Assessing the Ability of Hardwood and Softwood Brush Mats to Distribute Applied Loads

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Abstract

In cut-to-length mechanized forest harvest operations, trees are cut, delimbed, and bucked to standard lengths directly in the harvest block. This in-stand processing, generates harvesting residue composed of tree limbs, tops, and foliage, which is frequently placed on machine operating trails to prolong trail trafficability and protect forest soils against heavy loadings. These so-called brush mats vary both in quantity and quality based on harvested wood and stand characteristics. The objectives of this study were to determine, quantify, and compare the load distributing capabilities of hardwood and softwood brush mats of different amounts (10, 20, 30, and 40 kg m^{-2}) compared to no brush (0 kg m^{-2}). This was done by laboratory tests analyzing the difference in strain recorded below brush mats at small scale when exposed to single and repetitive loadings. Brush mats (approx. 37 cm x 37 cm in area) were placed inside a test structure including a top open box with the bottom filled with a 15 cm thick layer of sand, below which strain gauges were installed. The entire test structure was positioned on a load frame programmed to lower a loading disk directly over the brush mat, thereby applying increasing loads up to 10 kN on the mat. Results suggest that for specific brush amounts and loadings, softwood brush showed a slightly better capacity to laterally distribute exerted loads than hardwood brush, especially at brush amounts of 10 and 20 kg m^{-2}. At higher brush amounts, the differences of recorded loadings (strains) between the tested softwood and hardwood brush were reduced and at 40 kg m^{-2} hardwood brush contributed to a lower response of the strain gauges than softwood brush when subjected to 5 and 10 kN loadings.

Keywords: brush mat, brush compressibility, strain, load distribution, soil protection, forest operations

1. Introduction

During mechanized forest operations, forest machinery is operated off road directly on the ground, thus exerting high surface contact pressures on the unbound surface of forest stands. These types of operations may have adverse effects on forest soil productivity and stand vitality and growth. As an alternative, operating heavy machines on a layer of harvesting residue (tree limbs, tops, and foliage) created during the processing phase and placed on the machine operating trail as a brush mat can reduce these negative impacts and attenuate high surface contact pressures by laterally distributing machine loads over a greater area (Labelle and

Jaeger 2012). In particular, machine operating trails covered with a brush layer showed reduced rutting and less pronounced decreases in porosity and hydraulic conductivity (Jakobsen and Moore 1981, McMahon and Evanson 1994, McDonald and Seixas 1997, Han et al. 2006, Eliasson and Wästerlund 2007, Gerasimov and Katarov 2010, Poltorak 2011). Unlike machine related parameters used to minimize soil disturbance (reduced payload, flotation tires, steel flexible tracks, etc.), brush is most often available on harvesting sites and its use does not negatively affect machine productivity. However, since branches used to create brush mats are obtained from processed trees, the quantity and quality of material available as a protective layer is dependent on

the particular forest stand as well as on the type and intensity of silvicultural treatment applied and the characteristics of harvested wood.

With an increase in partial harvest frequency, mainly through commercial thinning and shelterwood silvicultural treatments, the amount of brush available from harvested trees for soil protection is much less than in clearfelling operations. Since smaller sized harvesting machinery is commonly used in thinning operations, one could assume that thinner brush mats of the fewer available brush would be sufficient for soil protection. However, despite employing lighter and narrower harvesters during partial harvests, forwarders, used to transport wood from the felling site to roadside landings, are usually the same as those used in clearfelling operations. Such forwarders, with loaded mass of 15 to 40 metric tons exert high static ground pressures (70 to 180 kPa, Kozlowski 1999) and often require a thick brush mat to effectively reduce peak loads. Therefore, it becomes important to predominantly apply available brush to those sections of the operating trails, which are most susceptible to soil disturbance by machine traffic (i.e. terrain depressions with high soil moisture, high traffic areas, machine operating trails with acute intersection angles, etc.).

While brush quantity proved to be a significant factor for determining the capability of brush mats to effectively reduce peak loadings by laterally distributing applied loads (Labelle and Jaeger 2012), the impact of tree species on load distributing pattern of brush mats of identical quantity needs more investigation. Branches of different species (e.g., hardwood and softwood) have diverse physical and, in particular, mechanical properties, which might impact their ability to reduce surface contact pressures once they are used to form a brush mat. To determine and quantify the ability of hardwood and softwood brush mats in distributing applied loads, the following research objectives were studied.

1.1 Research objectives

Determine and quantify the capability of hardwood and softwood small scale brush mats of varying quantities to reduce vertically downward transferred loadings when exposed to single loadings compared to tests without applying brush mats.

Analyze the lateral load transfer capability of various hardwood and softwood small scale brush mats (similar conditions as outlined in number i).

Quantify the capability of hardwood and softwood small scale brush mats of 20 kg m^{-2} to reduce vertically downward transferred loadings compared to applying no brush when exposed to repetitive loadings.

Analyze the lateral load transfer capability of hardwood and softwood small scale brush mats of 20 kg m^{-2} exposed to repetitive loadings.

In this study, strain below brush mats is defined as the deformation of steel channels (below which strain gauges were installed) relative to a reference length. These steel channels were located below a 15 cm layer of sand above which different brush mat amounts of different species were subjected to vertical loadings.

2. Methodology

2.1 Brush mat characteristics

To determine the relative competence of brush in distributing applied punctual loadings when placed over a layer of sand, we constructed hardwood and softwood small scale brush mats from green (fresh) branches collected from living trees during a timber harvesting operation within a natural forest stand in Fredericton, New Brunswick, Canada in summer (August). Hardwood mats were composed of yellow birch (*Betula alleghaniensis* Britton) branches, while softwood brush mats were formed from balsam fir (*Abies balsamea* (L.) Mill.). Yellow birch and balsam fir were chosen because of their wide natural distribution range and high frequency in forest stands throughout eastern Canada. Even though branch diameter was not individually tallied during this study, hardwood and softwood branches were limited to a diameter of 3 cm at the large end.

To determine brush water content, sub-samples from branches used for each brush mat were oven dried at 105 °C until constant mass was achieved. Quantifying branch water content was of interest due to potential implications on brush compressibility and associated ability of laterally distributing applied loads.

2.2 General description of test scenarios

Hardwood and softwood brush mats of varying quantities (10, 20, 30, and 40 kg m^{-2}) were each replicated once for a total of two test series per brush amount. Once placed inside the test structure (additional details in section 2.3), the mats were exposed to increasing loadings up to a maximum of 10 kN. The vertically downward transferred loadings were recorded below the mats by strain gauges installed on steel channels at the bottom of the test structure and covered with a layer of sand upon which the varying brush mats were positioned. The purpose of adding a sand layer inside the test structure was to allow for a consistent flexible medium, below which load distribution capabilities of various small scale brush mats

