

Ryynänen (1994), studying an agricultural tractor and a carriage with a crane mounted harvesting head, noted that 2.1 % of the remaining trees were damaged in a first thinning of a pine stand. In an earlier study (1992) on a front axle, crane mounted tractor, the same researcher found a damage level that ranged from 0.9 to 3.8 %. Gullberg and Johansson (1992) report that the tractor they studied, a Ford Versatile tractor with a rear axle, crane mounted harvesting head, produced wounds larger than 15 cm^2 at 7 % of the remaining trees. In the present study, if wounds smaller than 20 cm^2 are disregarded, as Björheden and Fröding (1986) suggest, then damage level drops to 4.2 % for stand 1 and 5.3 % for stand 2.

Concentration of wounds in the part of the trees from the root collar and up to 1.5 m over the root collar was expected since the processing of trees is done at that height. This is in agreement with Lageson (1996), Ryynänen (1994), Bettinger and Kellogg (1993) who all observed a concentration of wounds at the lower part of the stem.

Fröding (1992) reported results from an inventory of stands harvested by a single-grip harvester, where processing accounted for more than 50 % of the damage to the residual trees and 40 % of the damage was due to driving (moving). Gullberg and Johansson (1992) found that 76 % of the wounds occurred during processing while only 16 % were due to the wheels when the tractor was moving. In the present study it was observed that 66 % of the wounds occurred during processing by the stems under processing or by the harvesting head. Five percent of the trees processed by the harvester produced some kind of damage to remaining trees. In stand 1, when the harvester was processing trees felled manually, 8.3 % of the trees being processed caused some kind of damage to remaining trees. When the harvester was both felling and processing trees, damage to the standing trees was caused by 5.4 % of the trees under processing. In stand 2 this level was 2.5 %. This difference can be explained by the low initial stand density in stand 2, allowing more space for processing.

Ryynänen (1994) reports that 60 % of the trees damaged during harvesting with a farm tractor equipped with a single-grip harvester were situated between 0 and 1 meters from the edges of the strip road. Bettinger and Kellogg (1993) studying a harvester-forwarder system found that 72 % of the damage, scar area per acre, occurred on trees that were within 2.9 m from the edge of the strip road. In the present study in stand 2, the number of damaged trees is distributed more or less evenly in the crane reach zone. The same is observed in stand 1 when the harvester operator selected trees within crane reach to thin as he progressed through the stand on strip roads. This can be partly explained by the fact that as the distance between the operator and the tree to be cut increases, it is more difficult for the operator to control the crane movements and collisions occur. When the harvester is processing trees felled manually, damage is concentrated at the trees near the strip road (0–1 m) since all work is localised close to the strip road.

Rut depth is found to be influenced by the number of passes of the machine (Wästerlund 1992) and a significant difference between the rut depth after one, two, four and six passes was expected. Higher static ground pressure of the front axle (88.5 kPa) of the vehicle, where the crane was attached, compared to 52 kPa of the rear, contributed to deep rut depths on road parts where the front wheels of the tractor where positioned when it was felling and processing trees. The dynamic load on the front wheels during felling and processing may increase the ground pressure considerably higher than indicated by the static ground pressure.

Continuous monitoring of the harvesting operation allowed an exact assessment of the farm tractor's ability to work as a single-grip harvester from the view point of damage to the remaining stand. Using more than one operators and machinery types might had increased the representativeness of the study, however, due to practical and economical reasons only one operator and one machinery type was used. The small percentage of wounds larger than 50 cm^2 suggests that eventual decay is not expected to substantially reduce the total value of the final harvest. Farm tractor based forestry equipment offer possibilities for mechanised harvesting with considerably small capital investment for small scale harvesting operations or where careful thinning and selective tree harvesting is required.

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