Soil Disturbance by Off-Road Traffic of Forwarders; Magnitude, Persistence and Mitigation

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Abstract:
Timber harvesting and extraction machinery is commonly used for economic reasons and enhanced safety of the operators. However, there is the risk of soil disturbance caused by off-road traffic of this heavy machinery. These disturbances may result in compaction or displacement of soil leading to rutting.
Three test sites were established in New Brunswick (Canada) to assess the magnitude and persistence of soil disturbances caused by forwarders of cut-to-length harvesting systems. Soil density changes were analyzed and relative soil bulk densities (relative compaction) were derived by relating field soil bulk densities before and after off-road traffic impacts to site specific standard Proctor densities. One test site involved the use of forest biomass (residue from timber harvesting such as limbs, branches, foliage and tree tops) as a covering layer (mat) on machine operating trails to mitigate soil disturbances from machine traffic. Brush mats of varying quantities ranging from 5 to 20 kg softwood brush per square meter were compared to analyze their capability to lower density increases. Finally, in a laboratory test we compared the load dispersing capabilities of softwood and hardwood brush of varying quantities.
The test results showed soil bulk density increases of 17 to 46% after single to few passes of loaded forwarders. Two of the three test sites were monitored for 6 years to identify potential rehabilitation pattern of soil bulk density with respect to pre-impact values. The results showed no significant density changes during the multi-year period. The brush mats of 20 kg per square meter showed the highest reduction in soil bulk density increases. Furthermore, when analyzing relative bulk density this brush mat showed a significant reduction of measurements exceeding the 80% standard Proctor density threshold beyond which plant growth is deemed to be impeded. The lab comparison of hardwood and softwood brush indicated a slight advantage of softwood brush for load dispersion compared to hardwood brush at most of the tested brush quantities and exerted loadings. During repetitive loading the softwood brush mat showed a more constant load transferring performance than the hardwood brush mat.

Keywords: soil bulk density, brush mat, relative soil bulk density, cut-to-length harvesting, forest machinery

1 Introduction

Forest industry relies on heavy machines for timber harvesting and extraction because of economic reasons but also for improved occupational health and safety of operators. Ground based (off-road) operation of these machines bears the risk of soil disturbance. Design of harvesting and extraction machinery continuously improves traction while reducing ground pressure, i.e., by higher number of axles per unit to spread the load, increased number of driven axles, use of low floatation tires and tracks. However, load capacity of some extraction machinery went up to 20 metric tons at the same time, keeping the risks for soil disturbance. In Atlantic Canada, the most common harvesting method is Cut-To-Length (CTL) using a machinery system consisting of single-grip harvesters and forwarders (J.-F. Gingras, personal communication, 2008). Compared to other harvesting systems, CTL is considered environmentally sound for directional felling and logs lifted up from the ground when being extracted by forwarders. However, high payloads of the latter may cause soil property changes such as density increases. The general goal of our study was to assess the impact of off-road machine traffic of harvesters and, in particular, forwarders on soil density. The related objectives were to (a) analyze machinery induced soil density increases by comparing absolute and relative bulk densities along machine operating trails before and after machine operations, (b) assess the use of brush layers (mats) on machine operating trails to mitigate traffic induced soil bulk density increases, (c) analyze the duration (persistence) of soil density changes, (d) compare hardwood and softwood brush with respect to load distributing capabilities. Throughout this paper soil dry bulk density is referred to as soil bulk density.

2 Material and methods

Three harvesting sites were selected for our studies on forestland in New Brunswick in Atlantic Canada (Figure 1). One site was located at the Canadian Forces Base Gagetown in Southern New Brunswick at 129 m a.s.l. with a 4% terrain slope while the other two sites (Black Brook 1 and 2) were established at the JD Irving Limited industrial freehold forestland district Black Brook in Northern New Brunswick at 250 m and 225 m a.s.l. with terrain slopes of 9 and 3%, respectively.

