Effects of Forwarder Tyre Pressure on Rut Formation and Soil Compaction

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In Swedish forestry, final felling is usually done by a harvester and a forwarder. These machines are heavy and the risk for rutting and soil compaction can be considerable under unfavourable soil conditions. The aim of this study was to evaluate effects of forwarder tyre inflation pressure on rutting and soil compaction after final felling. Three levels of forwarder tyre pressure were studied, 300, 450 and 600 kPa, after 2 and 5 machine passages. The first passage was driven with a 19.7 Mg harvester, and the second to fifth passages with a fully loaded forwarder totalling 37.8 Mg. Rut depths were not significant affected by tyre pressures but increased significantly with the number of machine passages. Soil density was significantly increased by 0.075 $Mg\,m^{-3}$ by the harvester passage. Soil density increased significantly with increasing number of forwarder passages, and tyre pressure did not significantly influence this increase but the interaction between number of forwarder passages and tyre pressure was almost significant. Data suggest that density increases occur earlier in the 600 kPa treatment than in the other treatments. Only parts of an area harvested are trafficked in a normal harvesting operation. Outside the research area approximately 12.5 per cent of the area harvested was covered with ruts. On primary strip roads, which are heavily trafficked, soil compaction cannot be avoided by reducing the tyre pressure. On secondary strip roads, not passed more than once by the forwarder, a low forwarder tyre pressure may reduce soil compaction.

Keywords soil density, cone penetrometer, final felling, till soil
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1 Introduction

In Swedish forestry, final felling is usually done with a large harvester and a large forwarder. These machines are heavy, the mass of a large harvester can exceed 20 Mg and a laden large forwarder approaches 40 Mg. Thus the risk for soil disturbance, i.e. rutting and soil compaction, can be considerable under unfavourable soil conditions. Most studies of soil disturbance have been made of small to medium sized machines in thinning operations (Wronski and Murphy 1994, Jansson and Wästerlund 1999). However, a number of studies have been made after wood transport with medium to large forwarders (20–33 Mg). These studies reports soil compaction reaching deeper than 40 cm (Jacobsen and Greacen 1985, Jansson and Johansson 1998) and effects on rut depths by multiple machine passages (Wronski et al. 1990, Jansson and Johansson 1998). In thinning, one of the major disadvantages caused by machine traffic is damage to the roots of living trees which causes growth losses in the forest crop (Wronski and Murphy 1994). On the other hand, tree roots increase soil strength considerably (Björkhem et al. 1975, Wästerlund 1989), thus improving trafficability in the forest stand. In final felling, where most if not all trees are felled, the strengthening effects of the roots persist but as the tree crop is harvested no growth losses due to root damage will occur. However, compacted soil can cause growth reductions in the new forest crop (Sands and Bowen 1978, Wästerlund 1985).

In many harvesting operations logging debris, i.e. branches and tree tops, are used to reinforce the strip roads in the stand (Wronski and Murphy 1994), which results in a substantial increase in soil bearing capacity (Wronski et al. 1990). During the last decade there has been an increased interest in the Nordic countries to utilise this logging debris for energy production. Heating plants burning logging residues do not accept contamination of the fuel with soil particles. Thus, when logging residues will be used for energy production it is not possible to use the residues to reinforce strip roads.

In addition to the use of logging debris to reinforce strip roads, larger tyres, lower tyre pressure, and bogie-tracks are methods used to reduce the risk for soil disturbance, i.e. methods similar to those used on agricultural vehicles (Alakukku et al. 2003, Chamen et al. 2003). Myhrman (1990) reported that an increase of the tyre width from 600 to 800 mm reduced rut depths with approximately 50 per cent for a eight wheeled 22 Mg forwarder. Tyre pressures on large forwarders are high compared to those used in agriculture due to high wheel loads and the uneven terrain, with obstacles such as stones and stumps, in which they are used. In a study of the effects on rutting and soil compaction after traffic with a bogie axle load of 12.5–14 Mg, Bygdén et al. (2004) found that use of bogie tracks on the trailer reduced rut depth and that changes in cone index after traffic compared to the trailer without the tracks. This was an effect of the increased flotation caused by the bogie tracks. However, due to the risk of damage to the tyres, tyre manufacturers recommend that tyre inflation pressures are kept close to maximum levels when bogie tracks are used.