Fig. 1 A) Load frame with custom built load test structure, B) Three strain gauges installed below steel channels (channels were turned upside down to show strain gauges), C) Horizontal crosshead of load frame with load cell and steel circular loading disk resting on a softwood brush mat

could be equally compared amongst each other and with the no brush test scenario, where the loading was applied directly to the sand layer without any brush cover. The loading was generally performed in two steps: first, a consolidation loading of 10 kN was applied to allow for settling of branches for improved mat performance. After the load was completely released, the main-test loading followed exposing the mats again to a maximum load of 10 kN. This combination of consolidation and main-test loading constituted one test series. In total, two test series T1 and T2 were performed for all brush mat quantities. During the main-test loading of the mats, the vertically transferred loadings below the mats and the sand layer were recorded to assess the mats' abilities to reduce peak loadings by transferring loadings into side areas. Besides testing brush mats, we also recorded the response of strain gauges when no brush mat was applied and the loads were thus exerted directly to the sand. As for the brush tests, in total, two test series were also performed directly over sand, each of which constituted one consolidation and main-test loading. To avoid any consolidation of the sand due to multiple loadings during the different brush test scenarios, the sand was loosened with a spade, removed from the load box after each test, and refilled with special attention given to re-using the same mass of sand, thereby assuring a relatively constant density.
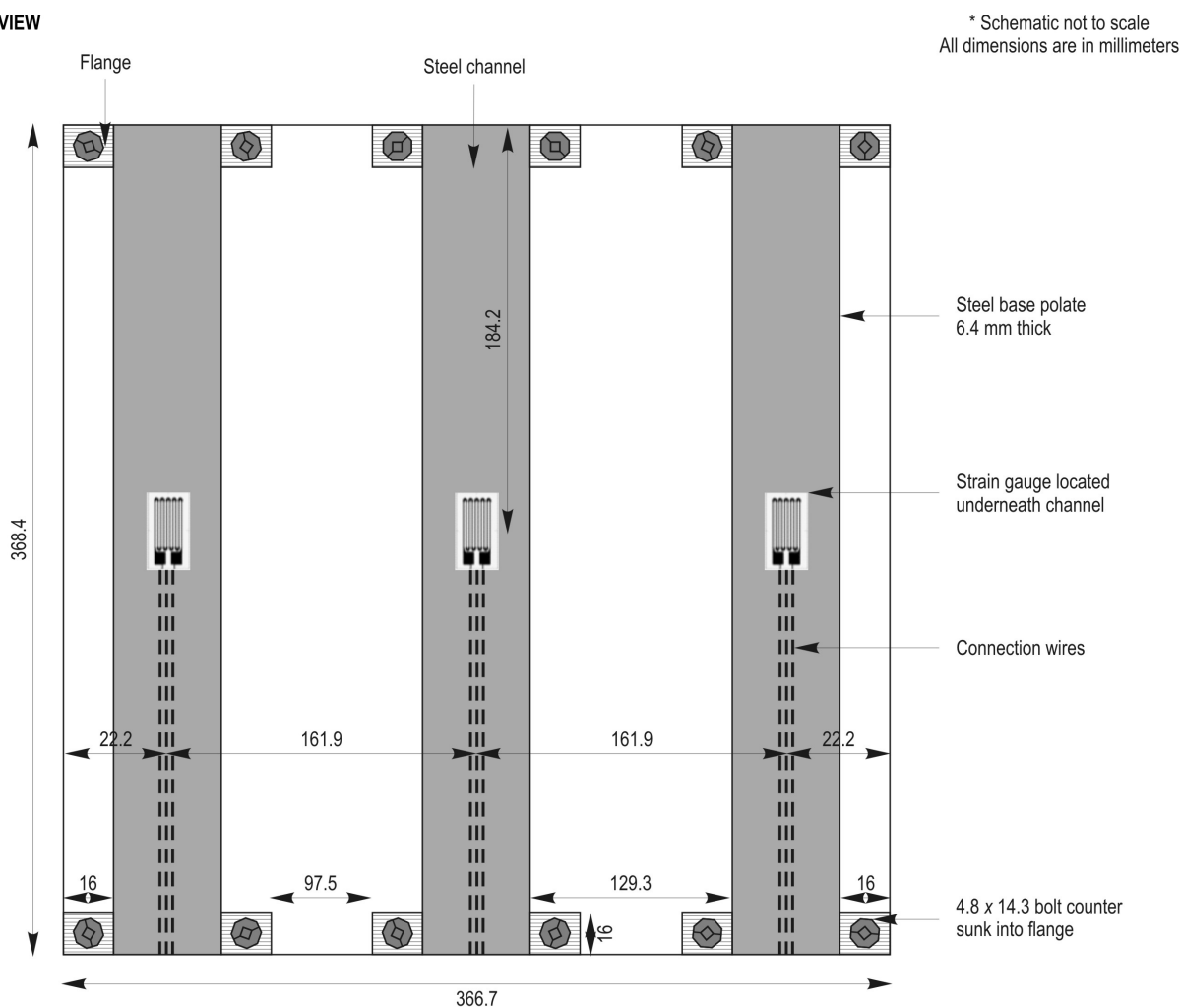
2.3 Compression and strain instrumentation

To reduce variability associated with in-field testing, we assessed the ability of hardwood and softwood brush mats of different brush amounts in transferring applied loadings in a more controlled laboratory test environment. To allow testing of different brush amounts, a test structure composed of a top open load box at its base (inside dimensions 36.7 cm long, 36.8 cm wide and 20.0 cm high) and a two sided brush support frame (90 cm high) was designed and constructed from structural lumber (Fig. 1 A). This test structure was designed with three main intentions:

⇒ confine branches to a defined area during testing,

⇒ allow a 15 cm thick layer of sand to be placed and contained in the load box of the test structure,

⇒ be small enough to fit inside the load frame of a universal testing machine.

The load box section of the test structure was filled with 15 cm of sand prior to any test. At the bottom of this load box, located below the sand, received loadings were measured by three (350 ohms) general purpose strain gauges installed in the middle of the downward side of three separately set up and independently operating steel channels (36.6 cm long x 2.5 cm wide x 0.6 cm thick; Fig. 1 B and Fig. 2). One steel channel and corresponding strain gauge were positioned in the middle of the test structure directly below a loading disk, and the other two steel channels and associated strain gauges were offset 16.2 cm adjacent to each side of the centre gauge to detect any lateral load distribution in relation to the middle gauge. All three strain gauges were connected in a three wire (excitation, ground, and nominal gauge resistance 350 ohms) quarter bridge circuit to a strain indicator and recorder. This three wire connection type offered the benefits of intrinsic bridge balance, automatic compensation for the lead wire temperature change on bridge balance, and increased mea-

TOP VIEW

* Schematic not to scale
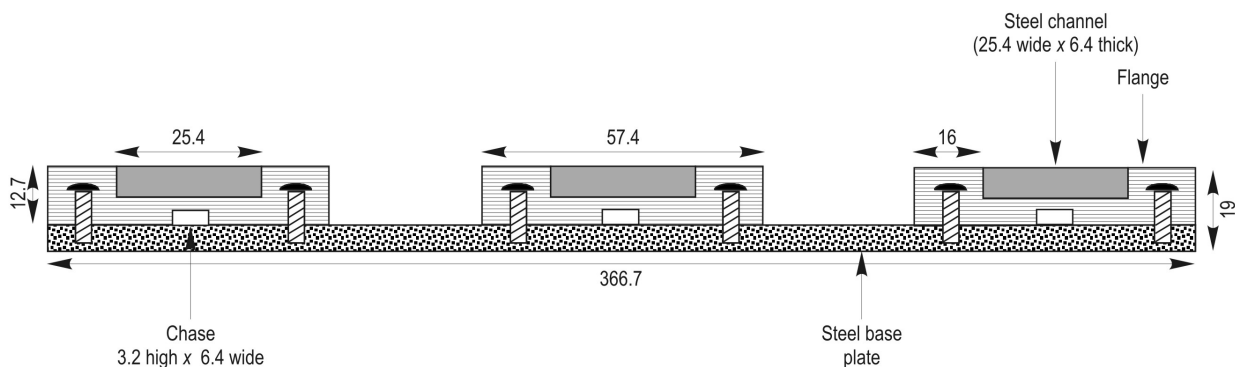All dimensions are in millimeters

Flange

Steel channel

Steel base polate
6.4 mm thick

Strain gauge located
underneath channel

Connection wires

4.8 x 14.3 bolt counter
sunk into flange

**SIDE VIEW
SCALE EXAGGERATED**

All dimensions are in millimeters

Steel channel
(25.4 wide x 6.4 thick)

Flange

Chase
3.2 high x 6.4 wide

Steel base
plate

Fig. 2 Top and side view schematic of base plate, steel channels, and strain gauges installed at the base of the load box

surement sensitivity compared to a two wire configuration (Micro Measurements 2011). To assure unbiased measurements, all three strain gauges were independently subjected to an identical vertical load and their responses in micro strains were monitored. The strain indicator and recorder was set to record data at a rate of one reading per second for each of the three channels used.