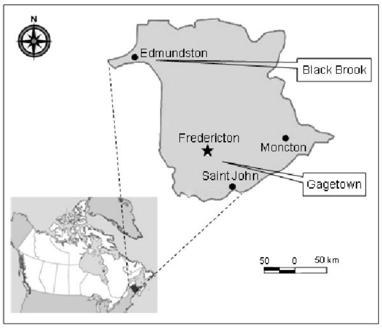

Figure 1: Map of New Brunswick (Canada) indicating the locations of the Gagetown and Black Brook research sites

The soil type at the site in Gagetown was classified according to the Unified Soil Classification System as sandy silt and at the two sites in Black Brook as silty sand with gravel and silt loam (Table 1). All soil types showed low plasticity.

Table 1: Soil properties according to the Unified Soil Classification System

Sites	Particle size distribution (%)				Average organic matter content (%)	Atterberg limits (%)		Classification
	Gravel > 2.0 mm	Sand 0.02 ≤ x ≤ 2.0 mm	Silt 0.002 ≤ x < 0.02 mm	Clay < 0.002 mm	Depth (cm) 0-30	Plastic	Liquid	
Gagetown	6.1	43.6	29.4	20.9	5.3*	28.2	28.4	Sandy silt (ML)
Black Brook 1	15.3	42.7	34.3	7.7	5.7	41.6	49.0	Silty sand with gravel (SL)
Black Brook 2	4.5	11.1	58.8	25.6	7.0	40.5	48.0	Silt loam (ML)

* 0-20 cm

As indicated in Table 2, the three test sites were covered by softwood, mostly comprised of white spruce (Picea glauca (Moench) Voss) and balsam fir (Abies balsamea (L.) Mill.). The silvicultural treatments ranged from commercial thinning at Black Brook (site 1) to clear cutting operations on the other two research sites in Gagetown and Black Brook (site 2). At all sites the CTL method was applied. Stand specifics and applied silvicultural treatments are given in Table 2.

Table 2: Forest stands characteristics and silvicultural treatments

Sites	Forest cover	Stand age (years)	Silvicultural treatment	Total volume	Volume harvested	% harvested	Average harvested DBH* (cm, on bark)
				m^3 ha^{-1}			
Gagetown	mixed softwood	55	Clear-cut	112	112	100	22
Black Brook 1	white spruce	25	Commercial thinning	142	53	37	11
Black Brook 2	white spruce, balsam fir	89	Clear-cut	160	160	100	24

* diameter at breast height.

The machinery used for timber harvesting and extraction at the three sites is listed in Table 3. The nominal ground pressure was derived using the PASCAL ground pressure calculator from FP Innovations. The nominal ground pressure of the harvesting machinery ranged from 41 to 54 kPa whereas the ground pressure of loaded forwarders was significantly higher and ranged from 57 to 91 kPa. Trafficking of both harvesting and forwarding machinery was restricted to machine operating trails.

Table 3: Harvesting and extraction machinery with nominal ground pressures and number of axles

Sites	Single grip harvester			Forwarder		
	Type	Nominal ground pressure (kPa)	Number of axles	Type	Nominal ground pressure (kPa)	Number of axles
Gagetown	John Deere 120	41	Rigid tracks	Timberjack 610	57	2*
Black Brook 1	Enviro	50	2	Rottne Solid F9	73	2 (both bogie)**
Black Brook 2	Volvo FBR 2800 C	54	Rigid tracks	Timberjack 1110	91	2 (both bogie)***

*High flotation tires, 109 cm wide. **Chains on second wheel of front axle and steel flexible tracks on rear bogie axles. ***Steel flexible tracks on rear bogie axle.

Along these operating trails we measured soil bulk density as an indicator of soil disturbance due to machine traffic before and after timber harvesting and extraction. The measurements were performed using a nuclear moisture and density gauge (NMDG, Humboldt 5001 EZ). This device enabled us to do in-place soil density assessments of low disturbance allowing for repetitive measurements at identical locations, e.g., before and after harvesting operations. Soil density at machine operating trails was assessed along transects perpendicular to the trail centerlines. Along each transect density measurement locations were spaced by 0.5 m over the full width of the trails, which were 4.0 m in Gagetown and 3.5 m in Black Brook (at both sites). Two adjacent transects spaced 1.0 m apart comprised a test plot or compartment. Sidewise to the test plots with at least 3.0 m distance from the machine operating trails, control plots with eight or six measurement locations in Gagetown and Black Brook, respectively, were established to monitor soil density at the control areas not impacted by machine off-road traffic.

