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Soil displacement during ground-based mechanized forest operations using mixed-wood brush mats

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A R T I C L E I N F O

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A B S T R A C T

The goal of this research was to examine the mitigating effect of brush mats on soil disturbance caused by off-road traffic of forest machinery, specifically how brush quantity affects rutting and soil displacement in a cut-to-length (CTL) harvesting operation. A field test was performed to analyze the effects of brush mats of varying quantities on the severeness of soil disturbance. At the project test site, located in a mixed-wood stand on silty soils in southern New Brunswick, Canada, two machine operating trails were covered with five different brush amounts (0, 5, 10, 15, and 20 kg/m^2). A Logset F-series forwarder with a total loaded mass of 35,800 kg completed three traffic cycles (each consisting of one loaded and one unloaded pass) plus one additional empty pass to simulate the passage of a harvester. The resulting soil disturbance was assessed by determining the area of displaced soil in cross sections of trail segments covered with brush mats of 5, 10, 15, and 20 kg/m^2. Results indicated that indent areas of individual tire tracks were between 0.0 and 0.6 m^2 when covered by 15 kg/m^2 brush mats and normally < 0.2 m^2 when covered with 20 kg/m^2 mats. Relative to the no brush (0 kg/m^2) treatment, 5, 10, 15, and 20 kg/m^2 brush mats offered reductions of indent areas of 0.0, 14.3, 71.4, and 90.5%, respectively. ANOVA results indicated that brush mats of 15 and 20 kg/m^2 along machine operating trails significantly reduced soil disturbance caused by timber harvesting equipment when compared to trail segments with no brush mat. Because regression trees were able to predict minimum indent area (0.0 m^2) and rut depth (3.8 cm) based on soil moisture and brush amounts, extending CTL forest operations into soil moisture conditions beyond 50% is not being recommended in this study.

1. Introduction

Forest soils commonly exhibit low bulk densities with corresponding low bearing capacities and as a result may not be capable of withstanding high axle loads of off-road vehicles. This issue is becoming more prevalent since the frequency of mechanized harvesting and magnitude of machine weight and payload being used during off-road timber transportation are both increasing. Forest machines such as single-grip harvesters, forwarders, and skidders are being operated directly in the forest stand on cleared corridors referred to as machine operating trails. These trails are normally spaced systematically 20–40 m apart and allow timber extraction from the felling site to the landing.

During traffic, forest machines can cause soil disturbance in the form of soil compaction, rutting, and displacement (plastic deformation coupled with shearing deflection). Soil compaction, defined as an increase in soil bulk density, occurs when the applied axle load causes particles of soils with moisture below saturation to move closer together, thereby decreasing macropores essential for air exchange, hydrological flow, and root growth (Craig, 2005). Rutting commonly results from transporting heavy loads during a period of wet soil conditions (at or near field capacity) leading to creation of trenches or furrows in the soil (Burger et al., 1995; Sutherland, 2003). Ruts can also reduce the lateral flow of water, thereby creating a localized rise in the water table and pockets of heavily saturated soil, which in turn results in ponding of water (Sutherland, 2003). Visually, the most damaging type of soil disturbance is soil displacement where soil is moved laterally during plastic deformation under saturated soil conditions thereby creating bulged areas adjacent to an indent area. This type of disturbance can occur in weaker saturated soils after a single machine pass and in stronger soils after several passes (Eliasson, 2005). Soil displacement results in many negative impacts similar to those caused

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by soil compaction, however, root shear, surface runoff and increased erosion potential are common effects of displaced soils.

Mitigation techniques to alleviate the disturbances of machines on forest soils have been studied: use of steel flexible tracks on bogie axles, high flotation tires, lower tire inflation pressure (Douglas, 2002), brush mats (McDonald and Seixas, 1997; Han et al., 2006; Labelle and Jaeger, 2012), operating in dry season or frozen ground conditions (MacDonald, 1999), etc. This study will focus on the role of brush mats, created from timber harvesting debris, on their ability to reduce ruts and soil displacement.

During normal operating conditions these brush mats are created within a cut-to-length (CTL) mechanized operation, where a single-grip harvester places brush (tree tops, branches, unmerchantable timber, and foliage) from harvested trees in front of the machine directly on the operating trail to increase the overall trail bearing capacity for securing technical trafficability of the trail and to offer some soil protection, especially when the soil is wet or close to or above field capacity (Jakobsen and Moore et al., 1981). Once trees within the harvester's boom reach from a machine operating trail have been harvested, processed logs are transported from the stand to roadside with a forwarder operated on machine operating trails. As the forwarder tends to exert the highest ground pressures and requires the highest traffic frequency on a site when compared to other equipment, it has the greatest potential to cause soil disturbance and will therefore be the focus on this study (Partington and Ryans, 2010). In the past, brush mats were intentionally left on operating trails during CTL operations to prolong trafficability while reducing the risk of soil disturbance (Sambo, 1999). From a forest industry perspective, the main function of brush mats on machine operating trails is to act as soil reinforcement, thereby distributing the mass of forest machinery over a larger area (Labelle and Jaeger, 2012) and providing the necessary traction required for the primary transport of forest products. Recent studies have found that soil disturbance and, in particular, soil compaction can be reduced by a layer of brush (Hutchings et al., 2002; Wood et al., 2003; Labelle and Jaeger, 2012). The degree of protection provided by a brush mat depends primarily on the quantity and quality of brush, the soil type and moisture content, as well as the axle loads and number of passes performed by the machines (Han et al., 2006; Labelle and Jaeger, 2012; Labelle et al., 2015). The most common brush amounts that have been field tested are 0, 10, and 20 kg/m^2 (McDonald and Seixas, 1997; Han et al., 2006).

