PREDICTION OF SPATIALLY DISTRIBUTED SITE IMPACTS FROM FOREST HARVESTING SYSTEMS

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Abstract

The soil-water characteristic curve of an unsaturated soil can be used to estimate strength-related properties of soil as a function of suction. The practical implementation of soil mechanics theories of traction and compaction for variable site conditions can benefit from representation of functions of unsaturated soil properties over the landscape. In this study, the variation of soil shear strength and compressibility over a forested site in central Saskatchewan was estimated from data for soil texture, bulk density and water content measured systematically over the site. Results were compared with site impact data obtained from harvesting operations involving rubber-tires skidders and a tracked feller-buncher. The severest soil compaction was concentrated on and near roads and landings, clearly a serious cause of soil degradation. Away from these areas, degree of soil compaction was correlated with soil shear strength.

1. Introduction

Many predictive studies of traction and compaction limit themselves to homogeneous conditions and average soil parameters will be determined and reported for some average bulk density and water content. However there is always significant variability of strength of field soils [1], even over an area reputedly small in size and 'homogeneous', such as a tilled field. The conditions found in natural forested areas are significantly more variable. There is increasing concern about the detrimental effects of forestry machine operations on the sustainability of forest ecosystems [2]. Forest machinery management could benefit from practical implementation of soil mechanics theories at the landscape level; however, it is unrealistic to have to measure soil strength parameters for each water content and bulk density. Although the large variability of site conditions is a challenge for managers, it also means that for real problems involving traction, tillage and compaction problems in the field, it is not necessary to have a lot of precision. It is sufficient to run models using reasonable *estimates* of soil strength parameters as they vary with soil water content or suction.

The soil-water characteristic (or moisture retention curve) of an unsaturated soil is a fundamental relationship for an unsaturated soil. The soil-water characteristic for a given soil structure (texture, bulk density, stress history) is a *constitutive* relationship, as it relates a strain state variable (*i.e.* water content) to a stress state variable (*i.e.* soil suction) [3, 4]. Conventionally, the soil-water characteristic has been used to estimate the variation of hydraulic conductivity as a function of suction. It can in fact be used to estimate a wide range of unsaturated soil functions, including soil strength [*e.g.* Ref 5]. Furthermore, the soil-water characteristic curve of a coarse textured soil can be estimated from the grain size distribution curve and bulk density data [6, 7, 8, 9] (prediction for clay soils requires knowledge of aggregation as well).

In this paper we used some of the prediction formulae reported in the literature and available in an unsaturated soils knowledge-base (*SoilVision*®, version 1.20, SoilVision Systems Ltd., Saskatoon, SK, Canada) to estimate the variation of soil strength over a forested site in central Saskatchewan, from data for soil texture, bulk density and water content. Results were compared with soil compaction data obtained from harvesting operations involving rubber-tires skidders and a tracked feller-buncher.

2. Materials and Methods

2.1 Site and System Description

The site was located in the Whiteswan Mid-Boreal Upland Region – Mixedwood section about 110 km northeast of Prince Albert, Saskatchewan at 54°10.5'N, 105°04.3'W. Figure 1a shows the configuration of the cut block. Dominant tree species included black spruce (*Picea mariana*), white spruce (*Picea glauca*), jack pine (*Pinus banksiana*) and trembling aspen (*Populus tremuloides*). The soils were well drained Eluviated Eutric Brunisols and moderately well drained to poorly drained Gleyed Eluviated Eutric Brunisols.

A pre-harvest site assessment was carried out in August, 1995 [10]. A 100 m x 100 m systematic random sampling grid was established over the undisturbed cutblock. At each grid location an approximately 10 m × 10 m area was surveyed based on the Saskatchewan Site Classification System [11] and a 70 mm diameter × 400 mm undisturbed soil core was obtained for determination of particle size distribution, bulk density and water content. Site elevation data were obtained using differential GPS (Model GSR2100, Sokkia Corp., Japan). The site topography was variable (Fig. 1b) with approximately 46.5% of the area having slopes less than 5%, 28.5%s slopes of 5% to 19%, 17.8% slopes of 20 to 39%, and 14.4% with slopes greater than 40%.