To assess the load distributing capability of different brush mats, varying brush quantities of hardwood and softwood were placed in the test structure on top of the sand filled load box. To compress brush, a 30 kN load capacity testing load frame was used. The load frame consisted of two vertical side columns allowing a horizontal crosshead to travel up to 1122 mm on the vertical axis (Instron® 2012). The load frame measured applied loads with a 30 kN capacity compression load cell directly mounted to the horizontal crosshead. Fastened below this load cell was a steel circular loading disk measuring 15.4 cm in diameter (area of 186.3 cm^2) and 1.9 cm in thickness used to exert loads from the crosshead to the brush mat (Fig. 1 C). During the loading process, the load frame software recorded displacement of the crosshead (mm) and associated load (kN) measured by the load cell.

Using the load frame, loads of up to 10 kN (equivalent to surface contact pressure of 537 kPa below loading disk at even load distribution) were exerted on top of brush mats placed inside the test structure with a constant 50 mm min^{-1} downward movement of the horizontal crosshead. We compared strain gauge responses when loading hardwood and softwood brush mats of varying quantities to the strain responses recorded when exerting the loadings directly over bare sand in the load box (without any brush cover).

2.4 Testing procedure

Before testing, the load box section of the load test structure was evenly filled with 15 cm (33 kg) of air dry sand. Due to size limitations within the load test structure and to reduce sidewall friction in the load box, all branches (hardwood and softwood) had to be trimmed to a 35 cm length before testing. Once a specific brush mat target amount was reached by using a scale (10, 20, 30, or 40 kg m^{-2} corresponding to 1.35, 2.70, 4.05, and 5.41 kg of brush per test series, respectively), a brush mat was created within the load test structure by placing the branches over the sand perpendicular to the orientation of the strain gauges and measuring its initial loose (no load) thickness. We then zeroed the strain gauges and the load frame (load cell and positioning of horizontal crosshead) and programmed the software to lower the horizontal crosshead at a constant speed of 50 mm min^{-1}.

First, the consolidation loading was performed to allow the brush mat to settle. With the movement of the crosshead both the load frame and strain recording systems started recording data (one reading per second) at the exact same time. The consolidation loading was paused when a load of 0.09 kN was reached (pre-loading state) to allow for standardized measuring of the thickness of the brush mat (summary of test procedure; Fig. 3). The load of 0.09 kN (surface contact pressure of 4.8 kPa below loading disk) on top of the brush ensured similar brush mat thickness measurement conditions as those applied by Labelle and Jaeger (2012) during laboratory testing of forwarder traffic over different brush mat amounts. By assuring similar measurement conditions, we could compare mat thicknesses of these lab scale tests to thicknesses of full scale brush mats. The thickness of the brush mat was measured as the vertical distance between the downward side of the loading disk and the top of the sand layer. Afterwards, the consolidation loading was resumed by programming the load testing machine to further increase the loading by downward movement of the crosshead and loading disk at a constant velocity until a terminal load of 10 kN was exerted to the brush mat covering the sand layer. Once this load was reached, we re-measured the thickness of the brush mat and the load was released by upward movement of the horizontal crosshead until the loading disk was out of contact with the brush layer, thus enabling it to rebound freely.

After completion of the consolidation loading, the main-test loading was applied to determine brush mat compressibility and corresponding strain gauge responses. In this context, we define brush mat compressibility as the length of crosshead and loading disk vertical travel from the pre-load stage until the target load was reached. The main-test loading event was identical to the consolidation loading event, as it included a pre-loading phase until a load of 0.09 kN was reached to allow again for standardized determination of brush layer thickness and then application of the full load (10 kN) with measurements of corresponding brush layer thickness.

Table 1 Brush water content by composition and amount for each of the two test series

Composition	Brush amount, kg m^{-2}	Brush water content, % green mass	
		Test series 1	Test series 2
Hardwood	10	52.4	54.4
Hardwood	20	51.2	52.6
Hardwood	30	55.0	52.2
Hardwood	40	55.2	51.1
Softwood	10	49.1	47.4
Softwood	20	50.3	48.3
Softwood	30	50.1	47.8
Softwood	40	50.6	52.2
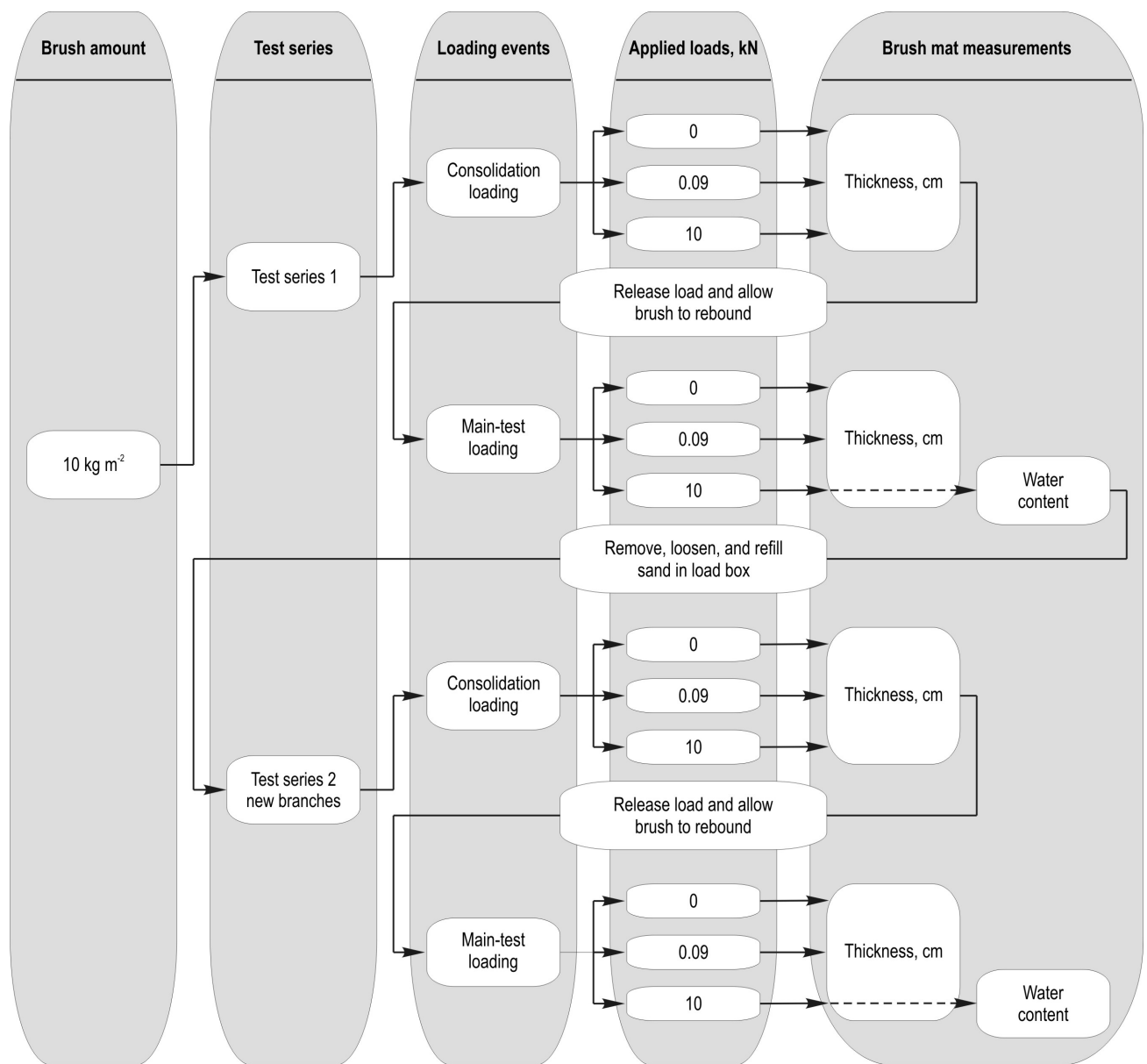
Fig. 3 General testing sequence (example of 10 kg m^{-2} brush mat) performed at the load test structure. The steps listed were also performed for 20, 30, and 40 kg m^{-2} brush amounts for hardwood and softwood brush mats. In addition, 20 kg m^{-2} brush mats were subjected to a third, fourth and fifth loading each consisting of the same applied loads as described above

