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Full Length Research Paper

Analyzing the use of mathematical models in South African forestry: A case study of the ProFor model

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Timber harvesting operations in plantation forestry in South Africa are rapidly being mechanised. However, machine movement in forest plantations may negatively affect soil quality. The forestry industry is introducing mathematical models to enable it address, limit or at least predict soil damage. One of these mathematical models is the "ProFor" model. The study was conducted in four harvesting sites namely KwaZulu Natal; Eastern Cape and the Western Cape. The impact of mechanised harvesting equipment on soil quality was assessed by observing changes in soil bulk density and critical soil water content. The changes in soil physical properties were then compared with ProFor's predictions. The results indicated that ProFor gave valid predictions for critical soil moisture content in most of the study sites. However, for observed increases in bulk density, ProFor predictions of soil damage were invalid (r^2 = - 0.1). The model can be adopted by the South African forestry industry for tactical planning of forest harvesting operations. Additionally, ProFor can be of even more use if a separate algorithm is developed to be used for the prediction of soil compaction which is a common hazard in South African forestry.

Key words: Bulk density, forest harvesting, ProFor, soil compaction.

INTRODUCTION

Timber harvesting operations in plantation forestry in South Africa are rapidly being mechanised. Contributing factors include the need to improve productivity, wood quality and safety of operations. The prevalence of HIV/ AIDS and depopulation of the rural areas has also led to the scarcity of manual labour in the South African forestry industry (Clarke and Moenieba, 2004). In addition, HIV/AIDS has had an impact on the fitness of the available labour to sustain high productivity levels under the prevailing conditions of manual harvesting operations. In the light of these factors, mechanisation of timber harvesting operations acts as both a remedy and an alternative, which make it attractive to South African plantation forestry industry. However, research has shown that forest that forest harvesting machines have the potential to cause soil disturbances such as soil compaction, ruts, which become water channels and cause subsequent soil erosion (Froehlich and Mc Nabb, 1984; Smith et al., 1997). These disturbances could have a harmful effect on site productivity (Murphy et al., 2004). Therefore, to sustain the produc-tivity of the major timber growing areas of South Africa it is important to prevent potential soil damage caused by forest machinery. One of approaches being used to solve this problem is through the use of mathematical models (Kolenka, 1978; Marsili et al., 1998).

Machine-soil interaction is influenced by a number of factors, the most important being soil physical parameters, total mass and mass distribution of the machine, number of wheels in contact with the soil and the tyre construction elements that is, ply rating, width, diameter and tyre inflation pressure (Hillel, 1980). The main soil parameters that affect the ability of the soil to carry a certain load without being damaged are soil water content, soil tex-ture, humus content, skeleton content (soil particles > 2

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mm) and the slope of the terrain. Of these parameters, only soil water content varies widely over relatively short periods of time (that is, seasonal effects) and can be monitored for scheduling mechanical operations on forest sites. This knowledge and data could therefore enable the calculation of critical soil water content for a given soil, as well as the machine and terrain conditions for the prevention of soil damage.

Atterberg (plastic and liquid) limits are defining plastic deformations and liquification in soil. The plastic limit refers to the soil water content dry enough to bear mechanical loads typical for forestry machinery without risk of deformation (Matthies et al., 2006). On the other hand, liquid limit refers to the soil moisture content at which the soil changes from plastic state to liquid state. Small amount of plastic deformation may be regarded as negligible, which means that adopting plastic limit as such may be unnecessarily restricting site accessibility. This then means that forest management operations in soils with a water content status closer to the plastic limit than to the liquid limit could be a better estimate of critical soil water content for operational purposes. Based on this premise, the Technical University of Munich in Germany developed a model "ProFor" for predicting the limiting moisture content of any specific soil type, beyond which, soil damage might occur (Ziesak, 2003). The limiting soil moisture content lies between the plastic and liquid limits of the soil being tested (Figure 1). According to Ziesak (2003), the model can be used as a tactical and strategic planning instrument enabling forest enterprises to prevent soil critical operations.