Economic downturns in the forest industry have inspired exploration of new sources of income in order to maintain the economic viability of forest operations throughout Canada. In New Brunswick, a biomass policy adopted in 2008 by the Government of New Brunswick, prompted commercialization of forest debris from timber harvesting (New Brunswick Department of Natural Resources, 2008). Under this policy, the preferred use of woody debris from timber harvesting (limbs and tree tops) from selected sites is for power generation. This change in priorities has the potential to interfere with the use of harvesting debris as a brush mat on machine operating trails to avoid soil disturbance during cut-to-length harvesting operations. Soil disturbance and related site degradation caused by timber harvesting must be minimized to maintain forest productivity (Powers, 2002) and thus long-term economic benefits. Once the brush mat is used for soil protection it is easily contaminated with mineral soil thereby limiting its use for fuel (Eliasson, 2005). Given the new competing uses of brush for bioenergy and biofuels, it is likely that there will be less use of brush mats for soil protection in the future. Further research into specific brush amounts for limiting soil disturbance on wet soil is therefore required to maximize the effectiveness of a limited brush resource for securing soil integrity.

The objectives of this study were to: 1) quantify soil displacement as a function of the amount of brush placed on machine operating trails during timber harvesting operations when soil moisture is high; and 2) examine the use of brush mats as a possibility of extending the window of CTL harvesting into saturated soil operating conditions.

2. Material and methods

2.1. Site description

The research site was located within the Canadian Forces Base (CFB) Gagetown in southern New Brunswick, Canada, with an average elevation of 130 m a.s.l. and a terrain slope of 6% with a west aspect. The site was a naturally regenerated 89-year-old mixed-wood stand of 20 ha selected for CTL clear-cut harvesting. Merchantable timber was predominantly softwood; white spruce (*Picea glauca* [Moench] Voss) and balsam fir (*Abies balsamea* (L.) Mill.) contributed to 58% of stand basal area and hardwood: yellow birch (*Betula alleghaniensis* Britton) and red maple (*Acer rubrum* L.) totaled the remaining 42%. The forest stand contained an average pre-harvest timber volume of 146 m^3/ha based on four 0.05 ha timber cruise plots established at the research site.

The soils on this site are derived from parent geological material of alluvial deposits of red-gray sandstone, conglomerates, siltstone and shale from the Pennsylvanian-Triassic era (Eyles and Miall, 2007). The field test was divided into four trials (areas located within the forest stand) where the influence of varying brush mat amounts on soil displacement was assessed (additional information in Section 2.2.). Mineral soil (2 kg) was taken in the center of each trial and collected below the organic horizon from 0 to 30 cm depth. Soil analysis was completed using the methods of Bowles (1992) via particle-size analysis (ASTM D 422-63 02), hydrometer testing (ASTM D 854-98), Atterberg limits (ASTM D 4318-00), organic matter content determination (ASTM D 2974-00) and standard Proctor test (ASTM D 698-91; Table 1). Soil samples did not indicate significant differences between soil properties of the four trial locations; however, because of relatively high silt content they indicated soils susceptible to rutting.

Table 1
Soil characteristics 0–30 cm below the organic layer.

	Particle size distribution, %										
	Gravel > 2.0 mm	Sand 0.02 ≤ x ≤ 2.0 mm	Silt 0.002 ≤ x < 0.02 mm	Clay < 0.002 mm	Liquid limit (%)	Plastic limit (%)	Organic matter content (%)	Optimum moisture content (%)[a]	Mean soil moisture (%)	USCS[b]	Soil type
Trial 1	1.1	12.9	60.0	26.0	26.0	19.0	2.3	14.5	54.3	CL-ML	Silty Clay
Trial 2	2.3	8.7	47.0	42.0	34.0	29.0	5.5	21.0	83.3	ML	Silt
Trial 3	2.8	12.2	54.0	31.0	35.0	29.0	5.0	21.7	49.4	ML	Silt
Trial 4	0.5	9.5	45.0	45.0	32.0	29.0	6.3	24.0	29.0	ML	Silt

[a] Optimum moisture content as derived from standard Proctor tests.
[b] Unified Soil Classification System.