Figure 2 shows the detailed test layout at the Gagetown research site which was similar to those at the two Black Brook sites. At each measurement location soil density (and soil moisture) were assessed at three depths within the top 20 cm of mineral soil in Gagetown and the top 30 cm in Black Brook. We measured soil densities and soil moisture at the established test plots and control areas pre impact before any machinery entered the sites. After timber harvesting and forwarding was completed we re-measured soil densities and soil moisture at identical locations to identify soil density increase on operating trails due to machine traffic (post-impact measurements).

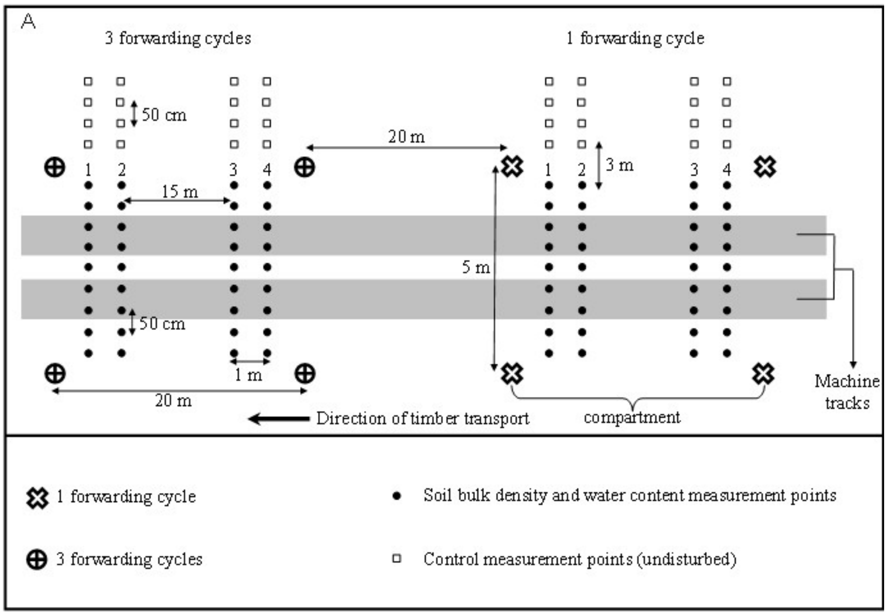

Figure 2: Test layout at the Gagetown research site

Machine traffic at the test sites consisted of one or three traffic cycles where a traffic cycle included one inbound and one outbound movement of each machinery (single grip harvester and forwarder) with the forwarder trafficking unloaded into the stand and loaded out. Test plots in Gagetown were exposed to either one or three traffic cycles whereas plots at the Black Brook site 1 were solely exposed to one cycle and at Black Brook 2 to three cycles. Test plots at the Gagetown site and at the Black Brook site 1 remained uncovered from any harvesting debris/brush (branches, foliage, tree tops) during machine trafficking whereas most test plots at the Black Brook 2 research site were covered with softwood brush amounts ranging from 5 to 20 kg per meter squared and had machines trafficking on top of the brush mats. The latter was done to investigate any mitigating effects of brush mats on soil disturbance and, in particular, on soil density increases due to off-road machine traffic. Once the operation was completed the brush was removed from the test plots and post-impact soil density measurements were performed similar to the procedure at the other two research sites.

To analyze the soil disturbing impact of machine traffic, we calculated the absolute density increases (in g per cm^3) from the differences of soil bulk densities pre and post impact and expressed density increases in percent of the pre-impact densities. To evaluate the severity of soil density increases we then related pre- and post-impact soil densities to site specific reference densities allowing us to determine the relative compaction of forest soils at the test plots. As reference densities, maximum bulk densities (MBD) were determined by standard Proctor tests using soil samples from the research sites. Recent studies in forestry (Zhao 2010) and before in agriculture (Carter 1990) showed significant decreases of plant growth once field soil density is increased to or beyond 80% MBD. At this point most of the macro pores and pore connectivity of the soil are lost resulting in reduced gas and water exchange and increased penetration resistance of the soil and, as such, impeded root and plant growth. Figure 3 shows field bulk densities (FBD) with related moisture contents as recorded pre and post impact at the Gagetown research site (Figures 3a and 3b, respectively). The inverse parabolas indicate moisture-density relationships as identified by standard Proctor testing to determine maximum bulk density (MBD) and the 80% MBD thresholds (indicated with the dashed horizontal lines).