The model essentially requires two main data input variables for the prediction of the limiting soil moisture content namely: soil parameters and machine configure-tion data, soil physical parameters including sand, silt and clay percentages as obtained from the particle size analysis, humus content (< 5, > 5%), whether the soil experiences alterations in the water table, the skeleton content (< 30, 30 - 50, > 50%) and slope (< 15, 15 - 30%). Machine configuration data include the name (weight, torque) of the machine being used, types, size and inflation pressures of tyres on both the front and the rear axles of the machine. This model is currently being used in some European countries such as Italy and France (Ziesak, 2003). However, for its application in the South African forestry industry, evaluation under South African conditions was necessary. The objective of the study was to evaluate on-site impacts of harvesting equipment on soil properties and comparing them with ProFor's outputs.

MATERIALS AND METHODS

Study sites

Three timber harvesting sites were selected in two of the major plantation forestry regions of South Africa including Eastern Cape and Western Cape. The selected sites provided for a range of climatic conditions, soil types and parent materials. In the Eastern Cape, the study was conducted in the Mountain Two Ocean (MTO) Forestry Company's Blue Lilies Bush plantation (34°04'50.77"S, 24°20'32.52"E).The site is stocked with 28-year-old *Pinus pinaster* and receives rainfall throughout the year. The mean annual rainfall for the area is 1082 mm. In the Western Cape, the trial was also conducted in the Mountain Two Ocean (MTO) Forestry Company's Grabouw plantation. In this plantation, the study was conducted in two compartments, namely B21 (34°05'09.40"S, 19°01'47.20"E) and M1 (34°11'56.57"S, 19°06'10.58"E. Unlike the other two sites, this area receives winter rainfall with mean annual rainfall of 1061 mm. Both compartments were stocked with 35 year old *Pinus radiata* trees. Prior to the study, management history of the site was obtained to avoid the selection of compartments with previous machine harvesting or thinning history which could affect the soils response to machine trafficking. The specifications of the machines that were used in the study are presented in Table 1.

Each study site was laid out on a sloping area to take advantage of the natural soil water gradient ranging from well-drained condi-tions at the top of the slope to water logging at the bottom. This set up would help in the evaluation of the impact of forest harvesting equipment on soils and the consequent comparisons with ProFor outputs under different soil water content regimes. All four study sites were located near a river to ensure the waterlogged conditions at the foot of the slope. For each study site the empty machines were allowed to make four passes at a normal infield speed (5km/h) and with minimal deviations from the original track as depicted in Figure 2. Smith et al. (1997) showed that only four passes are needed to reach 90% of the maximum density in surface soils although density continues to increase in amount and depth with the number of passes.

After four passes by each machine, sampling points were selec-ted systematically at 5 m intervals within the track and marked with paint. Adjacent to the sampling points in the track; 'control' sampling points (unaffected area) were also selected and marked. On each point, three undisturbed soil samples were collected at a depth of 7 cm. Soil sampling was done by using a hammer-driven core cylinder, was 7cm high and 7.1cm in diameter.

Soil texture was determined using the pipette method (Soil Clas-sification Working Group, (1991). The soil texture was described in terms of percentages of clay (< 0.002 mm), fine silt (0.002 - 0.02 mm), course silt (0.02 - 0.05 mm), fine sand (0.05 - 0.25 mm), medium sand (0.25 - 0.50 mm) and course sand (0.5 - 2.00 mm). Volumetric soil water content was determined gravimetrically. The soil samples were weighed on the same day they were collected to obtain initial masses. The samples were then dried in an oven (105°C) for a period of 24 h. The amount of water in the soil was determined by subtracting the oven-dry mass from the initial field soil mass. The mass of the water was then divided by the volume of soil (Equation 1).

$$W \text{ (volume-\%)} = ((W_w - W_d)/ \text{mass of soil})^* \text{ bulk density (g/cm}^3)$$

Where; W= Volumetric water content (%); W_w = mass of wet soil (g) W_d = mass of oven dried soil (g)

Soil bulk density which expresses the ratio of the mass of dried soil to its total volume was determined using the following equation.

$$_d = M_1/V_1$$

Where; $_d$ = Dry soil bulk density (g cm^{-3}); M_1 = Mass of oven dried soil (g); V_1 = Volume of soil (cm3)

The plastic limits of the soils were determined using the 3 mm thread rolling method (Head, 1980), while the liquid limits were determined using the Casagrande apparatus (Head, 1980). In both cases, the dry method procedure for preparing the samples was used.