The aim of the present study was to evaluate effects of forwarder tyre inflation pressure on rutting and soil compaction after final felling, to see if a decrease in forwarder tyre inflation pressure could be used to reduce rutting and soil compaction after final felling where logging residues are not used to reinforce strip roads.

2 Material and Methods

The study was done in a Norway spruce (*Picea abies* (L.) Karst.) stand close to Össjö in southern Sweden (56°16´N, 13°04´E). The experiment was a factorial with two factors, forwarder tyre pressure and number of machine passes. Three levels of forwarder tyre pressure were studied, 300, 450 and 600 kPa, where 300 kPa is equivalent to the lowest tyre pressure permitted for the tyre load, and 600 kPa is the pressure recommended when using bogie tracks. The effects of 1, 2 and 5 machine passages were studied. The number of passes was chosen to control 1) the effect of the harvester, 2) to describe the effects of the tyre pressures after one forwarder passage, and 3) to describe the effects of the tyre pressures on a moderately high trafficked strip road.

The first passage was driven with the harvester, which at the same time felled and processed the trees in the stand. The harvester was a Timberjack 1270D equipped with Nokian 700/50×26.5 tyres on the front bogie axles and Nokian 700/55×34 on the rear single axle. The harvester had a total mass of 19.7 Mg. The tyre pressure was 450 kPa in the bogie tyres and 260 kPa in the rear tyres. The second to fifth pass were all driven with a loaded Timberjack 1710B eight wheel forwarder totalling 37.8 Mg (unloaded mass 21.2 Mg). The forwarder was considered fully loaded, as the load weight was 16.6 Mg and the rated load capacity of the machine is 17 Mg. Tyre loads on the forwarder front part were on average 3.02 Mg per tyre and on the rear part 6.42 Mg per tyre. The machine was equipped with Trelleborg twin forestry 428 tyres size 750/45-30.5 LS2 on all four bogies. The tyre pressure of the forwarder was carefully adjusted to the levels specified (300, 450 and 600 kPa) in the experiment by staff from Trelleborg Wheel Systems. 300 kPa was seen as the minimum acceptable tyre pressure considering the tyre load on the rear part of the machine and the terrain at the test site, and 600 kPa is the recommended pressure when using bogie tracks on the machine.

Three blocks were established in the stand, two blocks on a dry sandy silty till soil and one on a moist sandy silty till soil (Fig. 1). The bearing capacity of the site was fairly high, as indicated by an average cone index of 985 kPa in the upper 10 cm of the soil. Terrain classification was done according to Berg (1992). The stand had an even ground surface (surface structure class 1) but the research area was located in a small valley, so the plots in block one were situated in a gentle downhill slope (slope class 2), the plots in block two were on flat land (slope class 1), and the plots in block three were situated in a gentle uphill slope (slope class 2). In each block three experimental plots were established and measurement of soil density, soil moisture, and cone resistance were made before trafficking and after 1, 2 and 5 machine passages. Rut depths were measured after 1, 2 and 5 machine passages. Measurements were made in two permanent sample points, one in each track, per plot except for cone resistance, which was measured in six sample spots per plot. Soil samples were collected from 20 and 40 cm depth adjacent to the northern sample point in each plot. The soil samples were gathered using 50 mm high steel cylinders with 72 mm diameter, thus the soil samples do not contain any stones or rocks. However, stones or rocks were found in all sample pits in block 1 and 3.