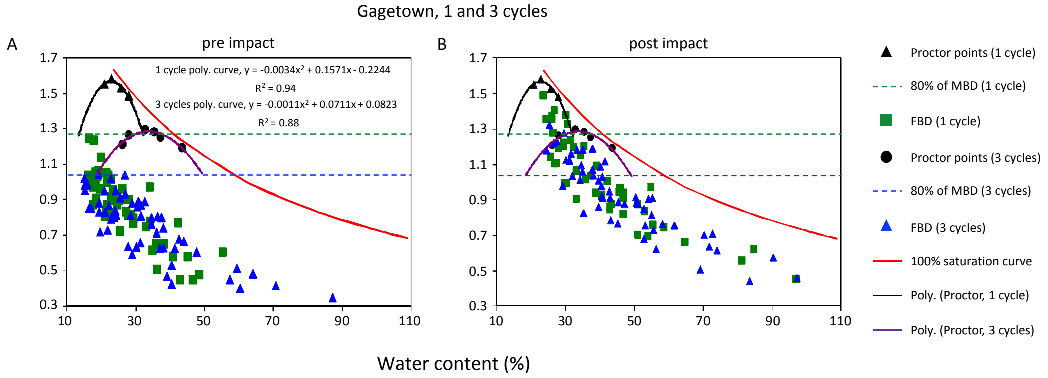

Figure 3: Field bulk densities (g/cm^3) at related soil water contents (%) as determined with the nuclear soil moisture and density gauge at track areas of the Gagetown research site (adapted from Labelle and Jaeger 2011)

The short-term persistence of soil density increases was monitored at two research sites (Gagetown and Black Brook 1) by measuring soil bulk density at all measurement locations every year for six years.

To determine the relative competence of hardwood and softwood brush mats in mitigating soil disturbances we performed pilot laboratory testing on load distribution pattern of brush mats. By exerting loadings on top of these mats and measuring received loadings below the mats we assessed the mats' competence to reduce peak loadings acting on the soil by transferring loadings into side areas. Using an Instron testing machine (Figure 4A), we exerted loads of up to 10 kN on a steel disc of 15.24 cm (6 inch) diameter (Figure 4C) on top of brush mats covering a load box (inside dimensions 37 cm long, 36 cm wide and 19 cm in height) filled with sand. At the bottom of the box the received loading was measured by three strain gauges mounted to small steel bars of 36 cm length and 2.54 cm width, one of which located in the middle of the box directly below the loaded disc and two strain gauges spaced at 13.7 cm adjacent to each side of the first one (Figure 4B).

Figure 4: A) Instron testing machine with load box, B) Three strain gauges at the bottom of the load box, C) Loading piston with disc

We compared the strain gauge responses when loading hardwood and softwood brush mats of varying quantity (10, 20, 30 and 40 kg per m^2) to the strain responses we recorded when exerting the loadings to bare sand in the load box (without any brush cover). The tested brush was comprised from green branches from yellow birch (Betula alleghaniensis Britton) and balsam fir (Abies balsamea (L.) Mill.) with a diameter less than 3 cm since this branch size is commonly found in brush mats of CTL operations in New Brunswick (Labelle and Jaeger 2012).

3 Results

At all three research sites most of pre-impact soil bulk densities increased due to off-road traffic of forest machinery. At the Gagetown site 67% of all measured densities increased while at Black Brook sites 1 and 2 89% and 94% of all measurements showed increased densities post impact, respectively. Pre-impact soil densities ranged from 0.44 to 1.10 g/cm^3 at all three sites and increased due to machine off-road traffic to 0.50 to 1.27 g/cm^3 post impact. Not surprisingly, the highest soil bulk density increases were noted in areas of the operating trail, which were directly impacted by the tracks or tires of the machines (contact area), we named these areas track areas to separate them from the remaining trail area, so called 'outside-track areas'. At the Gagetown research site and at the Black Brook 1 site mean soil bulk density of the track areas of the trail increased by 17.4 to 18.9% at test plots exposed to one traffic cycle and by 22.9% on plots exposed to three traffic cycles in Gagetown (Table 4). Despite the brush mats covering the operating trail at the Black Brook 2 site, we recorded the highest increases of mean soil bulk densities there. While test plots without any brush coverage (0 kg/m^2) showed a mean bulk density increase of 41.3% in the track areas, test plots covered with more than 10 kg/m^2 brush layers showed lower density increases. At the Black Brook 2 site, the lowest mean soil bulk density increase (26.7%) was found at test plots covered with 20 kg/m^2 brush.