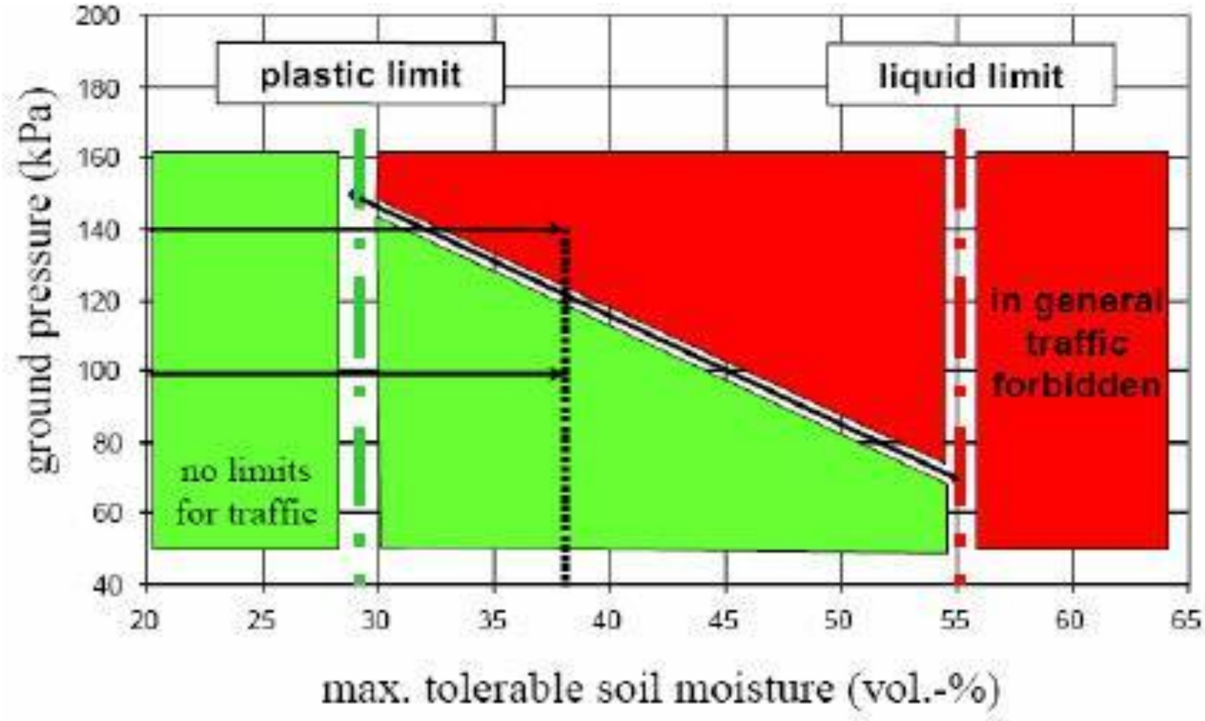

Figure 1. A schematic diagram of ProFor predictions of the critical soil moisture contents for sandy loamy soil (Ziesak, 2003).

Table 1. Specifications for machines used for evaluation of ProFor model.

Site	Machine specifications							
	Machine name	**Operating tare mass**	**Tyre name**	**Tyre manufacturer**	**Tyre size**	**Tyre ply rating**	**Tyre width (mm)**	**Tyre pressure (bars)**
Blueliliesbush plantation	John Deere 648G-111 TC Grapple Skidder	13934 kg	Logger	Firestone	30.5 - 32	16	774	(1.8^a, 1.75^b)
Grabouw Plantation (B21)	Timberjack 380C Cable Skidder	10355 kg	General	Bridgestone	23.1 - 26	16	587	(2.65^a, 2.3^b)
Grabouw Plantation (M1)	Clark Ranger F66 Cable Skidder	7893 kg	General	Bridgestone	23.1 - 26	16	587	(2.0^a, 1.95^b)

Superscripts a and b refer to front and rear axle tyre pressure.

Data analysis

The data was analysed using repeated measures analysis of variance (RMANOVA) and nonparametric tests that is, Wilcoxon matched pairs test (Gomez et al., 2002). All the data was analysed at 95% level of significance.