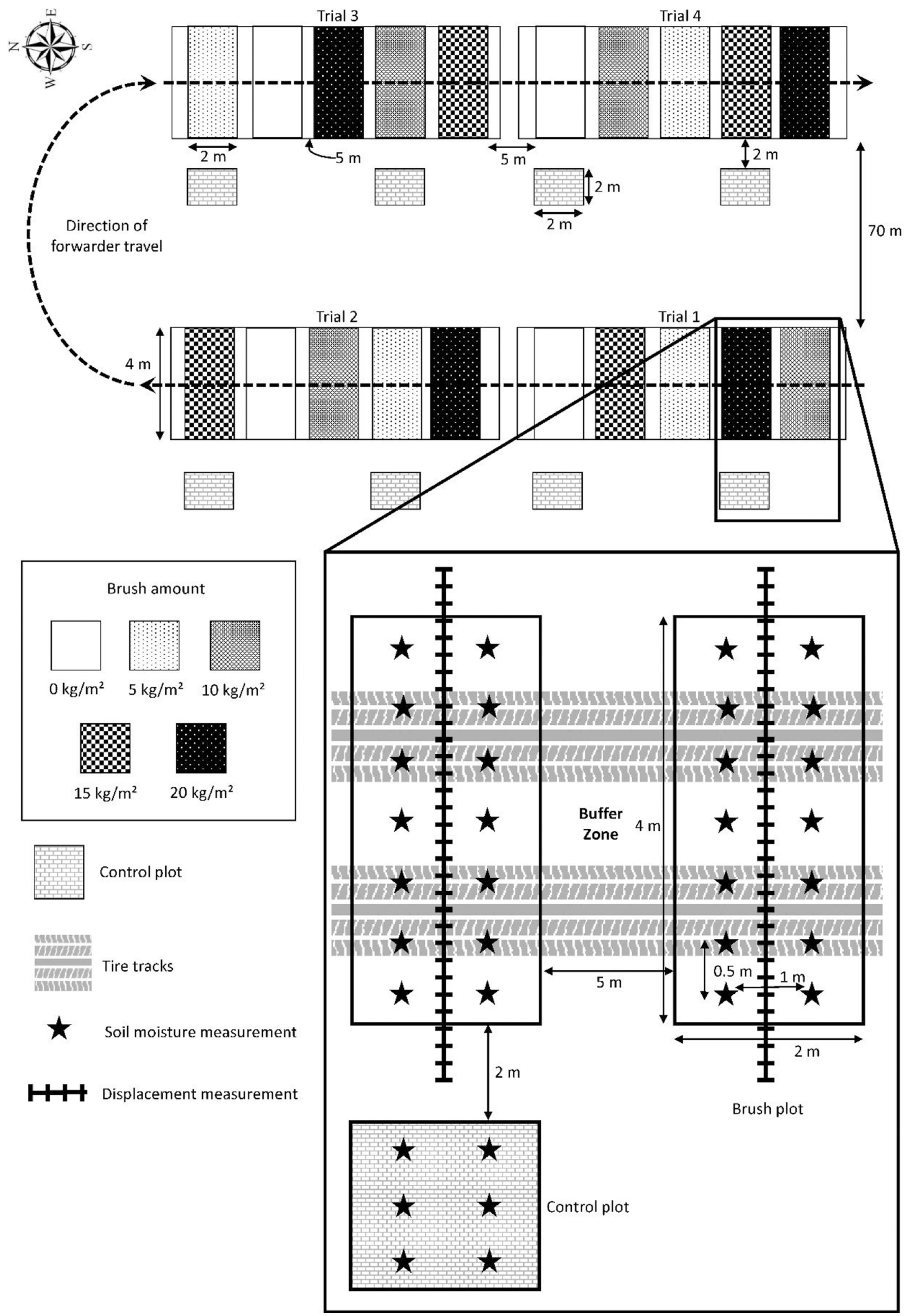

Fig. 1. Experimental design and plot layout of trials 1–4 each with five different brush amounts.

2.2. Experimental design, instrumentation and sampling

Two parallel strips 75 m in length and 4 m wide with a maximum terrain longitudinal gradient of 3% and no lateral gradient were selected and used as machine operating trails later. Each trail was divided into two sections and used for four trials (1–4). Within each trial, five brush amounts (0, 5, 10, 15, or 20 kg/m^2) were randomly assigned to five different test plots measuring 2 m long and 4 m wide (Fig. 1). In the forest stand, assigned brush amounts were applied using a suspended scale for measuring the biomass to the nearest kilogram. Control plots 2 m by 2 m established 2 m adjacent to the test plots were used to collect soil moisture at untrafficked and uncovered (0 kg brush) sites.

Fig. 2. A. Tigercat H822 single-grip harvester and B. Logset 8F forwarder used in the study.

At each test plot, pre-forwarding data collection involved the removal of vegetation and organic litter on 14 (15 cm × 40 cm) measurement locations. These locations were orientated along two transects, spaced by one meter, and aligned perpendicular to the centreline of the planned operating trail. Within a transect, measurement locations were separated by 0.5 m to adequately capture the full footprint of the forwarder (Fig. 1). Volumetric soil moisture content was determined from the mineral soil surface down to a 6 cm depth with a HH2 moisture meter using Frequency Domain technology (Delta-T Devices Ltd, 2005). In total, 280 soil moisture measurements (14 measurements per plot × 20 plots) were taken across the entire study area. Similar pre-forwarding measurements were also conducted on adjacent control plots where two transects were established and contained three soil moisture measurement locations each.

Once the pre-forwarding field data collection was completed, the stand was clear-cut. The operation used a Tigercat H822 single-grip harvester and a Logset 8F forwarder (Fig. 2). Harvester and forwarder traffic was performed sequentially from trial 1 through trial 4. However, to allow for exact brush allocation at all research plots, the harvester was not operated on the laid-out operating trail nor within the control areas but rather on a bypass trail. Brush was then manually placed in the appropriate amount on each plot by orienting the branches perpendicular to the axis of forwarder travel, in order to emulate brush placement by the harvester when delimbing stems on the operating trail (McDonald and Seixas, 1997; Han et al., 2006; Labelle and Jaeger, 2012). Similar to the species composition of the stand, brush mats were comprised of a mixture of softwood and hardwood material each at 50% mass.

A Logset 8F eight-wheel forwarder with an unloaded mass of 19,240 kg and a loaded mass of 35,800 kg was used to perform required traffic cycles in our study. These masses were assessed by portable wheel load scales model SAW 10C (PAT Equipment Corporation, 1990). The forwarder was equipped with eight tires (710/45-26.5, measuring 71 cm wide) inflated to 200 kPa and was equipped with steel chains on one tire per side located below the logbunk. The forwarder, exerting a static nominal ground pressure of 126 kPa, completed three cycles with each cycle comprising of one loaded and one unloaded pass across all trials plus an additional empty pass to simulate the passing of a harvester. After completion of forwarding, the trafficked brush mats were manually removed from test plots to facilitate post-forwarding measurements. As a result of excessive soil displacement, post-forwarding measurements included cross-sectional measurements of surface elevation through the center of each test plot. These were recorded by measuring a vertical elevation distance from a level guide placed above the test plots where measurements occurred at every point of soil elevation change and at a maximum spacing of 10 cm. Pre-forwarding cross-sectional elevations were determined by linearly relating the surface elevation of the two outmost cross-sectional points on each side of the operating trail which were not impacted by forwarder traffic, thus creating a linear pre-forwarding soil level. For each cross section, separate measurements of bulge and indent areas were taken from both tire tracks (left and right side). Comparisons of pre- and post-forwarding cross sections of the test plots allowed for identifying soil bulge areas (in m^2), defined as segments of the cross section where post-forwarding elevations exceeded pre-forwarding elevations, while segments with elevations below pre-forwarding levels led to calculation of rut area or indent area (also in m^2; Tepp, 2002). A similar method of separating the left and right side tire tracks for analysis was used by Saarilahti et al., 2003 for the development of models used for forwarder cycles and rut depth calculations. In our study, these measurements permitted cross-sectional analysis with RoadEng (Softree, 2007), a computer software with functions for data collection, terrain modelling, contouring, earthwork calculations used in both civil and forest engineering disciplines (Softree, 2007). As a result of the extensive displacement, excess water and site access issues, post-forwarding moisture measurements with the HH2 were only possible on the control plots one week after forwarding. This permitted comparison of soil moisture content pre- and post-forwarding in the control plots. All other post-harvesting measurements were also completed one week post-forwarding.

