EFFECT OF SOIL WATER STATUS AND STRENGTH ON TRAFFICABILITY

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PAUL, C. L. AND DE VRIES, J. 1979. Effect of soil water status and strength on trafficability. Can. J. Soil Sci. **59**: 313–324.

Trafficability tests with typical farm vehicles were carried out on three lowland fields at various degrees of wetness. Structural damage after the first and third passes was assessed in terms of bulk density, aeration porosity, pore-size distribution and rut depth. These indices could not be used per se as criteria for trafficable conditions because of lack of information concerning their relationship to plant growth. Instead, a trafficability criterion oriented toward traction efficiency was established by determining for each soil the relationship between its strength (assessed with a cone penetrometer) and traction efficiency measured by wheelslip. A critical value of strength for trafficability was inferred from this relationship. This was then used to obtain soil water tension limits for trafficability from known relations between tension and strength. Soil strength was found to be linearly dependent upon water table depth in spring when evapotranspiration was small and when the water table depth was less than 80 cm. Consideration of these relationships led to the establishment of critical water table limits for trafficability. These were 53, 45, and 60 cm for Lumbum muck, Hallart silty clay loam (SiCL) (grassland), and Hallart silty clay loam (cultivated), respectively.

Des épreuves de praticabilité pour les véhicules agricoles courants ont été réalisées sur trois champs de terre basse manifestant divers degrés de mouillage. L'endommagement causé à la structure du sol après les 1^er^ et 3^e^ passages a été mesuré d'après la densité apparente, la porosité en air, la distribution des calibres des pores et la profondeur de l'ornière. Ces indices ne peuvent toutefois pas servir en eux-mêmes de critères de praticabilité à cause de l'absence d'information sur leurs rapports avec la croissance des plantes. On a préféré alors s'orienter vers un critère axé sur l'efficacité de traction, ce que l'on a fait en établissant pour chaque sol les rapports entre sa résistance (évaluée au pénétromètre à cône) et l'efficacité de traction mesurée par le dérapage des roues. Un seuil de résistance a été déduit de ces rapports et on s'en est servi pour déterminer les limites de la tension hydrique du sol en fonction de la praticabilité à partir des relations déjà connues entre la tension et la résistance. La résistance du sol s'est révélée être linéairement dépendante de la profondeur de la nappe phréatique au printemps quand l'évaporation est peu intense et que la nappe se situe à moins de 80 cm. L'examen de ces rapports a permis de déterminer les limites de profondeur de la nappe en fonction de la praticabilité. Elles s'établissent, dans l'ordre, à 53, 45 et 60 cm pour la terre organique Lumbum, le loam argilo-limoneux Hallart (SiCL) sous prairie et le loam argilo-limoneux Hallart sous culture.

In agriculture, soil trafficability may be defined as the ability of a soil to support traffic without receiving damage to its structure beyond limits for good crop growth.

The importance of the trafficability problem around the world has prompted recent activity (Reeve and Fausey 1974).

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However, questions of optimum field water status for soil manipulation, the effects of operating tractors at high soil water contents on traction efficiency and the resultant effects on agricultural productivity due to soil compacting forces still remain largely unanswered. Studies which provide information on machine-soil interrelationships are, therefore, urgently required.

The objectives of this study were (a) to examine the effects of traffic on soil structure with a view to establishing trafficability criteria, (b) to establish a relationship between soil strength and traction efficiency measured by wheelslip, and (c) to determine the level of drainage that is adequate to allow soils to efficiently support farm traffic typically encountered in the Lower Fraser Valley of British Columbia.

MATERIALS AND METHODS

Experimental Design and Layout

The effects of soil water status and strength on trafficability were studied on selected strips of land at different soil water tensions and water table depths located on the experimental fields described by Paul and de Vries (1979). Different drain spacings provided strips of land parallel to tile lines at various soil water tensions and water table depths. Three tests were run on Hallart SiCL (grassland), four on Hallart SiCL (cultivated), and four on Lumbum muck (cultivated). All tests on a particular soil were completed within 4 h. East test consisted of running a tractor with attachments along a 30.5-m strip of land. The layout of each test is shown diagrammatically in Fig. 1.