The site was harvested in September, 1995. As part of a larger study comparing two different harvesting systems [10], about two thirds of the 24 ha area was harvested using a 'mechanical' system (tracked CAT 325 feller-buncher/rubber-tired John Deere 748G grapple skidder/mechanical roadside process) while the remaining one third was harvested using a 'conventional' system (handfalling/three rubber-tired Clark 664 cable skidders). A haul road was constructed which acted as a separation between the mechanical and conventional system cut block areas, and as the main access road (Fig. 1a). Several short block roads were constructed in the mechanical block area for decking in order to keep skidding distances to a maximum of 110 m. Approximately one-half of the conventionally harvested area was designated a "short skid" area (0-170 m). The maximum skidding distances for the conventional crews were 250-450 m [12].

A detailed post-harvest site impact study was carried out in September 1995 [10]. A 60 m systematic sampling grid was laid out over the site and at each of the 68 grid locations a 2 m × 2 m quadrat with one corner at the grid point was established as the sampling region. Within this sampling region two sets of readings of density versus depth to 300 mm were taken using a neutron/gamma gauge (Model 110-MC-1DR, CPN Corp., Martinez, CA) and the corresponding rut depth recorded. Average volumetric water content in the top 200 mm was measured using TDR (Model 6050X1, Trace Systems). If the area was partially disturbed (*e.g.* a rut crossed within the boundaries of the quadrat), a paired reading of undisturbed versus in-the-rut density was made. Where the quadrat area was either totally undisturbed or completely covered by a disturbance, two sets of readings were taken as replicates and averaged. Spatial data were input into *ArcView*® (v. 3.1, ESRI, Redlands, CA) Geographic Information System. The 'undisturbed' data were input to establish 'initial' dry bulk density and water content distribution over the site. The in-the-rut dry bulk density and rut depth were input, along with type (*e.g.* compacted, forest floor removal) and cause (*e.g.* multipass skidder) of disturbance to establish spatial distribution and intensity of soil compaction [13].

2.2 Estimation of Spatially Varying Soil Strength

Soil-water characteristic curves were predicted from grain-size distribution curves using the routine developed by Fredlund et al [9] which is implemented in *SoilVision*. The predictions were based on porosity determined using mass-volume relations for a given soil structure (*i.e.* average bulk density and water contents for a given texture determined at the site classification survey locations). For each soil structure, soil-water characteristic curves were estimated for a range of dry bulk density values from 1.0 to 2.0 Mg m^{-3}. Based on the results, several 'structure' classes were identified based on texture–bulk density combinations that resulted in soil-water characteristics curves that fell within fairly small water content ranges. Bulk density values of 1.6 – 1.8 Mg m^{-3} were also used as transition values, because some studies suggest that for coarse textured soils these may be 'critical' values inhibiting root growth [*e.g.* 14, 15]. Within each texture–bulk density class, the predicted soil-water characteristic data were averaged to establish a representative curve.

The power law proposed by Brooks and Corey [16] was then used as the curve-fitting equation for the predicted soil-water characteristic curves to establish mathematical relationships between water content and suction for each texture–bulk density class:

$$\theta_w = \theta_r + (\theta_s - \theta_r)\left(\frac{a}{s}\right)^n \tag{1}$$

where a = bubbling pressure (kPa), n = pore size index, θ_r = residual volumetric water content, θ_s = saturated volumetric water content, and s = matric suction (kPa). Eq. (1) was adopted because it provided a good fit to the data and is easily rearranged to write suction as a function of water content. Based on the determined parameters, the soil suction was calculated from water content at each 60-m grid point and data interpolated over the site using the spline interpolation algorithm available in *ArcView Spatial Analyst*. The resulting curves (1) are theoretical relationships and measured water contents may exceed the estimated maximum (saturated) water contents. Therefore, for each texture–bulk density class, if water content was greater than the θ_s for the maximum bulk density in the range, then suction was set equal to 0.01 kPa ('saturated').