RESULTS

General information on soils textures, plastic limits and liquid limits of the soils for this study is presented in Table 2.

Soil bulk density

Significant increases ($p < 0.005$) in soil bulk density were observed both at the Blue lilies bush and a Grabouw (compartments B21 and M1) plantation upon the test passes of machinery. However, a decrease in soil bulk

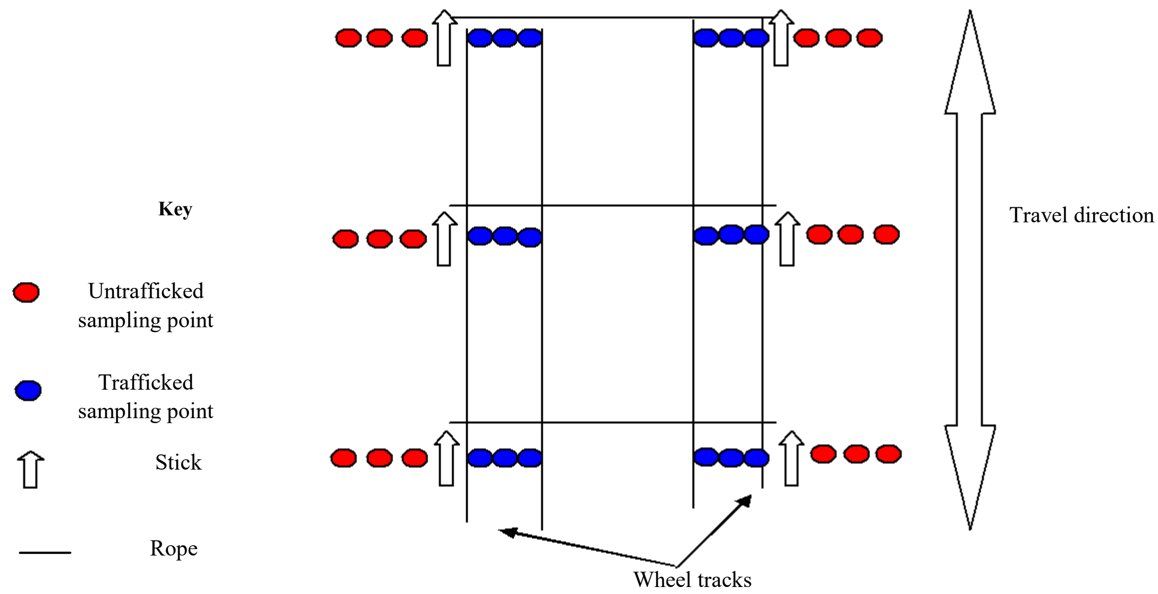

Figure 2. General set up of the experimental area.

Table 2. General information on classes, textures, moisture contents and Atterberg limits of the soils from the study sites.

Site	Soil class	ProFor value (%)	Initial moisture content (%)	Atterberg limits		Soil texture		
				Plastic %	Liquid %	Clay%	Sand %	Silt %
Grabouw Plantation (Compartment B21)	Sandy clay loam	30	30	21	31	20	62	18
	Clay loam	30	39	34	46	29	42	29
	Clay loam	30	33	35	51	33	31	36
	Clay loam	30	40	30	46	34	36	30
	Clay loam	30	48	35	46	37	35	28
Bluelilies- bush plantation	Loam	27	14	21	23	17	49	34
	Sandy loam	24	10	16	21	12	49	39
	Sandy loam	20	12	16	20	13	65	22
	Sandy loam	24	12	17	21	14	58	28
Grabouw Plantation (Compartment M1)	Clay loam	27	28	26	32	28	35	37
	Loam	27	30	27	33	23	36	41
	Loam	24	26	25	29	23	39	38
	Loam	30	29	25	30	25	43	33
	Loam	30	42	26	34	25	38	37

density was observed in Glengarry plantation (Figure 3. These findings support the known facts that repeated movements of forest harvesting machines results in the deterioration of site quality.

ProFor predictions and soil clay content

Figure 4 indicates that for soils with clay content lower than 15%, the predicted critical moisture content values are well above both the liquid and plastic limits thus the model over estimates the critical soils moisture contents for such soils, leaving them exposed to excessive deformation.