2.3. Brush measurements

In addition to reaching target brush amounts, other measurements made to the brush included water content, thickness of the mattress, branch diameter, branch length, and a measurement of how much brush is normally placed on operating trails. A total of 32 brush samples of approximately 0.5 kg each of hardwood and softwood material were collected at the test site and stored in sealed bags, labelled, and returned to the lab for water content (percent green mass) analysis. This included mass measurements, before and after oven drying at 105 °C until a constant mass. Brush thickness was measured for every test plot at six evenly distributed locations. These measurements took place pre and post forwarding to identify the vertical compression of the brush. Brush thickness measurements were made using a 10.6 kg mass placed on a 30 × 30 cm measurement board and a graduated ruler. Brush thickness was measured from the forest floor to the bottom of the measurement board. This apparatus allowed establishment of a standard, as used by Labelle and Jaeger (2012), for comparison because the thickness of a brush mat (a solid with an undefined random top boundary of many branches) is otherwize difficult to measure.

Brush quality was assessed by measuring branch diameter, where the diameter of the butt-end of every branch was assigned to one of four diameter classes; ≤10.0 mm, 10.1–30.0 mm, 30.1–60.0 mm, and > 60.0 mm) and one of four length classes; ≤100.0 cm, 100.1–200.0 cm, 200.1–300.0 cm, and > 300.0 cm as individual branches were placed in the brush mat. To evaluate brush masses normally placed on machine operating trails at the discretion of the harvester operator, 16 randomly aligned, paired 1 m × 1 m sample plots separated by 20 m on two brush covered machine operating trails were located adjacent to the study site. At these sample plots, fresh brush mass was recorded out of the track area of the mats and compared to brush quantities used in the study.

2.4. Statistical analyses

To statistically analyze the relevance of soil moisture and brush amounts for rutting, one-way ANOVA tests were performed. All tests were completed at the 0.05 probability level using the software Minitab. Dependent variables were indent area (m^2), bulge area (m^2), total effected area (m^2) and independent variables were brush amounts (kg/m^2). Multivariate regression trees, computed using R statistical software, were used to identify key factors influencing displaced soil (indent area) and rut depth across the trials (R Core Team, 2008). The analyses examined the residual deviance at individual nodes as a percentage of the total deviance to determine the most influential variables. Analyses of the cross sections including graphics and statistical computations were completed using Sigmaplot Version 11.0 (Systat Software Inc., 2008).

3. Results and discussion

3.1. Soil properties

According to the Unified Soil Classification System, soil samples collected at the research site were classified as silt to silty-clay with an average plastic limit of 26.5% and an average liquid limit of 31.8% (Table 1). Gravel content averaged 1.6%, sand 10.8%, and amount of fines 87.6%. Organic content averaged 4.8% and mean optimum soil moisture content, derived by standard Proctor test, was 20.3%. Due to the high content of fines, especially silt, one would expect the site to be highly susceptible to rutting even at relatively low soil moisture contents during most of the year (Jansson and Johansson, 1998).

3.2. Brush

In our study, pre-forwarding mean brush mat thickness was 15.1, 24.2, 48.9 and 56.9 cm for 5, 10, 15 and 20 kg/m^2, respectively. Thus, 15–20 kg/m^2 of brush corresponded to brush mats of 48.9–56.9 cm thickness pre-forwarding. The post-forwarding brush mat thickness for outside tracked locations was 7.9, 13.4, 19.3 and 27.7 cm for the 5, 10, 15 and 20 kg/m^2 brush mats, respectively. Likewise, the post-forwarding brush mat thickness for tracked locations was 5.4, 6.4, 13.4 and 9.8 cm for the 5, 10, 15 and 20 kg/m^2 brush mats, respectively. The range of brush water content (related to the mass of the wet samples) was between 20.9 and 78.7% with a mean of 47.8%. Dry masses of the brush mats were 2.6, 5.2, 7.8 and 10.4 kg/m^2 for brush mats of 5, 10, 15 and 20 kg/m^2, respectively. Branch diameter of 176 hardwood branches was composed of 22.7, 35.2, 25.6, and 16.5% of ≤10.0 mm, 10.1–30.0 mm, 30.1–60.0 mm, and > 60.0 mm, and of 211 measured softwood branches the branch diameter was 30.8, 47.9, 17.1 and 4.3%, respectively. Branch length for the hardwood material was 11.4, 32.4, 36.4, and 19.9% of ≤100.0 cm, 100.1–200.0 cm, 200.1–300.0 cm, and > 300.0 cm, and for the softwood material was 21.8, 58.3, 14.2, and 5.7%, respectively. The natural range of brush mat amounts in this CTL forest harvesting operation (clear-cut) within a mixed-wood stand was observed to be between 3.9 and 50.2 kg/m^2 on the tracked areas. The mean of this large range of variation for 16 samples was 27.8 kg/m^2. Although this amount of brush along operating trails seems high, it can be explained by the hardwood brush component and the wood density of hardwood material used in the brush mats.

3.3. Soil rutting and displacement

The time between pre-forwarding measurements and trafficking was approximately four weeks due to operational constraints (unable to access the site due to military live training activities), and the time between trafficking and post-forwarding measurements was one week. Over this time period, a large change in soil moisture conditions occured immediately after trafficking, when two rainfall events in excess of 60 mm resulted in complete saturation of the site (Environment Environment Canada, 2009). This caused the tire tracks to fill up with water and made the full set of post-forwarding measurements impossible. The average HH2 soil moisture content pre-forwarding was 38.1% across all test plots and 43.4% post-forwarding. Due to the post-forwarding precipitation that was experienced, pre-forwarding soil moisture measurements were considered a better representation of soil moisture at the time of forwarder activity despite the mentioned four-week time gap between moisture assessment and forwarding operations.