Along each test plot and before each test, soil water tension was measured at depths of 1, 5, and 15 cm with tensiometer-manometer systems. Cone penetration resistance used as an index of soil strength was measured at depths of 0, 1, 5, 10, and 15 cm. Depth to the water table was measured in open wells located within the test plots. Details of the manner of measurement of these variables were given by Paul and de Vries (1979). Locations of sampling stations are shown in Fig. 1.

During the first pass, wheelslip, used as an index of traction efficiency, was recorded by placing a marker on the circumference of one of the drive wheels and counting the number of revolutions completed by the wheel as the tractor traversed the entire length of the test strip. Position of the marker was read relative to the face of a clock. This fixed the precision of measurement to 1/48 of a revolution. The circumference of the drive wheels was measured when the tractor stood on a flat concrete surface. Wheelslip was then expressed by (Gill and Vanden Berg 1968):

$$\%\ \text{wheelslip} = \frac{a - b}{a} \times 100$$

where
a = distrance travelled by point on wheel and
b = distance travelled by vehicle.

There are many errors associated with wheelslip measurements. These include flexing of tires during travel, differential sinkage along the travel path and wide fluctuation of stresses at the wheel-soil interface. Unfortunately, one can do very little about these errors (Gill and Vanden Berg 1968).

After the first and third passes, rut depth was measured at each station by placing a long plank across the wheeltracks and recording the vertical depth of rut below the bottom straight edge of the plank as it lay on the natural soil surface.

Core samples 7.5 cm × 7.2 cm diameter were taken at each station before passage and after the third pass. From these samples, bulk density, aeration porosity at 60-cm tension and pore size distribution were determined by the methods described by Blake (1965) and Vomocil (1965).

Test Vehicles

The test vehicle used at SiCL sites is shown in Fig. 2. It was a 65 HP Massey Ferguson farm tractor pulling a Loewen 4500 liters full manure spreader. The ground pressure at the drive wheels was estimated as 0.8 kg $\cdot$ cm^{-2} from measurements of wheel contact area on hard ground and weights of the vehicles supplied by the manufacturers. The weight of the full manure spreader was calculated to be approximately 6500 kg giving an estimated ground pressure of 0.7 kg $\cdot$ cm^{-2}.

The test vehicle used on Lumbum muck is shown in Fig. 3. It was a David Brown 990 Selectamatic 48 HP farm tractor with front and back manure scrapers. Its ground pressure at the drive wheels was approximately 0.5 kg $\cdot$ cm^{-2}.