Lastly, brush mats containing 20 kg m^{-2} of hardwood or softwood brush were not only exposed to the consolidation and main-test loadings but to additional three loadings to determine the load diverting/distributing behaviour of brush mats under repetitive loadings.

Once testing of a specific brush mat was completed (consolidation test and main-test), all brush was removed from the test structure and discarded. Sand was also removed from the test box and for the next test series the load box was refilled with the same amount of sand and fresh, uncompressed branches were used for subsequent tests.

In addition to testing hardwood and softwood brush mats, we also performed two separate test series (both including consolidation and main-test loadings as for any brush mat) directly on top of the 15 cm sand layer to obtain strain responses under a no brush scenario.

2.5 Data analysis

To compare the relative competence of hardwood and softwood brush mats in distributing applied loads, we determined strain gauge responses at three target loads (1, 5, and 10 kN which correspond to surface contact pressures of 54, 268, and 537 kPa below the loading disk). However, as each loading ranging from 0.09 to 10 kN was controlled by the rate of the crosshead vertical displacement (50 mm min^{-1}) rather than by an actual rate of loading (e.g. 1 kN min^{-1}), exact strain responses at the three target loads had to be obtained by linear interpolation between the two nearest strain responses (one below and one above the target load).

According to the research objectives of this study, we analyzed the recorded data in different respects:

To assess the capability of a mat to reduce vertically downward transferred loads, the strain responses of the middle gauge was compared for hardwood and softwood brush mats of varying quantities at the three target loads and also for the no brush scenario.

To assess the capability of a mat to transfer loads laterally, we averaged the responses of both side gauges per test series (in total four strain responses of the two side gauges during two test series for each testing scenario) at the target loads mentioned above, and compared them to the average response recorded below the middle gauge for both test series.

Both analysis steps were applied to single loadings and repetitive loadings.

2.5.1 Statistical analyses

Statistical analyses were performed with the Minitab 17 statistical package. To assess the competence of brush mats at distributing applied loads below the mats, analysis of variances were made and differences between means were tested *post hoc* using Tukey pairwise comparisons. Response variables used were strain on middle gauge and strain on side gauges while using the amount of brush as the term for comparisons. A significance level of 5% was used throughout all statistical analyses.

3. Results

3.1 Brush mat characteristics

Branches collected in late August 2010 from the same stand and tested within a two day period had a water content (percent of green mass) varying between 49.1 and 50.6% for softwood test series 1 and between 47.4 and 52.2% for softwood test series 2 (Table 1). Hardwood brush mats had generally slightly higher water content ranging from 51.2 to 55.2% during test series 1 and between 51.1 and 54.4% during test series 2. When combining all brush mats from the same species, softwood branches had lower average water content by 3.5% compared to hardwood branches.

Aside from determining brush water content, we also measured brush mat thickness during different loading stages to determine if the various quantities of hardwood and softwood brush showed similar responses with respect to compression when exposed to identical loading. When combining results from both test series during the no-load stage (0 kN load), 30 and 40 kg m^{-2} brush mats of hardwood composition were each slightly thicker than softwood brush mats of the same amounts (Fig. 4 A). On average, hardwood brush mat thickness increased from 24 to 70 cm and softwood brush mat thickness from 24 to 62 cm when brush amounts were quadrupled from 10 to 40 kg m^{-2} brush amounts.

The application of the pre-load of 0.09 kN considerably reduced brush thickness to 11 and 42 cm and to 10 and 37 cm for 10 and 40 kg m^{-2} amounts of hardwood and softwood composition, respectively (Fig. 4 A). This translates to a compaction to 45.8 and 60.0% of the initial no-load thickness of the 10 and 40 kg m^{-2} hardwood brush amounts, respectively. Similar results were obtained when assessing softwood brush, where a compaction to 41.7 and 59.7% of the initial thickness was found for the 10 and 40 kg m^{-2} brush mats, respectively, when the pre-load stage was reached.

The difference in thickness was less apparent once the full-load of 10 kN was applied. Regardless of brush amounts tested during the consolidation loading event, thickness under full-load was below 10 cm for both hardwood and softwood brush mats. Also, when combining brush amounts (10, 20, 30, and 40 kg m^{-2}), all hardwood mats were compacted between no-load and full-load state from 14.2 up to 6.2% of initial thicknesses, while the softwood mats were compacted from 16.0 up to 7.9% of initial thicknesses. This indicated that despite differences in starting thickness, brush mats of hardwood and softwood composition presented similar compressibility behaviours throughout the three loading stages.