During the forwarder traffic cycles, the exerted loading of the forwarder often exceeded soil strength. Neither the friction and cohesion forces between soil particles, nor the load distributing effect of applied brush mats placed on test plots, and even of the forest root network were able to sustain the loads and avoid rutting (often > 30 cm deep) of the forwarder. Unfortunately, this level of rutting often occurs under suboptimal operating conditions on soils with high moisture contents. Similar rut depths (> 20 cm deep) occurred for example on loam soils when soil moisture was elevated in a CTL study in South Carolina (Carter et al., 2007). The outlined soil properties combined with high soil moisture content during all trials resulted in soil conditions susceptible to displacement.

To assess the observed soil disturbances due to soil displacement, rut depth and indent area were recorded. Rut depth is a one-dimensional measure of depth in indented track areas where indent area is a two-dimensional measure and considers rut depth and rut width. Rut depth was strongly correlated with indent area ($r^2 = 0.96$) using a quadratic equation (Fig. 3). Therefore, rut depth and indent area measurements were both used as indications of soil disturbance. Rut depths within the study ranged from 0 to 70 cm and occurred within a wide range of brush mat amounts.

Soil displacement was observed on 75% (15/20) of the test plots. In comparison, full-tree harvest operations caused 43% rutting on

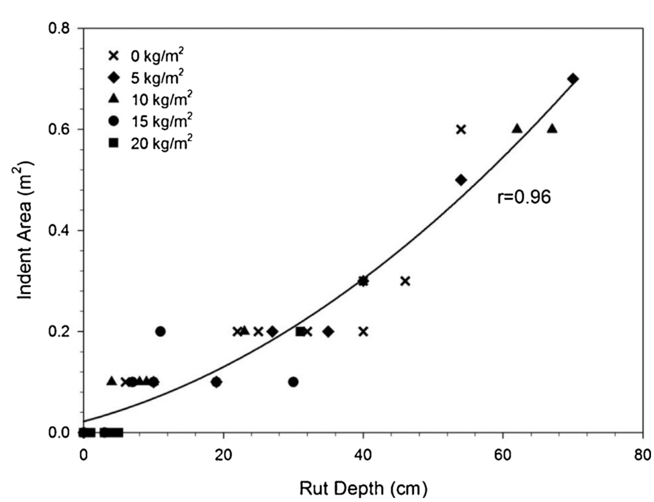

Fig. 3. Correlation between indent area and rut depth of individual tire tracks following harvesting operation. Both the indent area and rut depth were derived from the RoadEng cross sections at each test plot on four different trials.

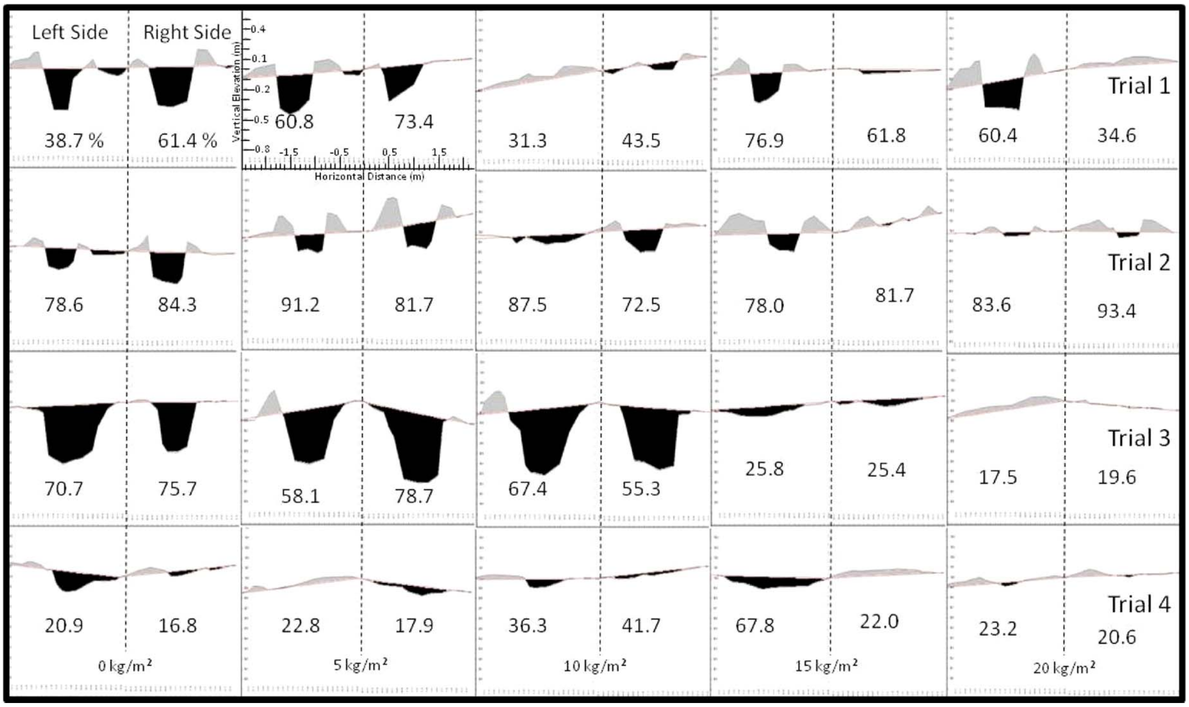

Fig. 4. Cross-sectional profiles as developed in RoadEng and calculated by measuring soil elevations across all test plots. Black represents the indent area and gray the bulge area (both expressed in m^2). Mean pre-forwarding soil moisture content (%) is indicated below each track area on left and right sides. Vertical exaggeration is a factor of two.