DISCUSSION

Soil bulk density

Significant increases in soil bulk density were observed in both Blueliliesbush and Grabouw plantations. The observed

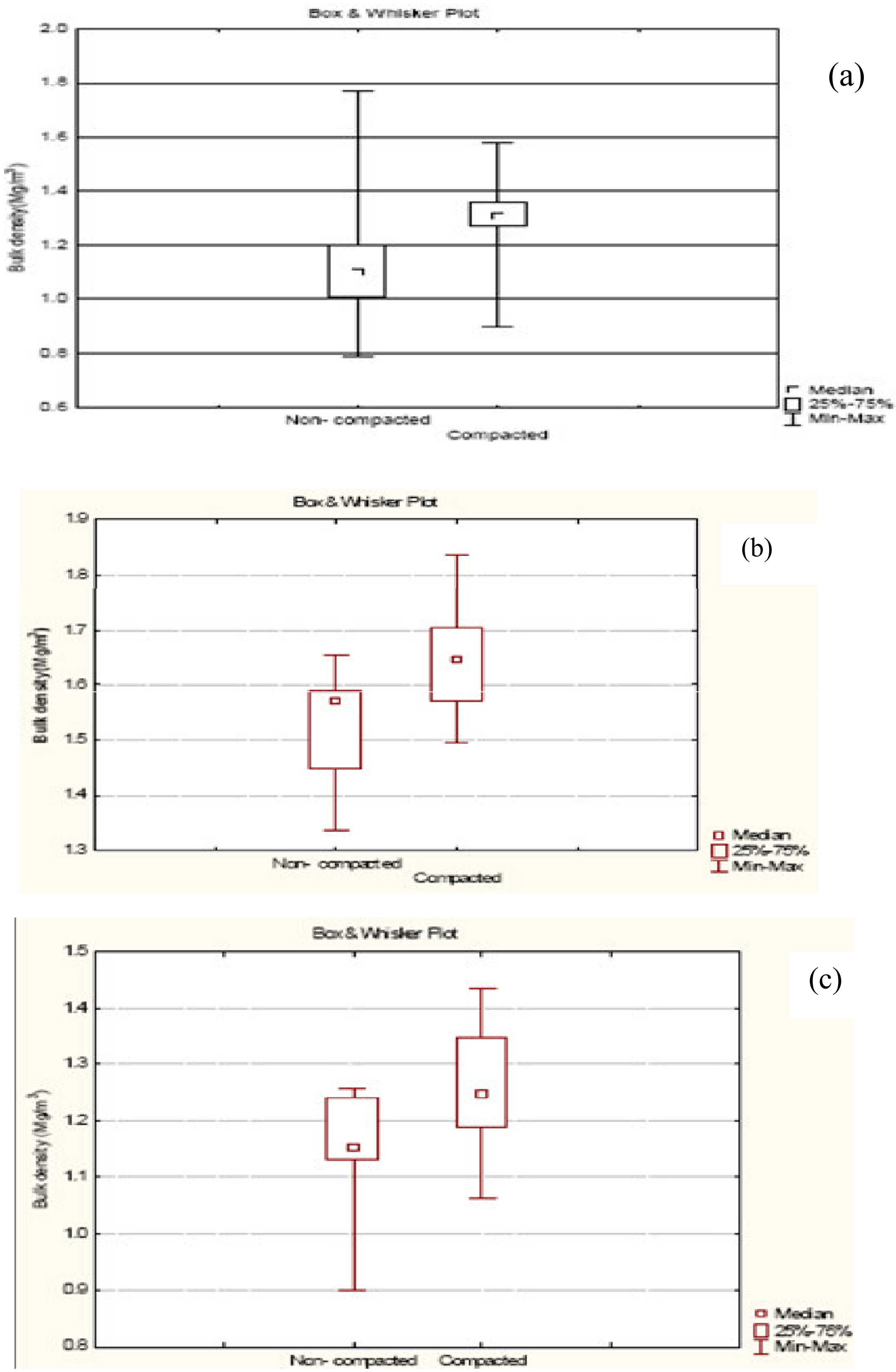

Figure 3. Box plots of changes in bulk density in Blueliliesbush plantation (a), Grabouw plantation, compartments B21 (b) and M1(c).