Aside from the anticipated reduced thickness due to the consolidation loading event, the same general trends as described above were also apparent for the main-test loading performed over the same brush mats (Fig. 4 B). However, once under full-load of 10 kN, brush mat thickness was only 4.0 and 5.3% lower during the main-test loading event compared to consolidation loading event for hardwood and softwood mats (all amounts combined), respectively.
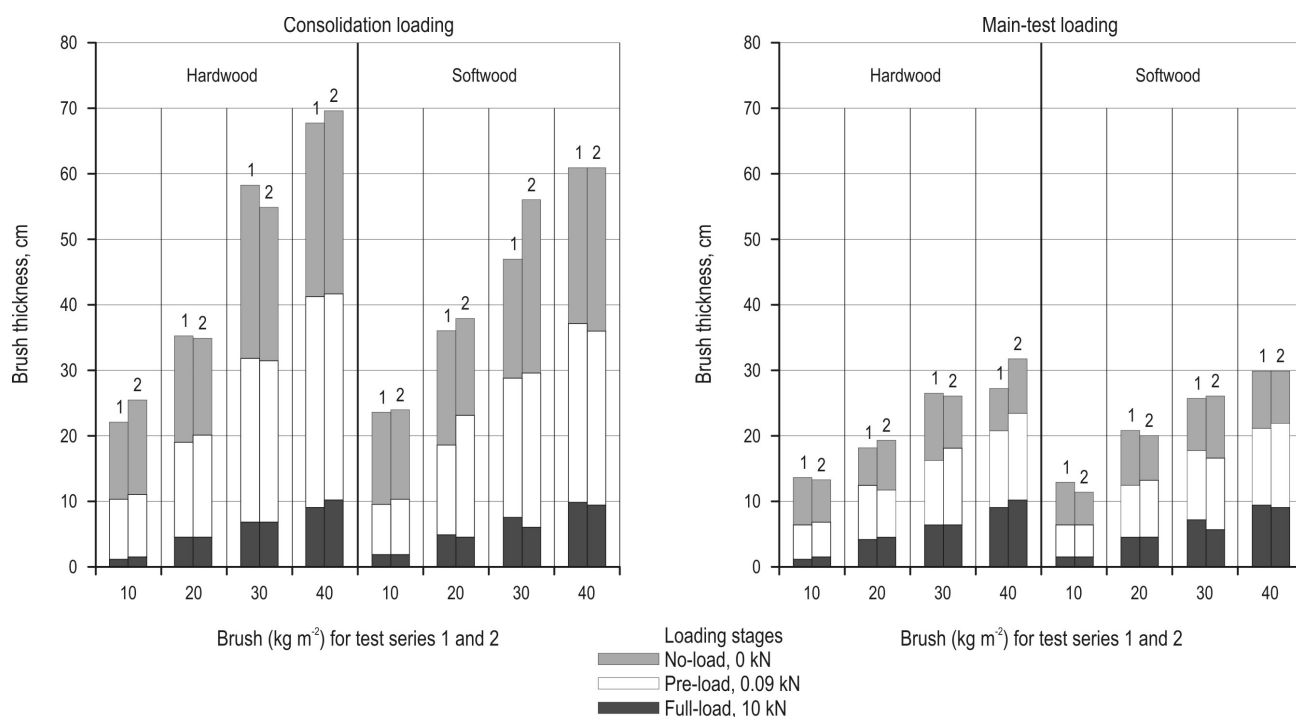
Fig. 4 Hardwood and softwood brush mat thickness of different brush amounts (10, 20, 30, and 40 kg m^{-2}) for test series 1 and 2 at different loading stages (no-load, pre-load, and full-load) for A) consolidation loading events and B) main-test loading events

Following consolidation and main-test loading events from each test series, sand was loosened with a spade and removed from the load box. Afterwards the load box was refilled using the same mass of sand. Average sand density, measured from four samples was 1.57 g cm^{-3} (1.58, 1.56, 1.55, and 1.58 g cm^{-3}) at 1.6 % gravimetric moisture content.

3.2 Difference between consolidation loading and main-test loading

For analyzing the performances of brush mats, it was important to identify a loading scenario (e.g., consolidation or main-test loading) most representative for the mats' behaviour. Therefore, we examined the differences between strain responses recorded during the consolidation and main-test loading events of the two test series T1 and T2 at mats of identical brush amounts. The analysis was based on the response of the middle gauge directly located below the loading disk recorded during both test series. Combining strain gauge responses from two tests series for each brush amount would yield an average loading curve not necessarily representative of what is occurring during each test, since each brush mat may have compressed at different rates. After initial analyses in section 3.1, very similar trends were noticed for both test

series. However, in an attempt to avoid any shadowing since the entire strain and load curves are of interest, only results obtained during test series 2 are presented in Fig. 5 and 6.

When exposed to the 10 kN load, strain recorded by the middle strain gauge during the main-test loading event was on average 22.8% lower (all brush amounts combined) compared to strain measured during the consolidation loading event (Fig. 5 A–D). The difference in response of the middle gauge between consolidation and main-test loadings generally increased as brush amounts increased from 10 to 40 kg m^{-2} and was more prevalent for hardwood than for softwood brush mats. In fact, in relation to consolidation loading, brush mats of 40 kg m^{-2} showed a strain reduction of 54.8% for hardwood and 29.1% for softwood during the main-test loading event at the full 10 kN load. Furthermore, the difference between consolidation and main-test loading curves could be observed at a much lower applied load, as brush amount increased from 10 to 40 kg m^{-2} for both hardwood and softwood mats. To reduce bias associated with combining both loading events, we used strain gauge responses from the main-test loading event and not from the consolidation loading for further analyses. In addition, off road traffic of forest machinery constitutes more than a
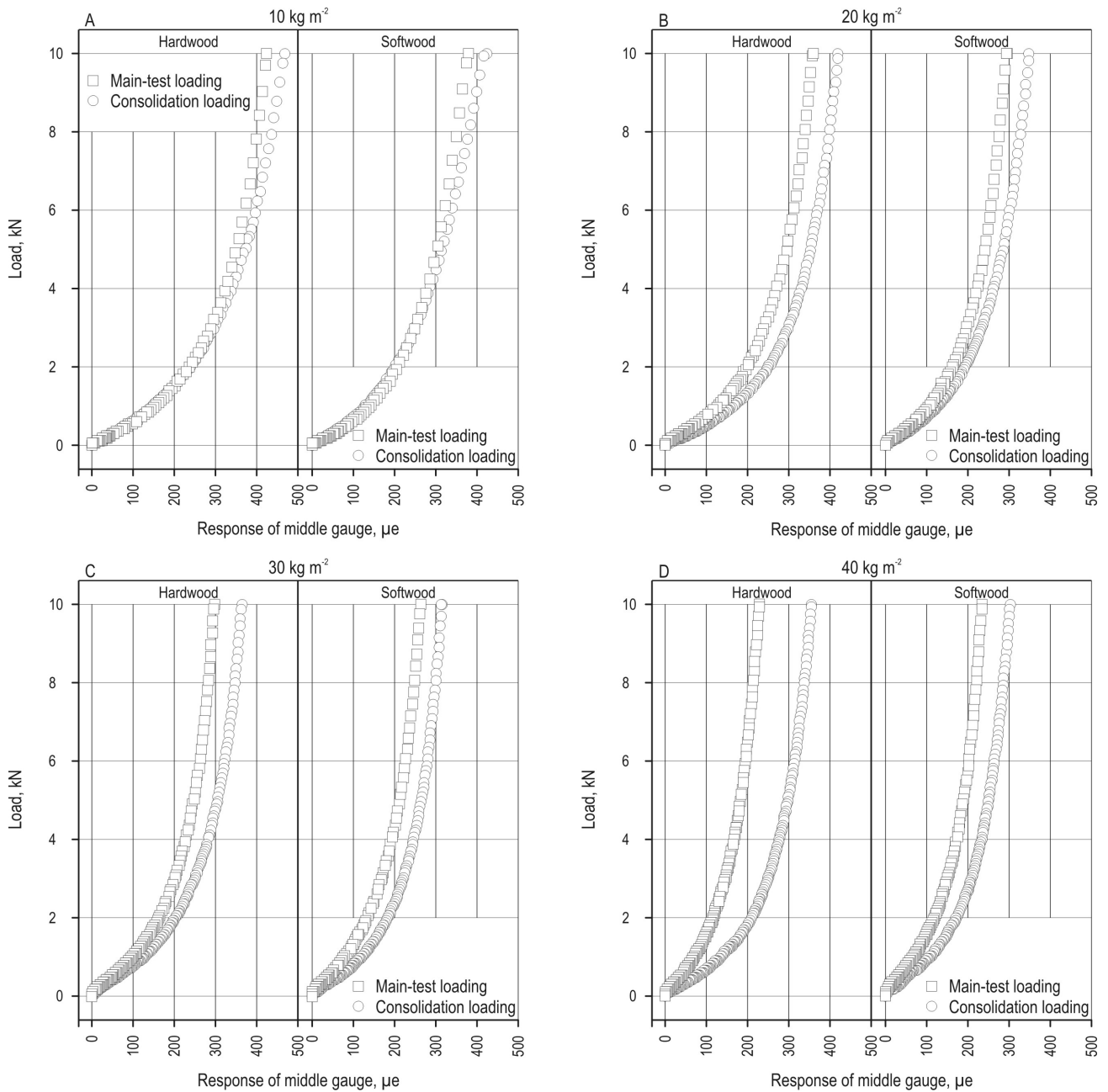
Fig. 5 Response of middle strain gauge to consolidation loading and main-test loading for A) 10 kg m^{-2}, B) 20 kg m^{-2}, C) 30 kg m^{-2}, and D) 40 kg m^{-2} brush amounts for hardwood and softwood mats obtained from test series 2

single loading event (impact of a single wheel), which also justifies the use of the results of the second loading event (main test).