Table 4: Mean soil bulk density (ρ_D) before and after machine traffic (pre, post impact) separated for track and outside-track area of the machine operating trail (considering only densities, which increased by the impact)

	Pre Impact		Post Impact					
	Track areas	Outside-track areas			Track areas		Outside-track areas	
Sites	Mean soil bulk density ρD [g/cm^3] (n)	Mean soil bulk density ρD [g/cm^3] (n)	Brush cover [kg/m^2]	Traffic frequency (n)	Mean soil bulk density ρD [g/cm^3]	Mean increase of ρ_D [%]	Mean soil bulk density ρD [g/cm^3]	Mean increase of ρ_D [%]
Gagetown	0.899 (41)	0.865 (27)	0	1	1.069	18.9	0.903	4.4
	0.752 (49)	0.762 (27)	0	3	0.924	22.9	0.824	8.1
Black Brook 1	0.909 (96)	0.891 (53)	0	1	1.067	17.4	0.937	5.2
Black Brook 2	0.801 (48)	0.847 (33)	0	3	1.133	41.3	1,056	24.6
	0.735 (46)	0.731 (34)	5	3	1.002	36.4	0.910	24.5
	0.655 (46)	0.687 (29)	10	3	0.953	45.5	0.792	15.2
	0.778 (45)	0.794 (35)	15	3	1.048	34.6	0.885	11.5
	0.753 (46)	0.723 (30)	20	3	0.954	26.7	0.820	13.5

However, soil bulk density increases were not limited to track areas of operating trails. Also so called outside-track areas showed increased soil bulk density post impact. Although not directly impacted by the tracks or tires of the machinery, these areas showed an average increase of bulk density of 4.4 to 5.2% after one traffic cycle and of 8.1% after three traffic cycles in Gagetown and up to 24.6% at Black Brook 2. Since the function of the brush mats is to divert the loads exerted at the contact area to a wider area (outside the tracks) any brush usage effects higher loadings of the side areas. Soil density increases outside track areas at test plots without brush cover indicated other load transfer mechanisms.

When analyzing post-impact field bulk densities with respect to site specific 80% MBD thresholds we noticed that some pre-impact measurements were already in excess of this threshold (Table 5). These may be attributed to soil compaction due to machine operations in the past or that our MBDs derived from soil samples in the 0 to 30 cm depth range were too low compared to the relatively high density of naturally developed and settled soils at 30 cm depth where most of the measurements in excess of 80% MBD were taken.

Table 5: Mean soil bulk density measurements exceeding 80% maximum bulk density (MBD) pre impact and post impact due to machine traffic in track areas

Sites	Traffic frequency (n)	Brush cover (kg/m^2)	Pre impact n >80% MBD (n track)	Post impact n >80% MBD (n track)	Post impact net increase of n >80% MBD (n track)
Gagetown	1	0	0 (51)	8 (51)	8 (51)
	3	0	2 (57)	18 (57)	17 (57)
Black Brook 1	1	0	25 (99)	54 (99)	29 (99)
Black Brook 2	3	0	2 (48)	29 (48)	27 (48)
	3	5	0 (48)	10 (48)	10 (48)
	3	10	0 (48)	10 (48)	10 (48)
	3	15	0 (48)	12 (48)	12 (48)
	3	20	1 (48)	4 (48)	3 (48)