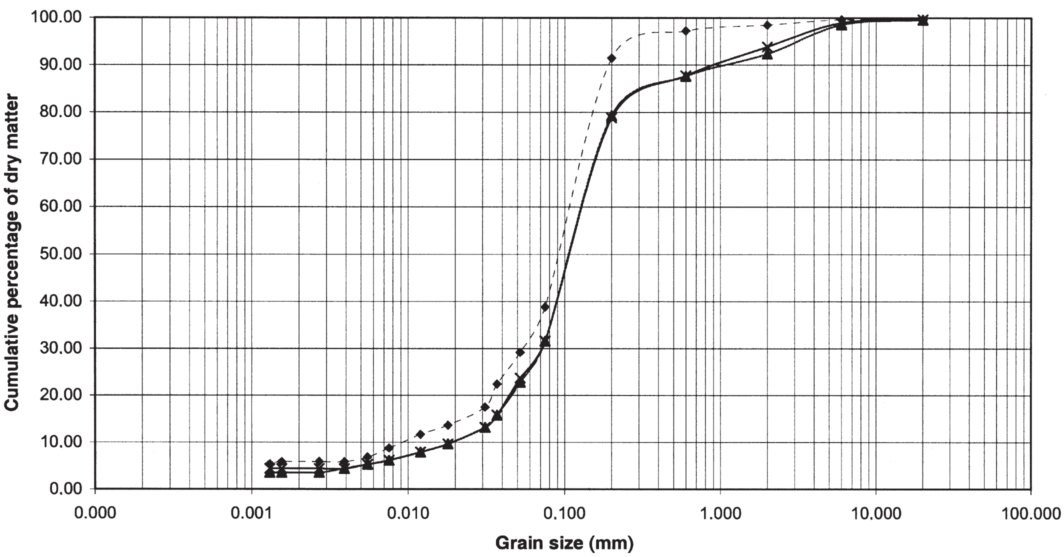

Fig. 1. Particle size distribution for particles <20 mm, block 1 (triangles) and 3 (crosses) were dry, and block 2 (rhombi) moist.

Soil wet density and soil moisture content were measured with a Campbell Pacific nuclear dual probe strata gauge MC-S-24 at 10, 20, 30 and 40 cm depth in the track after 0, 1, 2 and 5 passages on 2 permanent sample points per plot. The strata gauge was placed perpendicular to the direction of the rut and placed to be as centred as possible in the expected rut. The two holes for the probes of the gauge were filled with wooden rods between measurements, enabling measurements in the exact same location each time. As soil moisture readings from the strata gauge are known to have a risk for systematic deviations from the true values (Jansson 1998), soil moisture content readings were controlled using a comparison between relative moisture content from the soil samples and the relative moisture content from the same depth with the strata gauge. A linear regression was made to get a correction function for the moisture content and all moisture contents measured were corrected. Thereafter, soil dry density was calculated as the difference between wet density and moisture content. Rut depths were measured in the same sample points as soil density, a wooden rod was laid across the rut and the distance from the ground surface to the underside of the rod was measured between the holes for the probes.

Cone resistance was measured on 6 permanent sample spots per plot with an Eijkelkamp penetrologger equipped with a 3.33 cm^2 cone with 30° top angle. The sample spots were approximately 0.3 m × 0.3 m and situated in the rut centre. The aim was to, if possible, penetrate the soil to a dept of 30 cm. If the penetrometer struck a stone, one renewed attempt was made in the same sample spot. For each penetration, average cone index (kPa) was calculated for three depth ranges (1–10 cm, 11–20 cm and 21–30 cm), and the penetration depth were noted. Observe that the maximum penetration depth was set to 30 cm as a consequence of the field instruction.

There were no significant differences between treatments in pre-treatment soil dry density, initial soil cone index or in soil dry density after the harvester passage at any of the four depths studied. However, the average value for the soil dry density at 40 cm depth was high for the 450 kPa treatment, as in three measurement points (one in block 2 and two in block 3) there were stones between the measurement probes leading to high density values and a large variance in that treatment. Initial soil moisture content did not differ between treatments or measurement depths but the blocks were significantly separated from each other. Initial soil moisture content was 0.217, 0.324, and 0.247 $Mg\,m^{-3}$ in block 1, 2, and 3 respectively.

For all measurements plot mean values were used in the analyses. For comparisons of the effects of forwarder tyre pressure, soil measurements after the harvester were used as a base line, and differences from that were analysed using analysis of variance. Treatment effects were considered significant if $p < 0.05$.