3.3 Effect of brush mat amount and composition on strain

Table 2 shows the mean responses of the middle gauge located vertically below the loading disk during

test series 1 and 2 (in micro strains, με) for bare sand as well as for four brush quantities. Setting the recorded strain below bare sand at 100%, the table also shows the percent reduction of strain for the four tested brush quantities during the three target loadings of the main-test loading event.

Strain response recorded directly below bare sand increased from 337.0 με at 1 kN to 864.1 με at 5 kN and

Table 2 Mean response of middle strain gauge of both test series ($N=2$) in micro strains ($\mu\varepsilon$) and in percent reduction compared to the response of middle gauge under bare sand to three loads (1, 5, and 10 kN) when applying no brush (0 kg m^{-2}) or four brush quantities of hardwood or softwood after one preliminary 10 kN consolidation loading. Different lower case letters indicate a statistical difference at alpha 0.05 for a specific loading based on Tukey pairwise comparisons

Loading, kN		Sand	Hardwood			
		0 kg m^{-2}	10 kg m^{-2}	20 kg m^{-2}	30 kg m^{-2}	40 kg m^{-2}
1	$\mu\varepsilon$	337.0	155.6 *a*	123.0 *ab*	80.5 *bc*	61.9 *c*
	%	100.0	53.8	63.5	76.1	81.6
5	$\mu\varepsilon$	864.1	385.0 *a*	296.0 *ab*	224.9 *b*	177.0 *b*
	%	100.0	55.4	65.7	74.0	79.5
10	$\mu\varepsilon$	1310.0	465.5 *a*	362.0 *ab*	276.0 *bc*	222.0 *c*
	%	100.0	64.5	72.4	78.8	83.1
		Sand	Softwood			
		0 kg m^{-2}	10 kg m^{-2}	20 kg m^{-2}	30 kg m^{-2}	40 kg m^{-2}
1	$\mu\varepsilon$	337.0	125.8 *a*	112.7 *ab*	75.1 *bc*	60.1 *c*
	%	100.0	62.7	66.6	77.7	82.2
5	$\mu\varepsilon$	864.1	292.8 *a*	261.8 *ab*	214.5 *bc*	186.4 *c*
	%	100.0	66.1	69.7	75.2	78.4
10	$\mu\varepsilon$	1310.0	369.5 *a*	320.5 *ab*	266.0 *bc*	233.0 *c*
	%	100.0	71.8	75.5	79.7	82.2

up to 1310.0 μɛ at the maximum loading of 10 kN (Table 2). When adding branches on top of the sand, it became obvious that all tested brush mats contributed significantly to reducing strain on the middle gauge compared to tests using bare sand (0 kg brush m^{-2}). Furthermore, the more brush was applied, the higher was the reduction of the middle strain response at all target loadings. At the 5 kN loading, hardwood brush mats reduced strain from 864.1 μɛ to 385.0 μɛ and 177.0 μɛ, which translates to a 55.4 and 79.5% reduction of the strain recorded under bare sand for 10 and 40 kg m^{-2} brush mats, respectively. One-way ANOVA showed a statistical difference ($p=0.008$) between strain recorded by the middle gauge and brush amount. Based on Tukey pairwise comparisons, statistical differences existed between the strain recorded below 10 and 30 kg m^{-2} as well as 10 and 40 kg m^{-2} hardwood mats (Table 2).

At the same target loading of 5 kN, softwood brush mats reduced the strain response over bare sand from 864.1 μɛ to 292.8 μɛ with a 10 kg m^{-2} brush mat down to 186.4 μɛ under the 40 kg m^{-2} mat. This translates to a reduction of 66.1 and 78.4% of the strain for 10 and

40 kg m^{-2} brush mats, respectively, compared to the response recorded directly under bare sand. Likewise to hardwoods, one-way ANOVA showed statistical difference ($p=0.009$) between strain recorded by the middle gauge and softwood brush amount. Amongst tested brush amounts, means of strain on middle gauge were statistically different between 10 and 30 kg m^{-2}, 10 and 40 kg m^{-2}, as well as 20 and 40 kg m^{-2} (Table 2).

At same brush amounts and loadings, softwood showed a slightly better ability to distribute applied loads than hardwood, especially at the most practically implementable brush amounts of 10 and 20 kg m^{-2}. At higher brush amounts, the differences between the tested softwood and hardwood brush diminished and at 40 kg m^{-2} hardwood brush contributed to a lower response of the middle gauge by approximately 5% at 5 and 10 kN loadings compared to softwood mats.

A second analysis compared the mean responses of the two side gauges (again as means from both test series T1 and T2) to the mean response of the middle gauge to give additional evidence of the ability of the brush mats to transfer the exerted loading to side ar-

eas. We expected brush mats with a high load distributing capability to have relatively high responses of the side gauges compared to the middle gauge. Thus, lateral load transfer would be indicated by rather high responses of the side gauges. For this analysis, we compared the absolute strain responses of the side gauges and, in addition, we expressed these responses in percent of the middle gauge response.

In general, average side gauge response decreased with an increase in brush amount. This tendency was anticipated since lower total strain was recorded with an increase in brush. Average side gauge strain recorded at the 5 kN load decreased from 83.5 με to 59.5 με (28.7% reduction) between the 10 and 40 kg m^{-2} hardwood brush mats, respectively, and from 109.8 με to 75.5 με (31.3%) for softwood brush mats of the same amounts (Table 3). When considering the effect of the full 10 kN load, almost identical results were found, with 28.5 and 31.6% reductions of side gauge response between 10 and 40 kg m^{-2} hardwood and softwood mats, respectively.

The average response of the two side gauges in percent of the related middle gauge increased slightly with an increase in brush amount for both hardwood and softwood composition (Table 3). The only exceptions were observed at the 1 kN loading for both hardwood and softwood brush mats. For softwood, the percent strains were quite constant for any amount of brush, increasing from about 30% to approximately 40% as the load increased from 1 to 10 kN (Table 3). The percent strain for hardwood brush mats was higher with an increase in brush amount and load. Softwood brush mat showed higher absolute and relative responses of side gauges when related to the response of middle gauge, suggesting higher capability to transfer loads laterally compared to hardwood brush mats. However, since our benchmark used for comparison »average response of middle gauge« is also varying with brush amount, absolute strain readings of the side gauge were also considered.