However, after completion of harvesting and extraction using one to three traffic cycles at the Gagetown and Black Brook 1 sites 16 to 30% of all measured soil densities in track areas exceeded the 80% MBD threshold indicating severe compaction and difficult growing conditions for plants and trees because of lost macro pores. At the Black Brook 2 site even 56% (27 out of 48) of all measurements at track areas without brush cover exceeded the 80% MBD threshold. The mitigating impact of brush mats becomes very obvious at this site, too, because it reduced the numbers of density measurements exceeding the threshold from 21% (10 out of 48) at test plots with 5 kg/m^2 brush cover down to 6% (3 out of 48) at test plots with 20 kg/m^2 cover. In addition to assessing pre- and post-impact soil densities to evaluate the disturbance caused by off-road machine traffic on operating trails we investigated potential short term rehabilitation pattern of soil density due to frost heave and swelling and shrinking processes. Therefore, we continued to monitor soil density after completion of timber harvesting operations at the Gagetown and Black Brook 1 sites for six years (2005 to 2011). Figure 5 shows mean soil bulk densities of selected test plots. It is obvious that, so far, soil bulk density remains elevated and in some cases significantly higher compared to pre-impact densities.

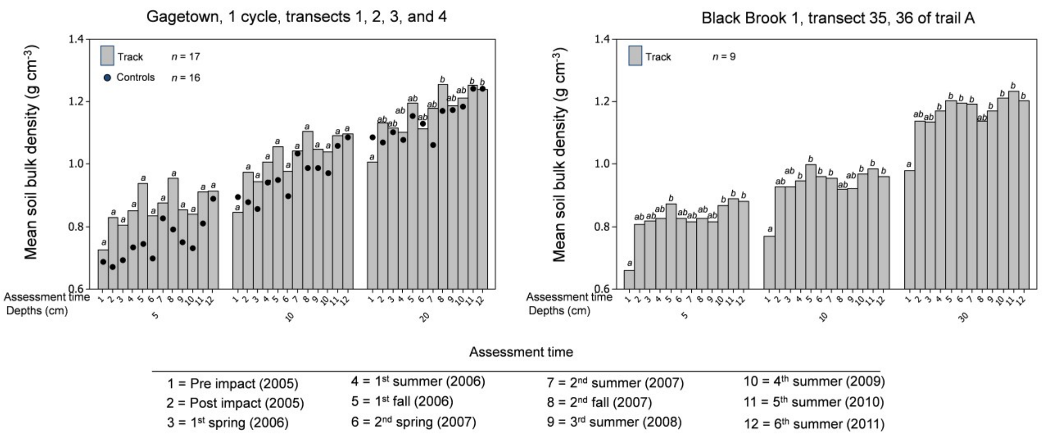

Figure 5: Mean soil bulk densities of test plots in Gagetown and Black Brook 1 indicating pre- and post-impact soil densities at three depths of track areas during the six year monitoring period

In order to compare the relative competence of softwood and hardwood brush in lateral transfer of punctual loads received we performed a laboratory test. Here, the capability of varying brush amounts to reduce punctual loading effects by load dispersion was tested by loading the different brush mats and recording the response of the middle strain gauge (vertically located below the loaded disc). Table 6 shows the responses of the middle gauge (in micro strains) during the three loadings after performing a first consolidation loading (10 kN) for all scenarios, for bare sand as well as for four brush quantities. When using no brush mat (0 kg/m^2) and setting the related recorded load as 100% (Table 6) the different brush amounts from 10 to 40 kg/m^2 were able to reduce the downward oriented loading to 28 to 37% when using 10 kg/m^2 brush mats and even to 17 to 20 % when using 20 kg/m^2 brush.

Table 6: Response of middle strain gauge (in micro strains) to three loads (1, 5, 10 kN) when applying no brush (0 kg/m^2) or four brush quantities (10 to 40 kg/m^2) of softwood (SW) or hardwood (HW) brush after one preliminary 10 kN consolidation loading

Loading	0 kg/m^2	10 kg/m^2		20 kg/m^2		30 kg/m^2		40 kg/m^2	
		SW	HW	SW	HW	SW	HW	SW	HW
1 kN	337 (100)	126 (37)	156 (56)	113 (34)	123 (36)	75 (22)	81 (24)	60 (18)	62 (18)
5 kN	864 (100)	293 (34)	385 (45)	262 (30)	296 (34)	215 (25)	225 (26)	186 (22)	177 (20)
10 kN	1310 (100)	370 (28)	466 (36)	321 (25)	362 (28)	266 (20)	276 (21)	233 (18)	222 (17)