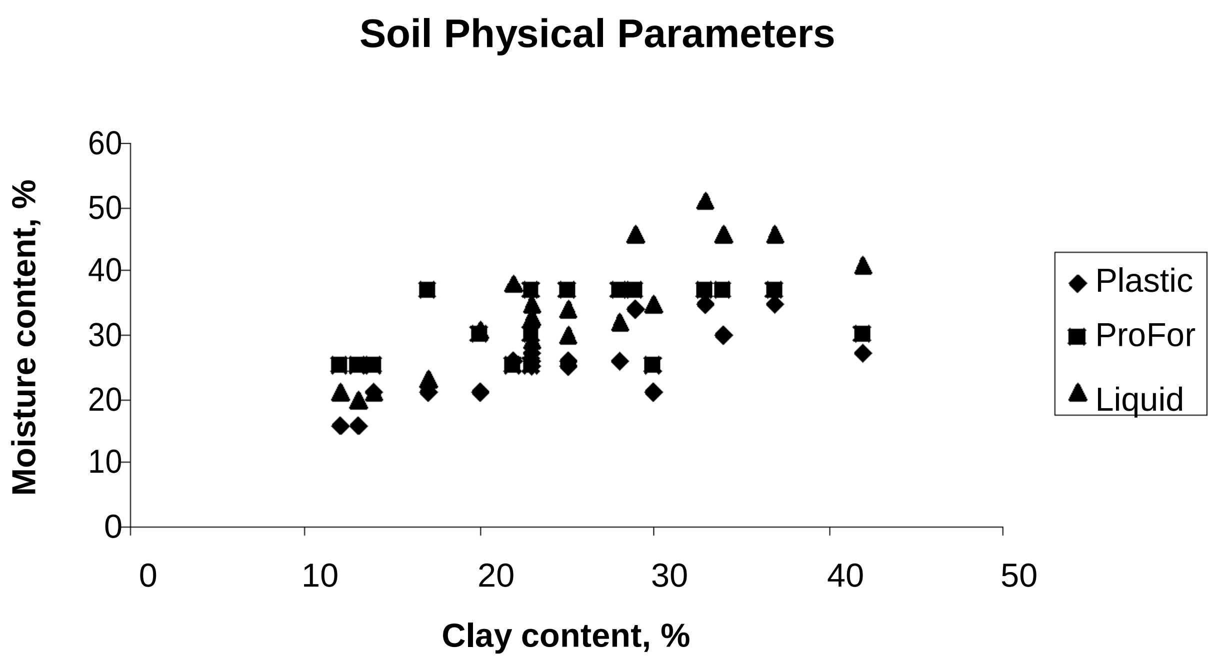

Figure 4. Relationship between the soils clay content, plastic limits, liquid limits and the predicted critical soil moisture contents.

significant increases in soil bulk density in the Bluelilies-bush could be attributed to soil texture than to soil moisture content at the time of experimentation. The dominant soil texture for the compartment was sandy loam. According to Smith et al. (1997) sandy loam textured soils are almost independent of soil moisture content when they are being compacted and increases in soil bulk density is almost entirely attributed to the increase in ground pressure. This is also supported by the findings of Panayiotopoulos and Mullins (1985) that sandy loam soils achieve higher bulk densities when it is very dry. This is the case because dry sands are always packed more closely under a given load due to the loss of annular bridges which are formed between sand particles when the soil is moist but are lost when the soil is dry. However, significant increases in soil bulk densities observed in the two Grabouw plantations' study sites could mainly be attributed to both the soil texture and the soil moisture content at the time of the study. The dominant soil texture for both compartments was clay loam. Hillel (1982) indicated that for clayey soils bulk density increases with an increase in soil moisture content until the optimum moisture content is achieved. In both compartments, the initial volumetric water content was between plastic and liquid limit (Table 2).