3.4 Relationship between load, strain, and brush mat compressibility

When combining all three measured parameters: applied load (through displacement of the crosshead), brush mat compressibility, and strain on middle gauge,

Table 3 Mean response of side gauges of both test series ($N=4$) to received loadings in micro strains (με) and in percent of the loading of the corresponding middle strain gauge for the different test scenarios of hardwood or softwood mats and bare sand after one preliminary 10 kN consolidation loading. Different lower case letters indicate a statistical difference at alpha 0.05 for a specific loading based on Tukey pairwise comparisons

Loading, kN		Sand	Hardwood			
		0 kg m^{-2}	10 kg m^{-2}	20 kg m^{-2}	30 kg m^{-2}	40 kg m^{-2}
1	με	17.2	28.0 a	25.5 a	19.9 ab	13.9 b
	%	5.1	18.0	20.7	24.7	22.4
5	με	53.9	83.5 a	79.5 a	70.3 ab	59.5 b
	%	6.2	21.7	26.8	31.3	33.6
10	με	51.8	109.5 a	103.3 ab	87.5 ab	78.3 b
	%	4.0	23.5	28.5	31.7	35.2
		Sand	Softwood			
		0 kg m^{-2}	10 kg m^{-2}	20 kg m^{-2}	30 kg m^{-2}	40 kg m^{-2}
1	με	17.2	39.3 a	34.4 ab	24.2 bc	16.9 c
	%	5.1	31.2	30.6	32.2	28.2
5	με	53.9	109.8 a	100.2 a	85.2 a	75.5 a
	%	6.2	37.5	38.3	39.7	40.5
10	με	51.8	147.0 a	130.0 a	109.5 a	100.5 a
	%	4.0	39.8	40.6	41.2	43.1
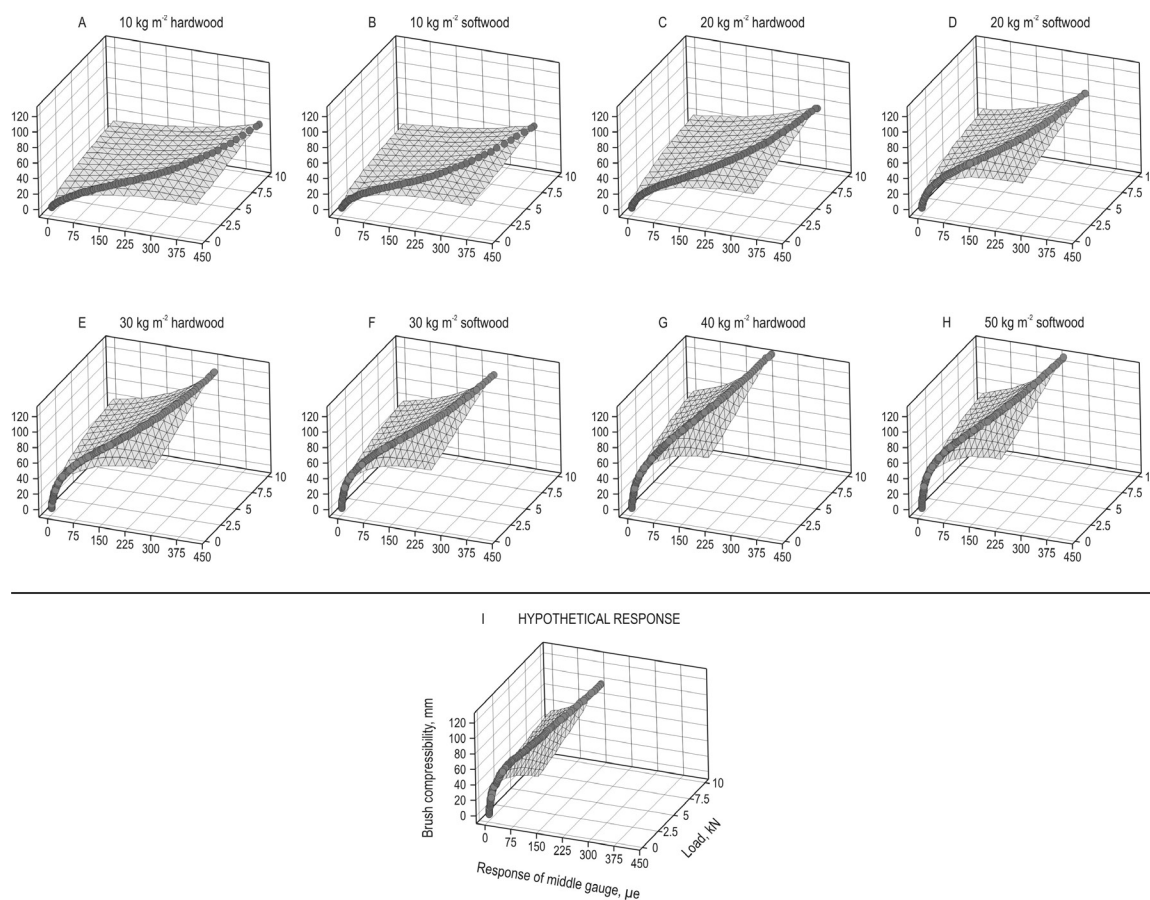
Fig. 6 Relationship between strain response of middle gauge, load, and brush compressibility recorded during main-test loadings of test series 2 on different brush amounts of hardwood (A, C, E, and G) and softwood (B, D, F, and H) composition along with a hypothetical brush mat (I) showing ideal performance with respect to brush compressibility and vertically transferred loads

it became apparent that softwood brush mats were more efficient at distributing applied loads through lower strain on middle gauge compared to hardwood brush mats throughout all test scenarios (Fig. 6). For most cases, we also noticed that hardwood brush mats offered slightly higher compressibility (demonstrated by a longer vertical travel of the crosshead) for the same applied load than softwood brush mats. Regardless of brush composition, we detected an increased compressibility at higher brush amounts (30 and 40 kg m^{-2}) especially at loadings of 5 kN and higher (Fig. 6 E–H), while mats with low brush amounts (10 and 20 kg m^{-2}) seemed to compress more slowly (Figures 6 A–D). Also, middle strain gauge response increased at a slower rate with an increase in brush mat amount for both hardwood and softwood mats.

To fully understand the interactions of all three parameters, a hypothetical (ideal) brush mat response to applied load was created (Fig. 6 I). In this idealized scenario, strain recorded from the middle gauge would increase at a slow and steady rate with increasing load. This would offer better protection against heavy machine loadings, since a higher percentage of the applied load would be transferred to side areas. A firmer and less compressible brush mat should be able to distribute applied loadings more efficiently compared to a looser brush mat offering higher compressibility. For this reason, the idealized scenario also demonstrates relatively low compressibility of the brush mat even at the maximum loading of 10 kN.

3.5 Effect of repetitive loadings on strain

Finally, we exposed hardwood and softwood 20 kg m^{-2} brush mats to five repetitive loadings to determine how this would affect their capability to distribute the loads exerted on top of the mats in vertical and lateral directions. The highest decrease of middle gauge response was observed between the first

Table 4 Response of middle gauge (in micro strains; με and percent change (+/-) compared to previous loading event) to repetitive loadings (one to five loadings) of 20 kg m^{-2} hardwood and softwood brush mats. The repetitive loadings were not replicated

Loading kN		Hardwood					Softwood				
		Repetitive loadings					Repetitive loadings				
		1	2	3	4	5	1	2	3	4	5
1	με	146.0	123.1	126.1	123.9	127.8	147.7	122.5	127.0	127.2	126.3
	%	0.0	−15.7	+2.4	−1.7	+3.2	0.0	−17.1	+3.7	+0.2	−0.7
5	με	330.2	297.8	298.8	296.6	299.6	329.4	280.7	281.8	277.8	275.8
	%	0.0	−9.8	+0.3	−0.7	+1.0	0.0	−14.8	+0.4	−1.4	−5.2
10	με	410.0	363.0	359.0	357.0	352.0	392.0	343.0	337.0	332.0	328.0
	%	0.0	−11.5	−1.1	−0.6	−1.4	0.0	−12.5	−1.7	−1.5	−1.2

two loadings for both hardwood and softwood mats at all three applied loads and ranged from 9.8 to 17.1% (Table 4). From there, percent changes decreased during the third to fifth loading to a maximum of 3.7% moving undirected around the strain responses of the main-test loading, somehow indicating a rather stable mat performance with respect to reduced vertically transferred loads. Even more, slightly decreasing response values of the middle gauge from the first to fifth loading events for the 10 kN load indicated enhanced performance of the mats as continued loading consolidated the mats. In fact, during the fifth loading an average decrease of strain of 3.7 and 4.2% compared to strain recorded during the main-test loading was apparent when comparing middle gauge responses at full compression load of 10 kN for hardwood and softwood, respectively.