3 Results

Rut depth (Table 1) was not significantly affected by the tyre pressure treatment ($p = 0.230$), but increased significantly ($p < 0.001$) with number of machine passages.

Soil dry density was significantly ($p < 0.001$) increased by the harvester passage with 0.075 $Mg\,m^{-3}$ (Fig. 2), and no differences could be established between measurement depths ($p = 0.973$).

Table 1. Rut depth (cm) separated on forwarder tyre pressure and number of vehicle passages.

No. of passages	Forwarder tyre pressure (kPa)		
	300	450	600
1 (harvester)	3.3	3.2	3.2
2	5.2	4.5	4.7
5	8.0	6.0	9.2

Table 2. Soil dry density increase ($Mg\,m^{-3}$) caused by the harvester and the p-value for that increase separated on measurement depth.

Depth	Density increase	p
10	0.084	<0.001
20	0.067	<0.001
30	0.074	0.026
40	0.076	0.052

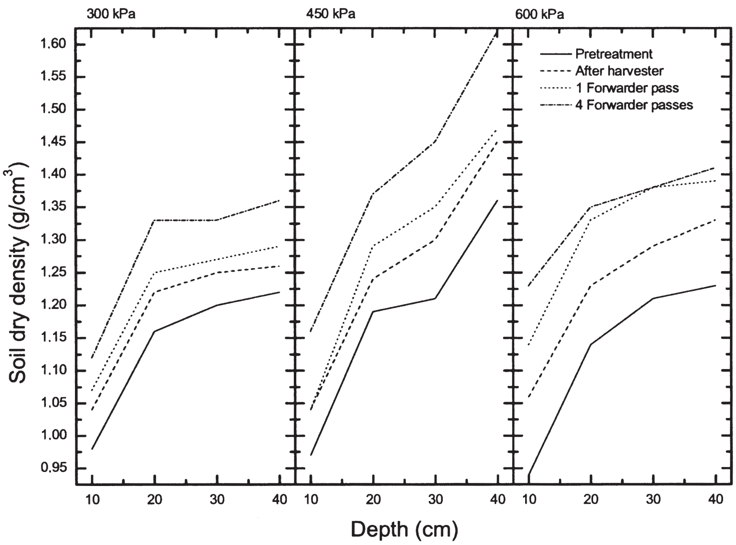

Fig. 2. Soil dry density separated on depth and number of passages. Solid line equates untrafficked soil.

Table 3. Analysis of variance (ANOVA) for the effect of forwarder tyre pressure (T) and number of forwarder passages (P) on soil dry density changes that occurred after the harvester passage.

Source	Type III SS	df	MS	F	p
Intercept	0.488	1	0.488	119.9	0.001
Block	0.001	2	0.0005	0.12	0.889
Treatment (T)	0.016	2	0.008	2.0	0.149
Passage (P)	0.082	1	0.082	20.2	0.000
Depth (D)	0.002	3	0.0006	0.14	0.933
T × P	0.021	2	0.010	2.6	0.088
T × D	0.015	6	0.003	0.63	0.702
P × D	0.004	3	0.001	0.29	0.831
T × P × D	0.007	6	0.001	0.27	0.947
Error	0.188	46	0.004		
Total	0.823	72			
Corrected total	0.335	71			

Table 4. Increase in soil dry density ($Mg\,m^{-3}$) caused by 1 and 4 forwarder passages with 3 different forwarder tyre pressures. Plots were passed by a harvester prior to forwarder passages, and density after the harvester passage was used as reference level. Mean values in the same column followed by different letters are significantly separated. Means followed by an ^{x} are significantly separated from 0.

Forwarder passage	Tyre pressure (kPa)		
	300	450	600
1	0.030a	0.033a	0.083a^{x}
4	0.093b^{x}	0.144b^{x}	0.111a^{x}

In separate analyses for each depth, the harvester caused a significant soil dry density increase at all depths but 40 cm (Table 2).