machine operating trails in a study by Plamondon (2001). Bulge and indent values were assessed as areas because cross sections of the trail were rather presented in 2D perspective to give emphasis to the discrete points of assessment along the machine operating trails in both vertical and horizontal perspectives. RoadEng profiles showed that the level of displacement for a specific cross section of machine operating trail varied substantially and ranged from 0 m^2 to 0.7 m^2 per tire track (Fig. 4). It becomes obvious that deep ruts occurred predominantly in plots with high soil moisture content (exceeding 50%) and low amount of brush cover (5 kg/m^2 and less). Surprisingly, excessive rutting and displacement were observed in trial 3 not only on plots with high soil moisture and up to 5 kg/m^2 brush mats (as in trials 1, 2 and 4) but also at plots with 10 kg/m^2 brush cover. Plots of this trial showed severe soil displacement indent values above 0.4 m^2 per tire track. To maintain trafficability of the forwarder in these areas with low bearing capacity the operator often offset machine passes from the already rutted areas resulting in a widening of impacted area; tire tracks on these test plots were wider than the tires themselves, approximately 1.2 m compared to the machine tire width of 0.75 m. However, this helped avoiding further deepening of ruts and impassability of the trails. Comparable effects were reported from turning manoeuvres for off-road military vehicles (Liu et al., 2010), which were found to significantly increase rut depth and width.

During rutting, soil was displaced laterally and upwards resulting in soil bulging adjacent to the tracks, while some soil was even moved in front of the tires and out of the test plot area. Therefore, the bulge area did not represent the full amount of soil displaced within a test plot. Instead, the indent area was a better representation of severity of forwarder impact on soil than the bulge area since the latter accounts only for lateral soil displacement and not for the additional lengthwise displacement. The mean indent area of displaced soil, caused by forwarding, decreased as brush amounts placed on the plots increased (Fig. 5A). However, the bulge area was not strongly related to brush amount (Fig. 5B). This may be because, as mentioned before, soil was moved outside the test plot profiles during the passing of the forwarder, as it adhered to the machine running gear and, in areas of severe rutting, additional soil was pushed in front of the forwarder tires. Mean total displacement (Fig. 5C) as a sum of bulge area and indent area, was also variable because of the effect of bulge area. The box plot representation of indent area (Fig. 5A) illustrates the trend of decreasing indent area with brush mat amount. When using a one-way ANOVA test at the 0.05 level, 15 and 20 kg/m^2 brush mats were shown to significantly reduce soil displacement areas when compared to 0 and 5 kg/m^2 brush mats (Fig. 5A). At a level of 15 kg/m^2 of brush mat, indent values from single tire tracks were between 0.0 and 0.6 m^2, while brush mats with 20 kg/m^2 better protected soils with indent areas normally < 0.2 m^2. Relative to the no brush (0 kg/m^2) treatment, 5, 10, 15, and 20 kg/m^2 brush mats offered reductions of indent areas of 0.0, 14.3, 71.4, and 90.5%, respectively. Thus, a 5 kg/m^2 brush mat offered no protection from forest harvesting when compared to bare soil and is therefore not recommended for protecting soil from rutting. The largest decrease of indent area (60.1% per tire track) was achieved when brush amounts were increased from 10 kg/m^2 to 15 kg/m^2.

The relationship between rut depth and brush mat amount showed a trend of decreasing rut depth with increasing brush mat amount (Fig. 6). Brush amounts of 15 and 20 kg/m^2 significantly reduced the depth of ruts when compared to test plots covered with 0 and 5 kg/m^2 brush mats. Brush mats of 20 kg/m^2 offered the best soil protection by reducing rut depth to 6.0 cm in average. Relative to no brush mat, treatments with 5, 10, 15, and 20 kg/m^2 brush mats resulted in rut depth decreasing by in average 3.8, 30.9, 69.8, and 81.9%, respectively. Similarily to its effect on indent area, a 5 kg/m^2 brush mat offered very little protection from rutting (31.9 cm average rut depth), but 15 or 20 kg/m^2 brush mats decreased rutting by 70.0 and 82.0% ($<$ 10.0 cm rut depth). Eliasson and Wasterlund et al., 2007 also examined the relationship between rut depth and brush mats, and found that layers of small brush amounts (0, 10, or 20 cm thick pre-forwarding, but not expressed as brush amount in kg/m^2) did not reduce rut depth.

3.4. Soil moisture

The study site indicates two main factors influencing indent area and rut depth; 1) soil moisture and 2) brush mat amount. To identify whether brush mat amount or soil moisture had a greater impact on soil