4. Discussion

4.1 Branch properties and brush mat compressibility

During this study, branch diameter was limited to 3 cm (at the large end) for both hardwood and softwood smallscale brush mats. Rational for this diameter limit is based on results obtained from Labelle and Jaeger (2012) and an associated MScFE project (Poltorak 2011; conducted from on-going in stand forest operations in New Brunswick), both indicating the most frequently tallied branch diameter in the creation of brush mats was within the 1–3 cm category. Likewise, McMahon and Evanson (1994) reported an average branch diameter of 3.3 cm in unconfined field brush mat tests. In general, pre-load thickness of the small scale brush mats was half of the pre-load

thickness of full scale brush mats of the same quantities as reported by Labelle and Jaeger (2012). The lower pre-load thickness of the small scale brush mats as compared to those used in full scale tests was anticipated since the latter permitted the use of tree tops and larger branch diameter (up to 7 cm) and length (up to 5 m) for its composition. In addition, all branches used in the current study were trimmed to a length of 35 cm to fit within the test structure. This was considered necessary because of the relatively small area used for supporting and testing brush mats (37 x 37 cm or approx. a 1:7 scale in comparison to one square meter). We believe that allowing larger diameter branches in such a confined space could have caused bias and yield erroneous results through increased friction between large diameter branches and side walls of the test structure. However, since our tested brush mats were composed of smaller branches than full scale mats, the test results may be influenced by the higher number of branch intersections causing increased internal friction adding to lateral load transfer. On the other hand, the thicker and longer branches used in the full scale mats may likely contribute to increased lateral load transfer, too, compared to the test results of this study. Further research is needed to gain more insight into load diverting pattern of full scale brush mats.

Average branch water content of 51% (in relation to green mass) for all brush mats is similar to water contents of 45–50% for Sitka spruce (*Picea sitchensis* Bong. Carr.) and 48% for mixed wood brush mats reported by Dibdiakova (2011) and Poltorak (2011), respectively. While an increase in branch water content could increase flexibility and potentially lower lateral load distributing capabilities compared to stiffer

branches of lower water content, it could also increase compressibility and internal friction. However, due to the low variation of brush water content, we were not able to further analyse the potential effect of brush water on load distributing capabilities.

Despite major differences in compressibility between loading stages (no-load, pre-load, and full-load), hardwood and softwood brush demonstrated similar compressibility for respective loadings stages. Perhaps the confined test structure influenced the compressibility of the small scale brush mats by increasing friction between branches and the side walls of the test structure. During an unconfined test, branches under loading would have the possibility of moving in both lateral and longitudinal directions, and we would anticipate hardwood brush mats to be less compressible under loading compared to softwood brush mats of the same amount because of fewer and in average more coarse branches per mass unit.

4.2 Applied loads

Applied loads of 1, 5, and 10 kN translated to 54, 268, and 537 kPa of surface contact pressure underneath the steel circular loading disk. Static nominal ground pressure exerted by loaded forwarders usually range between 70 and 180 kPa (Kozlowski 1999). However, these static nominal ground pressures assume a penetration into the soil equal to 15% of the wheel diameter, thus greatly increasing the contact area and reducing actual peak pressures that would be observed on harder surfaces. Labelle and Jaeger (2012) reported peak dynamic surface contact pressures up to 380 kPa below a 30 metric ton Timbco eight wheel forwarder when operated directly over a steel rigid surface. These peak dynamic surface contact pressures were in relation to the size of a loading plate (30.5 cm x 30.5 cm) and were likely higher directly underneath tire threads. In addition, many forwarders are equipped with 600 or 650 mm wide tires as opposed to the 710 mm wide tires installed on the Timbco, which would also contribute to higher ground pressures for the same loading. Considering these factors, the pressures applied to the smallscale brush mats during this study are within a realistic range.

4.3 Effect of brush mat amount and composition on strain

In general, an increase in brush amount corresponded to increased load distribution through higher strain readings at side strain gauges in relation to the gauge directly located below the loading disk. At a fixed load, higher brush amounts seemed to behave with more rigidity than thinner brush mats, thereby allowing applied loading to be distributed more efficiently away from the loading disk onto side gauges.

Increasing the amount of branches placed inside the test structure also placed further distance between the loading disk and strain gauges located below the sand layer and brush mat, which in itself could influence stress propagation within the brush mat and corresponding sand layer. Assuming that Boussinesq's (1885) stress propagation theory within a soil profile would also apply to the combination of a brush mat over a layer of sand, it is possible that with higher brush amounts, more stress was distributed to the side walls of the test structure, therefore reducing total vertical stress being transferred to the middle strain gauge. Although considerable differences exist between a soil layer and a brush mat, it is conceivable that the stress propagation formula would apply to a certain extent to how branches are capable of distributing applied loads.

Softwood brush mats were slightly more suitable at distributing applied loads laterally than hardwood brush mats. This can be attributed in part to a higher degree of small diameter branches in softwood mats compared to hardwood mats, which increases the number of contact and interaction points of the branches and with this the overall internal friction and overall brush mat stiffness. Hardwood branches have higher wood density and fewer secondary branches compared to softwood, which might impact their effectiveness to laterally distribute loadings.

4.4 Effect of repetitive loadings on strain

Once placed on machine operating trails, brush mats can be exposed anywhere from two to five loadings per machine pass over depending on the number and configuration of axles. Assessing strain gauge responses below brush mats receiving a single loading (consolidation loading) indicated in average 22.8% higher strain at the middle gauge compared to strain recorded during the main-test loading event at the full 10 kN load. Strain on side gauges indicated similar responses to a third, fourth, and fifth loading. Han et al. (2006) reported that brush mats (7.5 kg m^{-2} and 15 kg m^{-2}) were effective at minimizing compactive energy of a loaded eight wheel drive Valmet 890.1 forwarder (31,434 kg) equipped with bogie wheel tracks for only the first two to three passes, after which the mat deteriorated and ceased to be beneficial. Labelle and Jaeger (2012) showed a benefit of using 20 to 30 kg m^{-2} brush mats in reducing peak loads up to the maximum traffic frequency tested of 12 loaded passes, despite showing a significant peak load increase following the first two passes.

5. Conclusion

The use of brush as a covering layer placed on machine operating trails during cut-to-length forest operations can lower peak pressures by transferring applied loads to a greater area. However, since brush mat quality and quantity is dependent on stand characteristics and silvicultural treatment, this study attempted to quantify the difference in loading resistance recorded below hardwood and softwood small scale brush mats of different amounts. In particular, this study analyzed the performance of hardwood and softwood brush mats of varying quantity with respect to vertical and lateral load transfer. Results indicated that softwood brush mats offered slightly better protection against vertical load transfer and, in addition, showed a better performance in lateral load transfer compared to hardwood brush mats. Further research on larger scale brush mats should be performed before the effects of hardwood and softwood brush mats on load distribution can be extrapolated to actual in-stand forest operations.

Acknowledgements

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