Soil dry density increases caused by the forwarder increased significantly when the number of forwarder passages increased from 1 to 4 ($p<0.001$). The effect of tyre pressure did not significantly influence dry density change ($p=0.149$), but the interaction between number of forwarder passes and tyre pressure was almost significant ($p=0.088$, Table 3). The cause for this is that the density increase seems to occur earlier for the 600 kPa tyre pressure treatment than for the 300 and 450 kPa treatments (Table 4).

Average depth reached with the penetrometer was significantly affected by number of passes ($p=0.002$) and block ($p>0.001$), but not from the

Table 5. Analysis of variance (ANOVA) for the effect of forwarder tyre pressure (T) and number of machine passages (P) on the cone index between 11 and 20 cm soil depth.

Source	Type III SS	df	MS	F	p
Intercept	6706404	1	6706404	1349.8	0.001
Treatment (T)	31839	2	15920	3.2	0.061
Passage (P)	134500	3	44833	9.0	0.000
Block	60959	2	30480	6.1	0.008
T × P	55583	6	9264	1.9	0.135
Error	104335	21	4968		
Total	7050606	35			
Corrected total	385023	34			

Table 6. Average CI (kPa) between 11 and 20 cm soil depth separated on forwarder tyre pressure and number of machine passages.

Passage	Forwarder tyre pressure (kPa)		
	300	450	600
0	1214	1196	1130
1 (Harvester)	1384	1165	995
2	1647	1581	1736
5	1413	1515	926

tyre pressure treatment ($p = 0.130$) or the treatment by passage interaction ($p = 0.334$). Penetration depth was significantly smaller after 2 machine passes (17.3 cm) than after 0 (23.5 cm), 1 (23.2 cm) or 5 passes (22.6 cm), between which no differences could be found. Average depth was 19.8, 26.5, and 18.7 cm for block 1, 2, and 3, respectively, and block 2 was significantly separated from block 1 and 3. After five passes penetration depth for the 300, 450 and 600 kPa treatments were 20.5, 25.0, and 22.3 cm, respectively.

At 1 to 10 cm depth and at 21 to 30 cm depth, no significant effects of any factor studied could be found on average CI. At 11 to 20 cm depth there were significant effects on average CI for number of passes and block and an almost significant effect by tyre pressure (Tables 5 and 6). Soil cone resistance was significantly higher after 2 passes than after 0, 1, or 5 passes between which no differences could be found. Block 2, where the soil had higher moisture content, had significantly lower average CI than block 1 and 3. The 600 kPa tyre pressure treatment had on average lower CI than the other treatments, although not significantly so ($p = 0.061$).

4 Discussion

Ruts were measured in the same spots during the experiment, however as the ground was not completely flat, there might be a small overestimate of the rut depth caused by the uneven ground. As there are no differences in rut depths after the harvester passage there is no reason to believe that this measurement error should affect comparisons between forwarder tyre pressures.

No measurement point for the soil density measurements had to be moved during the study. It was unfortunate that three measurement points (one in block two and two in block three) in the 450 kPa treatment were located so that stones influenced the measurements on 40 cm depth leading to a large variation in plot mean dry density for the treatment at that depth. However, this has probably had no major effect on the density changes, as density changes in these points were of the same magnitude as those in the three other points. After treatment soil dry density had increased with 0.168–0.219 $Mg\,m^{-3}$, i.e. with approximately 17 to 23 per cent at 10 cm depth and 13 to 17 per cent at 40 cm depth. It seems as the highest forwarder tyre pressure gives a higher increase in soil dry density after the first forwarder passage, as it is only in this treatment where there is a significant increase in soil density compared to after the harvester passage. This is also indicated by the strong treatment passage interaction ($p=0.088$) in the ANOVA (Table 3). However, after four forwarder passages no trace of a treatment difference can be found. In hindsight, the experiment should have been replicated in at least one block more, but this was not possible due to limited resources and a tight time schedule.

Low pressure tyres is an established way to reduce soil compaction in agriculture (Alakukku et al. 2003). The fact that no significant effects of tyre pressure were found in the present experiment can partly be explained by the fact that compared to low tyre pressures as used in agriculture, i.e around or lower than 100 kPa, the lowest tyre pressure studied was comparatively high. These high pressures are needed because of the high wheel loads and the uneven forest terrain, with stumps and stones that can damage the tyres (Trelleborg Twin Forestry 2004).