It becomes obvious that all tested brush mats contributed to a significant reduction of the received loadings. At same brush amounts and loadings, softwood showed a slightly better capacity to disperse exerted loads than hardwood especially at brush amounts of 10 to 30 kg/m^2. At higher brush amounts the differences between the tested fir and birch brush diminished and at 40 kg/m^2 hardwood brush contributed to a lower response of the middle gauge at 5 and 10 kN loading than softwood. A second analysis compared the relative responses of the two side gauges to the middle gauge response to give additional evidence of the ability of the brush mats to transfer the exerted loading to side areas. Lateral load transfer would be indicated by relatively high responses of the side gauges. Table 7 shows the average response of the two side gauges in percent of the related middle gauge response.

Table 7: Mean response of two side gauges to received loadings in percent of the loading received by the related middle strain gauge when applying no brush (0 kg/m^2) or four brush quantities (10 to 40 kg/m^2) of softwood (SW) or hardwood (HW) brush after one preliminary 10 kN consolidation loading

Loading	0 kg/m^2	10 kg/m^2		20 kg/m^2		30 kg/m^2		40 kg/m^2	
		SW	HW	SW	HW	SW	HW	SW	HW
1 kN	5	31	18	31	21	32	25	28	22
5 kN	6	38	22	38	27	40	31	41	34
10 kN	4	40	24	41	29	41	32	43	35

The side gauges consistently received higher loadings underneath softwood brush mats than below hardwood mats indicating a higher capability of softwood brush to transfer loads laterally. Finally, we exposed brush mats of 20 kg/m^2 to repetitive loading (five loadings) to find out whether this would affect the capability to disperse the loads exerted on top of the mats. Table 8 shows the responses of the middle gauge to multiple loadings. The decreasing response values of the gauge (except for hardwood at the fifth loading) indicate improved performance of the mats as continued loading consolidated the mats and helped to further reduce downward oriented load transfer.

Table 8: Response of middle gauge (in micro strains) to repetitive loading (one to five times)

Loading	Softwood					Hardwood				
	1	2	3	4	5	1	2	3	4	5
1 kN	148	123	127	127	126	146	123	126	124	128
5 kN	330	281	282	278	276	330	297	299	297	300
10 kN	392	343	337	332	328	410	363	359	357	352

4 Discussion

Our analysis of soil bulk density changes due to off-road machine traffic showed increases of soil density at all three research sites. The most severe change was noted at the Black Brook 2 site where the mean increase of bulk density was 0.26 g/cm^3 in track areas and 0.12 g/cm^3 in outside-track areas. Test plots without brush cover showed mean density increases of 41% in track areas while the other two research sites showed significantly lower increases ranging from 17 to 23%. This may be due to the relatively high susceptibility of the Black Brook 2 soil to compaction. The soil type at this site was classified as silt loam having a high degree of fine particles (84% of its mass consisting of soil particles smaller than 0.02 mm) while both soils of the other two sites contained more coarse particles. In addition, the forwarder used at the Black Brook 2 site had the highest nominal ground pressure (91 kPa) of all used machinery at the three sites. This resulted in a high loading impact to a soil type which was more susceptible to compaction. Our recorded soil bulk density increases match the range of increases reported from North American long-term soil productivity sites where the compaction range was 1 to 58% (Page-Dumroese et al. 2006) or from CTL harvesting in mountain pine beetle (Dendroctonus ponderosae Hopkins) salvage stands in British Columbia where soil bulk density increased by 6-28% (Phillips 2001).