Matric suction acts like an all-round confining pressure that provides additional strength to the soil against compression and shearing. The predictive model we adopted for shear strength of an unsaturated soil, starts from saturated strength parameters (effective cohesion c' and effective angle of internal friction ϕ') and then integrates the soil-water characteristics curve to estimate the variation of the soil shear strength with soil suction and degree of saturation [4]. The resulting relationship can be written:

$$\tau_f = c' + s\,(S)^p \tan\phi' + (\sigma - u_a)\tan\phi' = c + (\sigma - u_a)\tan\phi' \qquad (2)$$

where τ_f= shear strength (kPa), $\sigma - u_a$ = mean net stress (kPa), σ = total applied normal stress (kPa), u_a = pore-air pressure (assumed atmospheric), S = degree of saturation of soil, p = a soil parameter related to soil texture, approximately equal to 1 for coarse textured soils, and c = 'total cohesion' at a given soil water content [5]. Eq. (2) was used with zero mean net stress to determine the variation of minimum shear strength (*i.e.* total cohesion) across the site.

Finally, a correlation was run between shear strength data and soil compaction, represented as the percent difference in 'disturbed' and 'undisturbed' bulk density data determined at the grid locations. Based on triaxial tests on soil samples from a limited number of locations, soil compressibility was found to vary little for the range of textures and suctions tested (*i.e.* λ_N = 0.22 – 0.24 for suctions from 0 – 15 kPa) [17] and was not included in this analysis. At the time this paper was written, there were problems with obtaining slope data from the DEM and so slope was also not included, although it is expected to be an important factor.

3. Results and Discussion

Figure 2 shows particle-size distribution curves determined for soils over the mechanical site (0-350 mm depth). Data were extrapolated to estimate clay content and coarse fragment content by curve-fitting experimental data using *SoilVision*. Grain size distributions were found to be generally very similar within the forest cover zones. The site map was therefore divided into texture zones based on dominant overstory species (Fig. 1a) with the exception of the upper slopes in the north-eastern edge bS zone which had a much finer texture, especially in the upper 200 mm. There was little variability in soil texture across the conventional site, which was sandy. Figures 1(c) and 1(d) show interpolated data for initial dry bulk density and degree of saturation.

Figure 3 shows predicted soil-water characteristic curves for the 0-200 mm depth soils in the mechanical and conventional sites adjacent to the main block road, along with experimental water content versus suction data determined using pressure-plate apparatus for single samples from each of these sites. The agreement is very good. Table 1 summarizes the parameters of the theoretical soil-water characteristic curves for each of the texture–bulk density classes selected. Figure 4 shows variation of estimated cohesion versus water content based on Eq. (2), the soil-water characteristic curves shown in Fig. 3, and c'_{sand} = 8 kPa, ϕ'_{sand} = 34º and c' = 10 kPa, ϕ' = 35º for the loamy sand and sandy loam (The strengthening effect of roots in the soil is reflected in the high value of effective cohesion determined for these frictional soils). Figures 5(a) and 5(b) show, respectively, the predicted matric suction and total cohesion over the site. The site impact study did show that soil compaction and forest floor removal caused by two harvesting systems were fairly similar, despite the fact that the machinery used in the mechanical system were almost double the weight of the conventional cable skidders [10]. The analysis suggests that this was to some extent because the conventional machinery were operating in lower soil shear strength conditions (machinery applied ground-pressures were also similar). There was a trend for percent bulk density increase (compaction) to decrease with increasing soil total cohesion, but because of the large scatter in the data, the relationship was not statistically significant. Figure 6 shows that most severe impacts were concentrated on and near roads and landings. We know from observations, that other severe impacts occurred in very wet areas and on steep slopes due to wheel slippage. In the next analysis step, slope and distance from the road will be included as independent factors.

Table 1: Parameters of the Brooks and Corey equation (1) curve-fitted to predicted soil-water characteristics for three soil textures and low, medium and high bulk density ranges.