In accordance with theory (Rohani and Baladi 1981, Koolen and Kuipers 1983), soil cone penetration was made to larger depths and with less resistance in the moister block 2 than in the other blocks. After the first forwarder passage penetration depth was reduced and soil resistance increased compared to the undisturbed measurements, why these changes disappeared after three further passes with the forwarder cannot be explained. During the experiment the cone penetrometer proved to be a difficult or, frankly, unsuitable piece of equipment to use in the stony soil. Even a small stone will stop the cone if hit by the tip of the cone. Thus, stones limited the penetration depth for quite many measurements. However, this should not have caused any differences between treatments, but the fact that all measurements except the last were made under stress, as the period of availability of the forwarder was limited, could have influenced the results. Thus, during measurements of untrafficked soil, after the harvester, and after the first forwarder pass, just one extra attempt was made if a stone was struck by the penetrometer. After the fifth passage measurements were made in a more relaxed way and there are suspicions that more than one extra attempt were made if the penetrometer got stuck early.

It was only at 30 and 40 cm's depth that soil reached dry densities in excess of 1.50 Mg m^{-3}, i.e. densities that should inhibit root growth (Wronski and Murphy 1994), and the average cone resistance rarely approached 2.0 MPa, i.e. levels that inhibit root growth. However, according to results from pot studies (Sands and Bowen 1978, Wästerlund 1985) surface soil density increase is large enough to reduce seedling growth, at least in the 600 kPa treatment. As the stand will be scarified, and surface soil thus loosened, prior to planting of the next tree crop, this negative growth effect will probably be reduced.

Outside the research area there was approximately 12 m between strip roads and consequently, as the tyres used were 750 mm wide, approximately 12.5 per cent of the area was affected by machinery traffic. This is comparable to the 12.1 per cent share of tracks Wågberg (2001) found in a survey of 20 final fellings. All of the trafficked area receive one harvester passage and one forwarder passage. The closer to the landing, where logs are unloaded, the larger the probability that strip roads will receive additional forwarder passages. Some of the compacted soil will be loosened when the harvesting site is scarified, probably with a disc trencher, prior to replanting (Miwa et al. 2004). Due to the low clay content in the soil at the study site, little natural recovery from compaction due to shrinkage and swelling or frost heaving can be expected (Greacen and Sands 1980, Webb et al. 1983, Miwa et al. 2004).

The gentle soil surface at the site studied allowed tyre pressures as low as 300 kPa with the tyre load used. A more uneven surface will, according to the tyre manufacturer (Trelleborg Twin Forestry 2004), necessitate an reduction of the load or an increase in tyre pressure on the rear part of the machine in order to reduce the risk for tyre damage. An increase to 400 kPa would be enough except for areas with very difficult terrain conditions, and as neither the 300 nor 450 kPa tyre pressures led to any significant density increases to the soil already compacted by the harvester, no increases should occur after one passage with a forwarder using a tyre pressure of 400 kPa. Considering the large tyre load, forwarder traffic outside the harvester tracks will probably lead to a soil density increase in the soil irrespectively of tyre pressure used.

It should be noted that although the pressure in all tyres was held at the same level during this study, this needs not to be the case in other operations. As tyre loads are lower on the front bogie, front tyres do not need to be inflated to the same high pressure as the tyres on the rear bogie.

5 Conclusions

On primary strip roads, with a large number of forwarder passes, soil compaction cannot be avoided by reducing the tyre pressure. However, on secondary strip roads which are not passed more than once or perhaps twice by the forwarder a reduced tyre pressure might limit soil compaction almost to that caused by the harvester.

To reduce the risk for soil compaction, tyre pressure should be reduced when forwarders that normally use bogie-tracks are used without them for longer periods of time. From an economical viewpoint it is necessary that the period of use at the lower tyre pressure is not too short due to the time, and thus cost, associated with reducing tyre pressures and refilling them to the recommended pressure for use with tracks.

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