Assessment of sensitivity of ProFor predictions

Sensitivity of ProFor predictions on soil bulk density

ProFor gives the user the maximum moisture content value below which the machine can operate without causing damage to soil physical properties on a given site. Since soil compaction is one of the most crucial soil physical properties for sustainable forest management in the South African forestry industry, an assessment of ProFor sensitivity to soil compaction was deemed neces-sary. According to Marsili et al., (1998), soil compaction is one of the criteria used to evaluate the environmental impact of agricultural machinery traffic on soil and has also been identified as one of the major problems causing soil degradation (Canillas and Salokhe, 2002). One of the restrictions to a sustainable forest develop-ment is related to machinery traffic during harvest opera-tions, which may cause soil compaction. In order to asses the sensitivity of ProFor predictions on soil compaction, ProFor predictions on soil compaction were evaluated based on the criteria presented in Table 3.

The criterion indicates that if the difference between the initial moisture content and the ProFor predicted moisture content is positive, it can be expected that the soil damage of some form will be expected. On the other hand, if a negative value is obtained, no damage would be expected. The same principle applies to change in soil bulk density thus if the difference between the initial soil bulk density and the bulk density after the machine movement is positive, it means soil compaction has occurred and a negative value is an indication that no soil compaction occurred. The evaluation indicated that ProFor predictions poorly correlated (r^2 = - 0.1) with the changes in soil bulk density. This implies that ProFor cannot correctly predict soil compaction. It is quite under-standable, since the model suggests only one critical soil water content which lies between plastic and liquid limits,

Table 3. Evaluation of the sensitivity of ProFor prediction on soil compaction. Where $_v$ refers to the initial moisture content and $^c{}_v$ refers to ProFor predicted critical moisture content and ΔBD refers to change in bulk density.

Parameter	Damage	No Damage
ProFor	($_v$ - $^c{}_v$) > 0	($_v$ - $^c{}_v$) < 0
Bulk density changes	BD>0	BD>0

while a different (much lower) water content level would be required to determine the optimal (maximal) compacttion conditions (Head, 1992).

Sensitivity of ProFor predictions on plastic and liquid limits

As discussed elsewhere in this paper, the ProFor model predicts critical soil moisture contents for a specific site using soil texture and the physical characteristics of the machine as inputs. Matthies et al. (2006) indicated that the plastic limit of a soil refers to the soil moisture content dry enough to bear mechanical loads typical for forestry machinery without risk of considerable deformation. This therefore means that forest management operations in soils with a moisture content status closer to the plastic limit than to the liquid could be acceptable. According to Porsinsky et al. (2006), plastic and liquid limits classify-cation systems are reliable in modelling wheel-soil, machine-terrain and transport-environment interactions studies. Based on this premise, plastic and liquid limits were used in this study to asses the quality of ProFor in the prediction of the critical soil moisture content for a range of soil textures used in this study.

The results also show that the ProFor models predictions fall between the observed plastic and liquid limits and closer to the plastic limits. This implies that the models predictions are within the acceptable ranges. However, the model is predicting well only for soil with clay content over 20%. In practice this overestimation may not be critical, due to the lower natural slope of the sands and ease of material movement to refill the rut. Furthermore, this study may only be regarded as a warning signal requiring additional studies on sandy soils; since the dataset collected in this experiment is not sufficiently large enough to reach a definite conclusion.

Conclusion

Our findings show that ProFor can be effectively used to evaluate and regulate access of heavy machinery to forestry compartments during the wet season. The results indicate that the model produced good predictions of the critical soil water content for rut formation in highly variable moisture conditions (from well-drained to waterlogged soils of widely varying textures).

The assessment of the accuracy of ProFor models prediction on critical soil water contents has revealed that the model is capable of predicting the critical moisture contents of the soils with clay content greater than 20%. The study has revealed that ProFor predictions of critical soil moisture content on sandy soils are substantially different from observed values. An additional study may be warranted for sandy textures to confirm our findings and if necessary - improve the model for sandy soils. This will also improve the overall model accuracy.

An attempt to asses the ProFor soil damage predictions on soil compaction indicated that ProFor is not suited for predicting this type of soil damage. However, in the South African context, most forest plantations lie in summer rainfall regions which receive rains for four to five months of the year. This means that for the rest of the year the areas are relatively dry and hence soil compaction may be another problem to consider besides the rut formation. In this case, the model could be of more operational use for predictions of possible damage if it could also be predict soil compaction. This could be achieved through the addition of another algorithm in the model aimed at the assessing observed soil water content against the compaction-optimal water content for different textural classes.

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