Soil Texture	*Dry Bulk Density, Mg m^{-3}*	*Parameter*			
		a, kPa	*n*	θ_r	θ_s
Sand	<1.2	0.80	0.930	0.030	0.574
	1.2-1.7	1.09	0.790	0.046	0.442
	>1.7	1.20	0.489	0.046	0.308
Sandy Loam	<1.2	0.04	0.218	0.000	0.586
	1.2-1.4	0.27	0.314	0.024	0.540
	1.4-1.7	0.61	0.299	0.027	0.416
	>1.7	1.15	0.224	0.000	0.308
Loamy Sand	<1.2	0.08	0.210	0.000	0.586
	1.2-1.6	0.29	0.455	0.013	0.472
	1.6-1.8	0.79	0.553	0.035	0.360
	>1.8	1.09	0.469	0.036	0.283

In ongoing work, we are using the *Avenue* script language to link *ArcView Spatial Analyst* and *SoilVision* to automate procedures for characterizing soil mechanical properties over a site and identifying zones of low, moderate and high compaction risk. Shi [17] used a simple critical-state finite element model to predict compacted bulk density vs. depth and rut depths caused by the feller-buncher and skidders used in this study. Results were very good especially considering the variability involved. The goal is to eventually be able to establish site impact indices for a site based on the type of information that will be collected as part of standard pre-harvest surveys, *e.g.* simple visual and tactile indices of soil properties (hand-texturing, soil drainage class, slope and aspect, etc.) [11].

4. Conclusion

Spatial distribution of site characteristics along with estimates of soil property functions may be used to predict distributions of soil strength suitable for use with predictive models of compaction and traction. Given the high variability of forest soils, it would be beneficial to incorporate the effect of sampling error in measurement of parameters into predictions, particularly if rather crude sampling grids are used over a site. The full benefit of such an approach as an aid in planning of forestry operations and selection of machinery could be achieved by combining a database of regional forest soil properties, site classification characteristics stored in a GIS, and simple mathematical models of soil-machine interaction.

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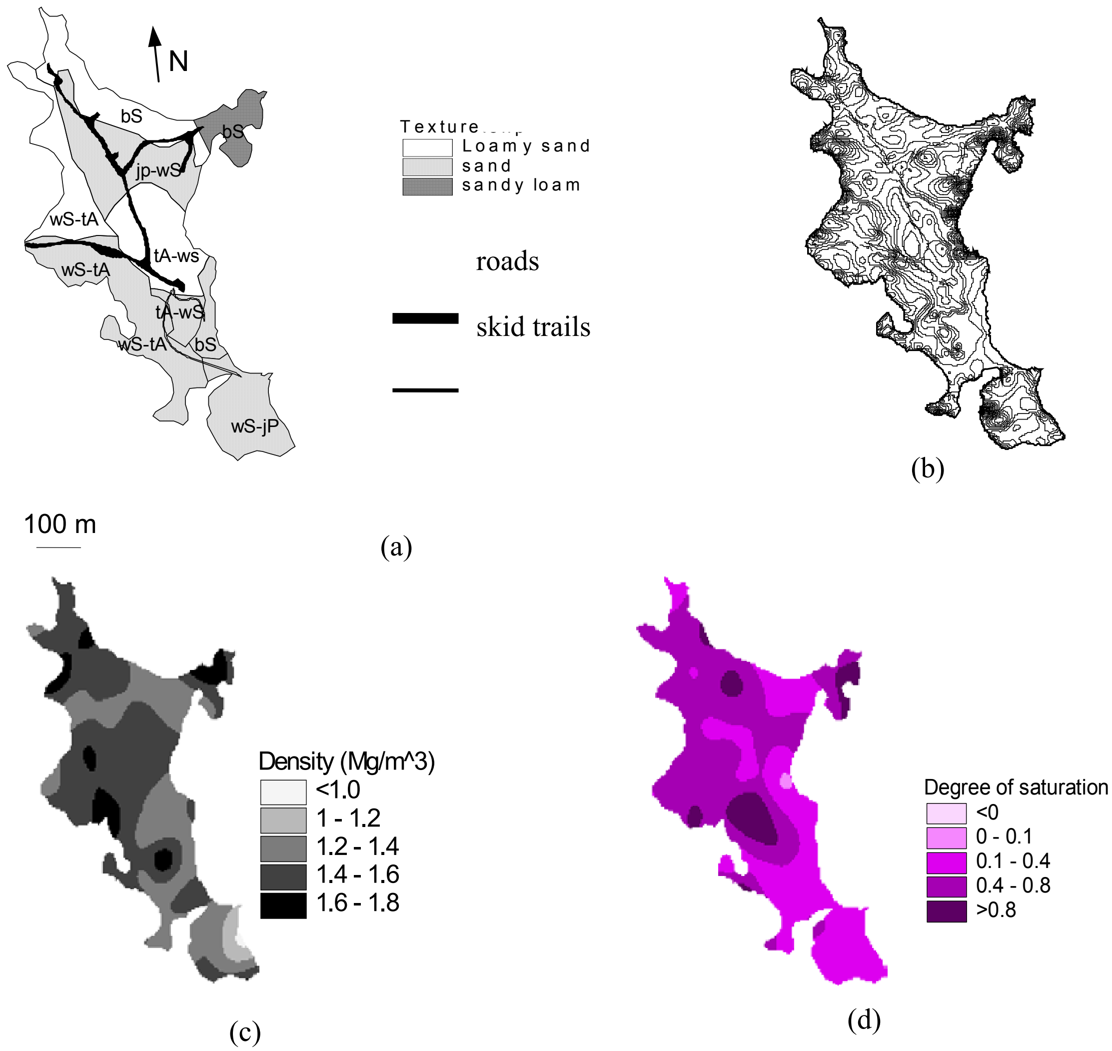