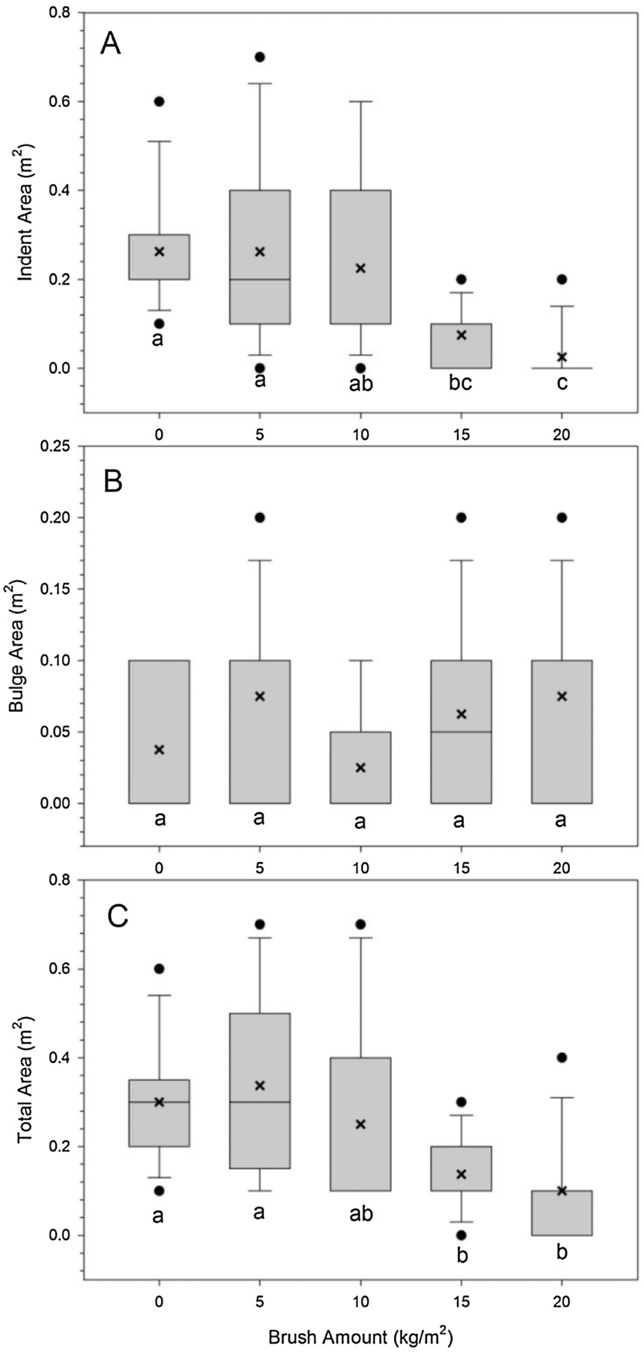

Fig. 5. Soil displacement caused after three forwarding cycles plus one pass of an unloaded forwarder to simulate the passage of a harvester for A. indent, B. bulge, and C. total area (all n = 8) as derived from RoadEng analysis. Different letters indicate significant differences based on a one-way ANOVA test at the 0.05 level. Mean disturbance at each brush amount is indicated by "X".

disturbance, a regression tree analysis was completed. The indent area regression tree (Fig. 7A) indicates that brush mat amount is the primary variable in explaining variation in indent area. At a brush mat < 12.5 kg/m^2 (left side), 27% of the total deviation in indent area is explained. Soil moisture is the next variable where the variation is divided between < 50% and > 50%. Soil moisture < 50% ends at a terminal node and the predicted indent area is 0.10 m^2. At > 50% soil moisture, the variation is divided between soil moisture contents of < 70% and > 70%, which has predicted indent areas of 0.48 and 0.24 m^2, respectively. At brush mats > 12.5 kg/m^2 (right side), 27% of the total deviation is explained, and the variance is split between soil moisture < 25% and > 25%. Fig. 7A predicts that indent area could be minimized to 0.0 m^2 if brush amounts applied to operating trails was > 12.5 kg/m^2 and soil moisture was < 25%.

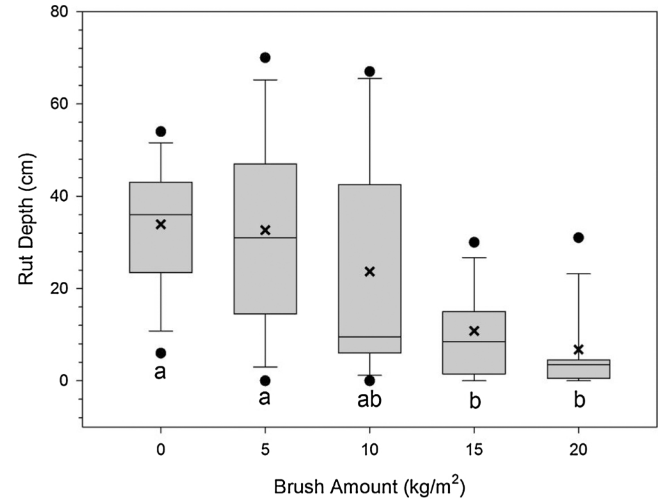

Fig. 6. Box plot distributions of soil rut depth as a function of brush amount (n = 8) after three forwarding cycles plus one pass of an unloaded forwarder to simulate the passage of a harvester. Significant differences are shown by different letters based on a one-way ANOVA test at the 0.05 level. Indent area values are derived from the RoadEng cross sections at each test plot on four different trials. Mean disturbance at each brush amount is indicated by "X".

Soil moisture is the first variable in describing rut depth variation in the regression tree analysis where soil moisture < 50% (left side) explains 33% of the total deviation (Fig. 7B). The next split is brush mat amount, separated into < 7.5 kg/m^2 and > 7.5 kg/m^2, which results in predicted rut depths of 16.2 and 3.8 cm, respectively. At soil moisture > 50% (right side), the variation is separated by brush amounts < 12.5 kg/m^2 and > 12.5 kg/m^2. At brush mats > 12.5 kg/m^2, a predicted rut depth of 12.9 cm occurs and ends at a terminal node. At brush mats < 12.5 kg/m^2, soil moisture further separates the variation at < 70% and > 70%, where predicted rut depths of 52.8 and 31.6 cm are observed respectively. Fig. 7B predicts that rut depth could be minimized to 3.8 cm if soil moisture was < 50% and brush mat was > 7.5 kg/m^2.

To identify the circumstances where brush mat application would help mitigate indent area and rut depth in CTL forest operations, variation within the regression trees was analysed. Terminal nodes explaining > 50% of the total deviation were identified on both regression trees. Terminal nodes with < 50% of the total deviation explained have other unaccounted factors influencing them; and as such, they have been disregarded. There are three terminal nodes in indent area (Fig. 7A) and another three terminal nodes in rut depth (Fig. 7B) with > 50% of the total deviation explained and in all cases soil moisture is the main factor. The one exception to this is that on the first branch of indent area (left side), brush mat amount explained slightly more variation (27%) than soil moisture (26%); however, in all other cases, soil moisture is the dominating factor when analyzing indent area and rut depth. This indicates that brush is helpful in reducing indent area and rut depth where soil moisture is < 50%. At a soil moisture content > 50%, a maximum total deviation of 67% is explained at four terminal nodes, and in all these cases soil moisture explains more than 40% of the total deviation. As a result, at soil moisture contents < 50%, the application of a brush mat has a strong effect on mitigating indent area and rut depth; however, at soil moisture > 50%, little benefit is observed with the use of a brush mat. This is an indication that the use of a brush mat (up to 20 kg/m^2) on wet soils (> 50% soil moisture) is not able to avoid extensive indent areas and rut depths.