Soil bulk density increased at all sites at measurement locations outside-track areas, too. While this was expected when using brush mats since loads get laterally transferred it was surprising to notice high density increases of outside-track areas of plots without brush cover. Most likely the root network of the forest stand is acting here similar to corduroy in transferring received punctual loads to a larger area adjacent to the track area. We clearly noted mitigation of machine induced soil density increases in particular in track areas when using brush mats on operating trails. The mean increase of soil bulk density in track areas was reduced from 0.33 g/cm^3 at test plots without brush cover to 0.19 g/cm^3 at test plots with 15 to 20 kg brush per m^2. However, because of a high variation in all soil density increases we could not prove significant differences of density increases between test plots with and without brush cover. Nevertheless, the analysis of relative bulk density showed a clearer picture; when comparing post-impact soil bulk densities to standard Proctor related maximum bulk densities (MBD) test plots without brush application showed 27 measurements exceeding the 80% MBD threshold while test plots with 15 or 20 kg brush cover per m^2 showed 12 or 3 measurements in excess of this threshold, respectively. This indicates that the use of brush significantly reduces the probability of soil compaction with severe impacts on plant growth. We monitored two sites with increased soil densities due to machine off-road traffic for six years after the machine impact. The recorded soil density data does not indicate any decrease of soil density towards pre-impact density levels although the soils were exposed to frost heave and swelling and shrinking processes. The lack of any slight soil rehabilitation six years after the impact suggests that soil density increases are long-lasting. This corresponds to the findings of Rab (2003) and Anderson et al. (1992) who described significant differences in soil densities even 10 and 25 years after machine traffic. Our pilot laboratory testing of load diverting capabilities of brush mats revealed a slight advantage of balsam fir brush compared to yellow birch brush when mats of same quantity experienced same loading. More research is needed in this respect.

5 Conclusion

Even few off-road traffic cycles of forest machinery on forested sites can cause considerable increases of soil bulk density with potentially long-lasting effects on stand productivity. Brush mats on machine operating trails help to reduce machine induced soil density increase. More comprehensive research is needed to explore the benefits of brush application at different soil and stand conditions. This may help to develop needed strategies to avoid soil density increases in order to enhance sustainable management of our forest ecosystems.

6 References

Anderson, H., Boddington, D., Van Rees, H., 1992: The long-term effects of sawlog-only harvesting on some physical and chemical properties in East Gippsland. Unpublished. Department of Conservation and Environment, Victoria, Australia. 29 p.

Carter, M.R., 1990: Relative measures of soil bulk density to characterize compaction in tillage studies on fine sandy loams. Can. J. Soil Sci. 70: 425-433.

Devlin, G. J., McDonnell, K., Ward, S., 2008: Timber haulage routing in Ireland: an analysis using GIS and GPS. Journal of Transport Geography 16(1): 63-72.

Gingras, J.F., 2008: Personal communication.

https://www.soils.org/publications/sssaj/articles/75/6/2314?highlight=JmFydGljbGVfeWVhcj0yMDExJnE9KGF1dGhvcjolMjJsYWJlbGxlJTIyKSZxPShqb3VybmFsOnNzc2FqKSZsZW49MTAmc3RhcnQ9MSZzdGVtPWZhbHNlJnNvcnQ9JmZhY2V0LWF1dGhvcj0lMjJKYWVnZXIrRGlyayUyMiZmYWNldC1qb3VybmFsPSUyMnNzc2FqJTIy

Labelle, E.R., Jaeger, D., 2011: Soil compaction caused by cut-to-length forest operations and possible short-term natural rehabilitation of soil density. Soil Sci. Am. J. 75: 2314-2329.

Labelle, E.R., Jaeger, D., 2012: Quantifying the use of brush mats in reducing forwarder surface contact pressure. Croatian Journal of Forest Engineering. Accepted for publication August 2012.

Page-Dumroese, D., Jurgensen, M., Tiarks, A., Ponder Jr., F., Sanchez, F., Fleming, R., Kranabetter, J., Powers, R., Stone, D., Elioff, J., Scott, D., 2006: Soil physical property changes at the North American Long-Term Soil Productivity study sites: 1 and 5 years after compaction. Can. J. For. Res. 36: 551-564.

Phillips, E., 2001: Partial cutting with a Timberjack harvester and forwarder in southern British Columbia. Forest Engineering Research Institute of Canada (FERIC). Advantage Report 21(2).

Rab, M.A., 2003: Recovery of soil physical properties from compaction and soil profile disturbance caused by logging of native forest in Victorian Central Highlands, Australia. For. Ecol. Manage 191: 329-340.

Zhao, Y., Krzic, M., Bulmer, C.E., Schmidt, M.G., Simard, S.W., 2010: Relative bulk density as a measure of compaction and its influence on tree height. Can. J. For. Res. 40: 1724-1734.