Figure 1: (a) Cutblock configuration, primary roads, forest cover types and soil texture. bS = black spruce, jP = jack pine, tA = trembling aspen, wS = white spruce; (b) Elevation (1-m contours); (c) Initial dry bulk density; (d) Initial degree of saturation.

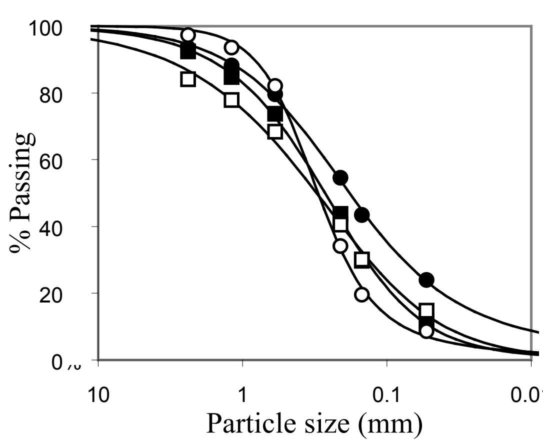

Figure 2: Particle-size distribution of the mineral components of the soil, based on texture analysis of samples taken at nine locations over the mechanical block in three forest cover zones (*c.f.* Fig. 1a). ■, bS zone (Loamy sand); ●, bS (Sandy loam); □, tA-wS (Loamy sand); ○, jP-wS (Sand).

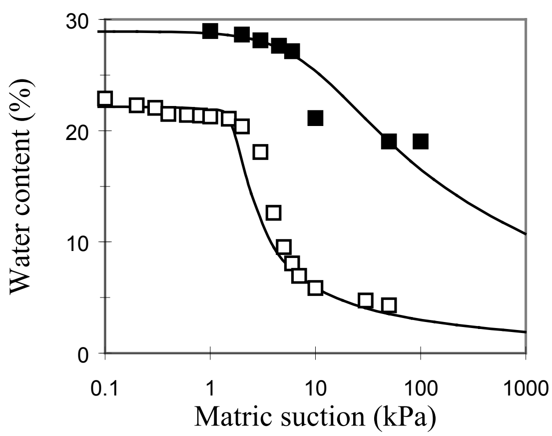

Figure 3: Soil-water characteristic curves. The symbols (■,□) are experimental data points for single samples obtained from loamy sand and sandy areas, respectively. The solid curves (—) were predicted from average particle size distribution curves).