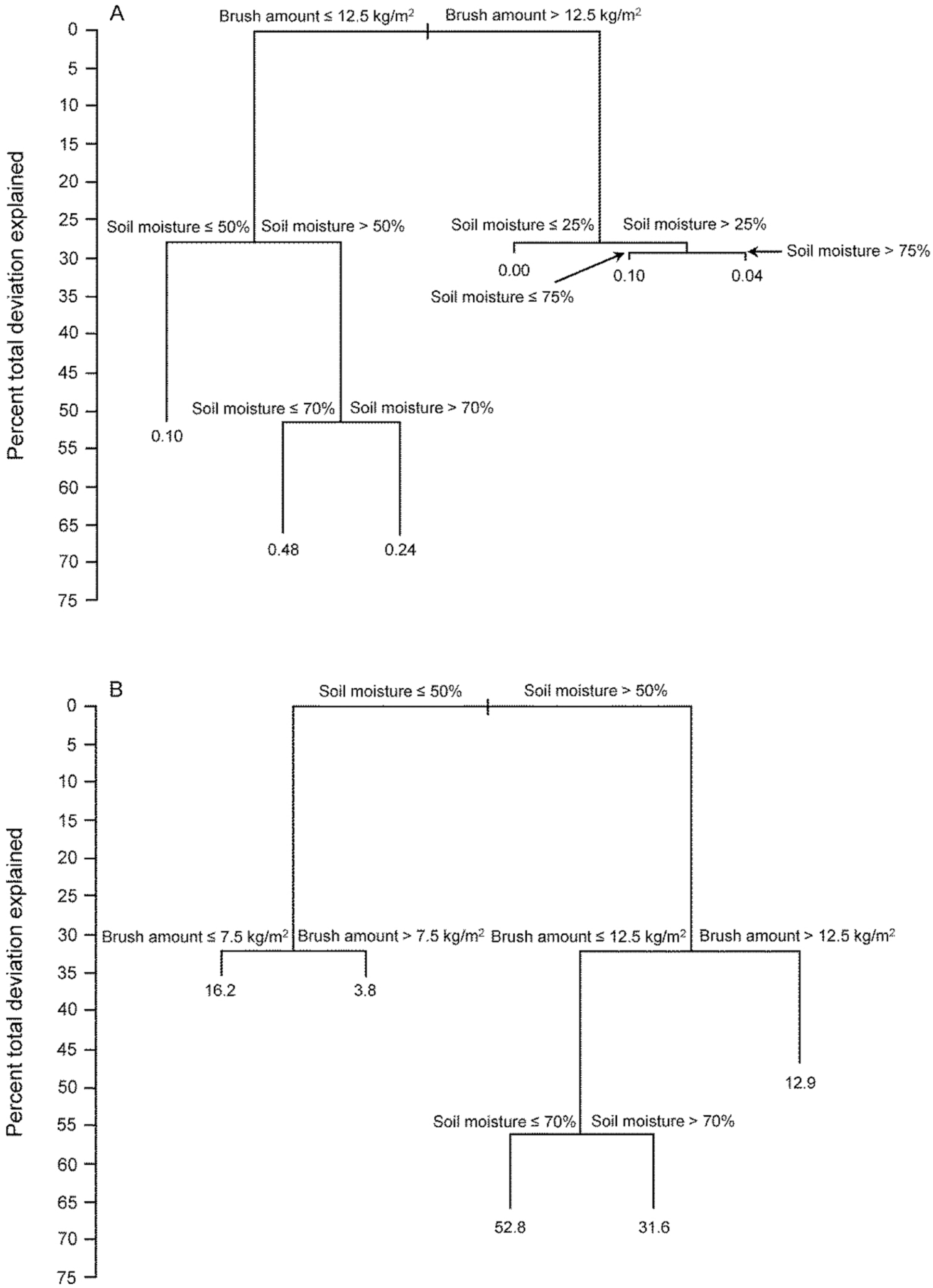

Fig. 7. Regression tree analysis of brush amount and soil moisture variables associated with indent area "A" and rut depth "B". The length of each branch is proportional to the amount of data variability explained by each split. Predictions are at the end of each terminal node.

4. Conclusion

The results of this study indicate that significant soil protection with respect to soil displacement and rutting can be achieved by brush covering layers (mats) of 15 and 20 kg/m^2 placed on top of machine operating trails in particular when soil moisture is below 50%. However, since an exact amount of brush mat is difficult to achieve during harvesting operations, a range of brush amounts may be a more appropriate recommendation. Brush amounts between 15 and 20 kg/m^2 (or about 50–60 cm loose thickness) would be capable of significantly reducing soil disturbance, such as displacement, when compared to the no brush scenario. Significant rut depth improvements compared to 5 and 10 kg/m^2 brush mats were also observed with the 15 and 20 kg/m^2 brush mats. In this study, applying a 20 kg/m^2 brush mat resulted in indent areas after forwarding of less than 0.2 m^2 and rutting depths < 31 cm at a wide range of soil moisture contents (17–93%), which occured within the 20 kg/m^2 brush covered plots in this study. There is no evidence to suggest that 15–20 kg/m^2 brush mats can completely avoid soil disturbance caused by forest harvesting on wet soils.

For practical application, it is suggested to apply brush mats on critical segments of machine operating trails with high susceptibility for rutting (wet spots, depression areas) rather than equally covering all operating trails with brush. Forest managers and local environmental policy should determine the amount of soil displacement on machine operating trails that is environmentally, operationally and physically acceptable. As our study reveals, although brush mats will not eliminate soil displacement, 15–20 kg/m^2 brush cover amounts have the potential for significant reduction of soil rutting when three cycles of a forwarder plus one pass with a harvester are used on silty soils with a wide range of soil moisture contents.

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