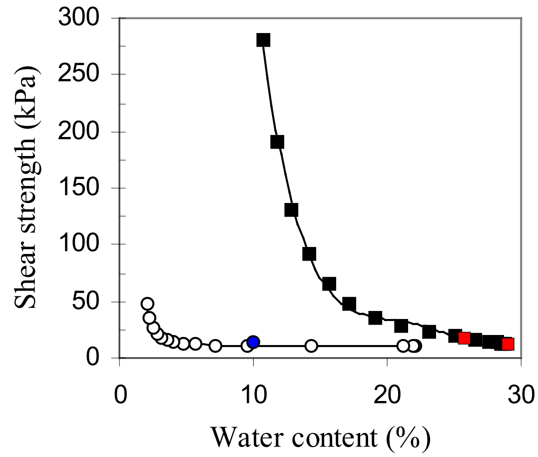

Figure 4: Minimum soil shear strength (total cohesion) versus water-content functions estimated using Eq. (2) and soil-water characteristic curves shown in Fig. 3. Symbols (●,■) are experimentally determined values of cohesion.

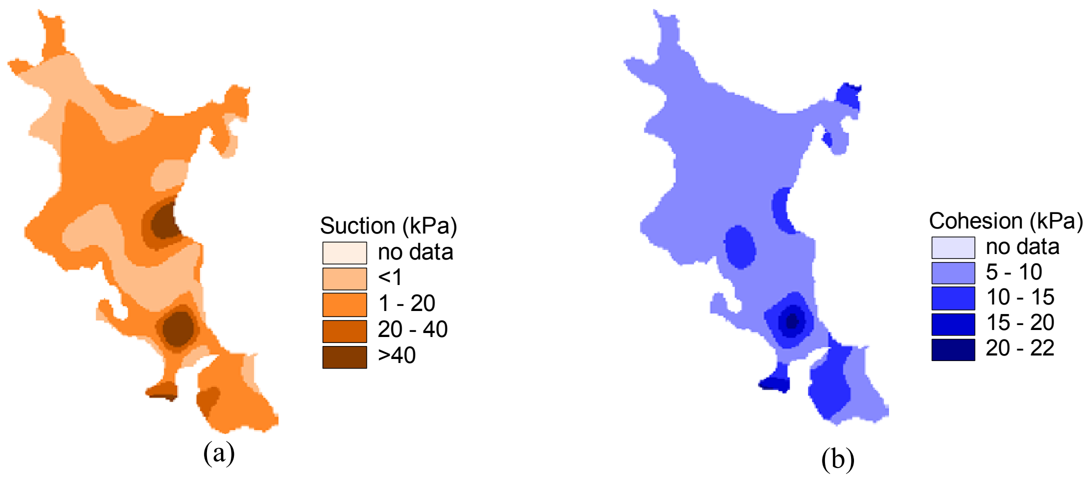

Figure 5: Estimated variation of (a) soil suction and (b) total cohesion over the study site.

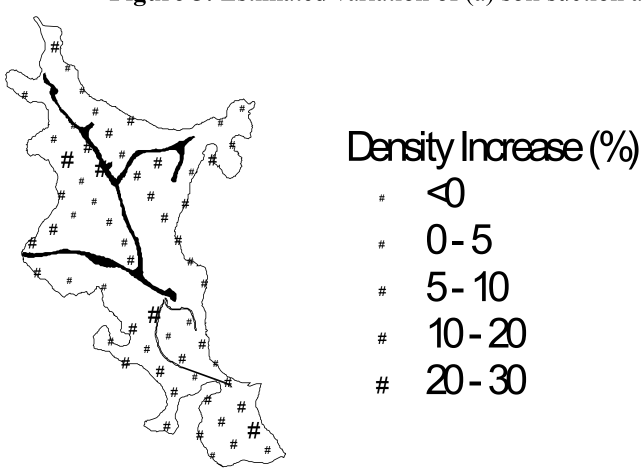

Figure 6: Measured soil compaction (percent increase in dry bulk density) at 60-m grid points.