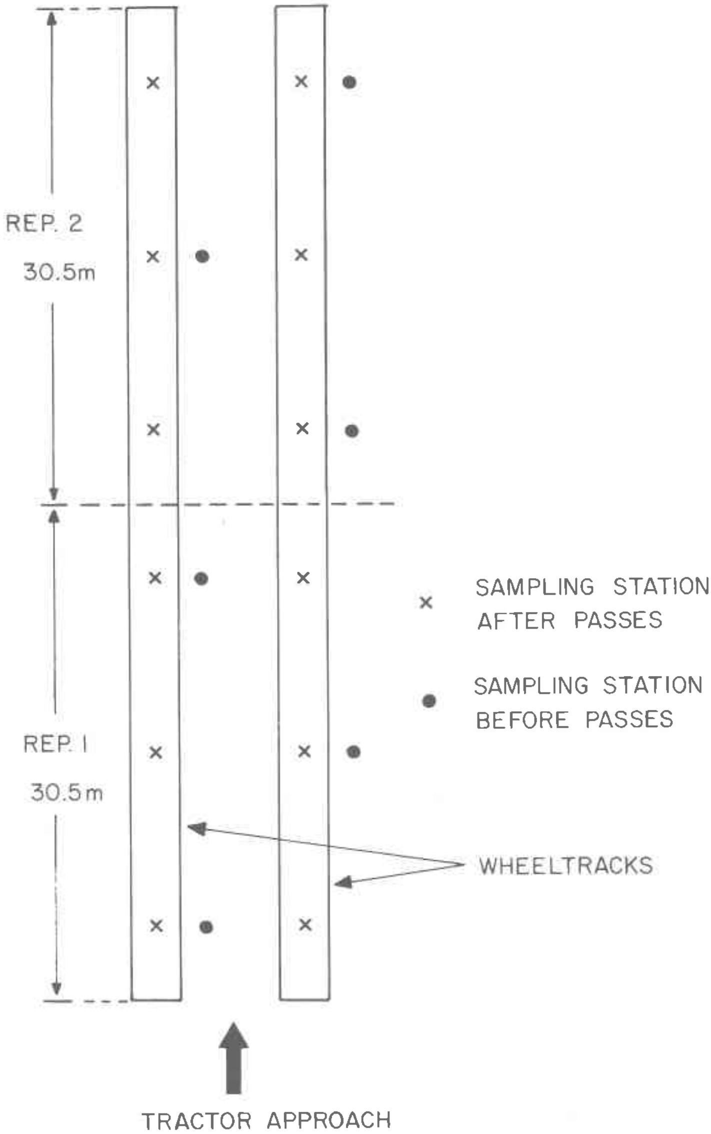

Fig. 1. Plan of test strip representing one degree of wetness for trafficability trials.

Fig. 2. Field machinery used on Hallart silty clay loam fields.

Fig. 3. Field machinery used on Lumbum muck.

The vehicles were operated in low gear with engines running at full throttle. Speeds of 2–3 km $\cdot$ h^{-1} were maintained as they were driven in a straight line path along the strips.

RESULTS

Effect of Traffic on Soil Physical Conditions

Changes in bulk density, aeration porosity, rut depth, and pore size distribution within the 0- to 15-cm layer due to passage of the field machinery are shown in Figs. 4 and 5. Also shown are the average soil water tension (numbers above line) and water table depth (below line) in the test strips during the experiments.

Significant changes in soil physical properties were recorded in some tests at all three sites.

In Lumbum muck the greatest increase (24%) in bulk density, ρ_b, was recorded in the test conducted at an average soil water tension of 38 cm. This increase was statistically significant at the 0.10 level of probability. However, the drop in aeration porosity (P = 0.10) was largest in the driest strip (average tension = 60 cm). This was probably a result of an initially high aeration porosity in this strip.

The drastic reduction in aeration porosity (>50 μm diameter) due to traffic on all the soils is apparent from the pore-size distributions before traffic and after three passes shown in Fig. 5.

On the grassland field of Hallart SiCL, bulk density increased significantly ($P < 0.05$) after three passes in all the tests, the largest increase of 34% ($P < 0.001$) occurring within the wettest plot. Aeration porosity decreased significantly ($P < 0.05$) in all plots. The wettest plot showed the greatest decrease of 65% ($P < 0.01$).

Bulk density increases due to traffic were small but significant ($P < 0.05$) within the cultivated field of Hallart SiCL. At the same time aeration porosity decreased ($P < 0.10$) with the largest drop of 86% ($P = 0.05$) occurring within the 12-cm tension test plot.

Rut depth increased significantly ($P < 0.05$) with wetness after the first and third passes in all the experimental fields. Intolerable rut depths (>10 cm) were observed in Lumbum muck in all plots and especially in the plot located in undrained land where an average value of 35 cm with a maximum of 60 cm was recorded. A bogging condition with 100% wheelslip was reached in this plot. Depth of rutting was not as severe on the silty clay loam fields except in the wettest plot located on the undrained section of the cultivated field where the average rut depth was 10 cm and a bogging condition was reached.

Effects of Soil Strength on Wheelslip

The relationship between soil strength before the first pass and wheelslip during the first pass is presented in Fig. 6. At all three sites wheelslip increased rapidly as soil strength decreased in response to poorer drainage. A bogging condition was obtained in Lumbum muck and Hallart SiCL (cultivated) in undrained plots. The highest wheelslip obtained on the grassland was only 27% and this was obtained at a soil water tension of 0 cm in the 0- to 15-cm layer.

Effect of Water Table Depth on Trafficability

Lowering of the water table increases the bearing strength of a soil and improves its ability to withstand field operations (Armstrong 1977). Control of the water table is, therefore, one direct means of controlling trafficability in wet soils.

The effect of water table depth on soil strength during spring 1976 and 1977 is shown in Fig. 7. The relationship appeared to be linear except for water table depths greater than about 80 cm after which soil strength increased more rapidly. This deviation was particularly true on some sunny days later in spring when drying of the surface soil caused increases in strength of the plough layer without appreciably lowering the already deep water table. For this reason it was thought valid to fit a straight line to the data for water tables

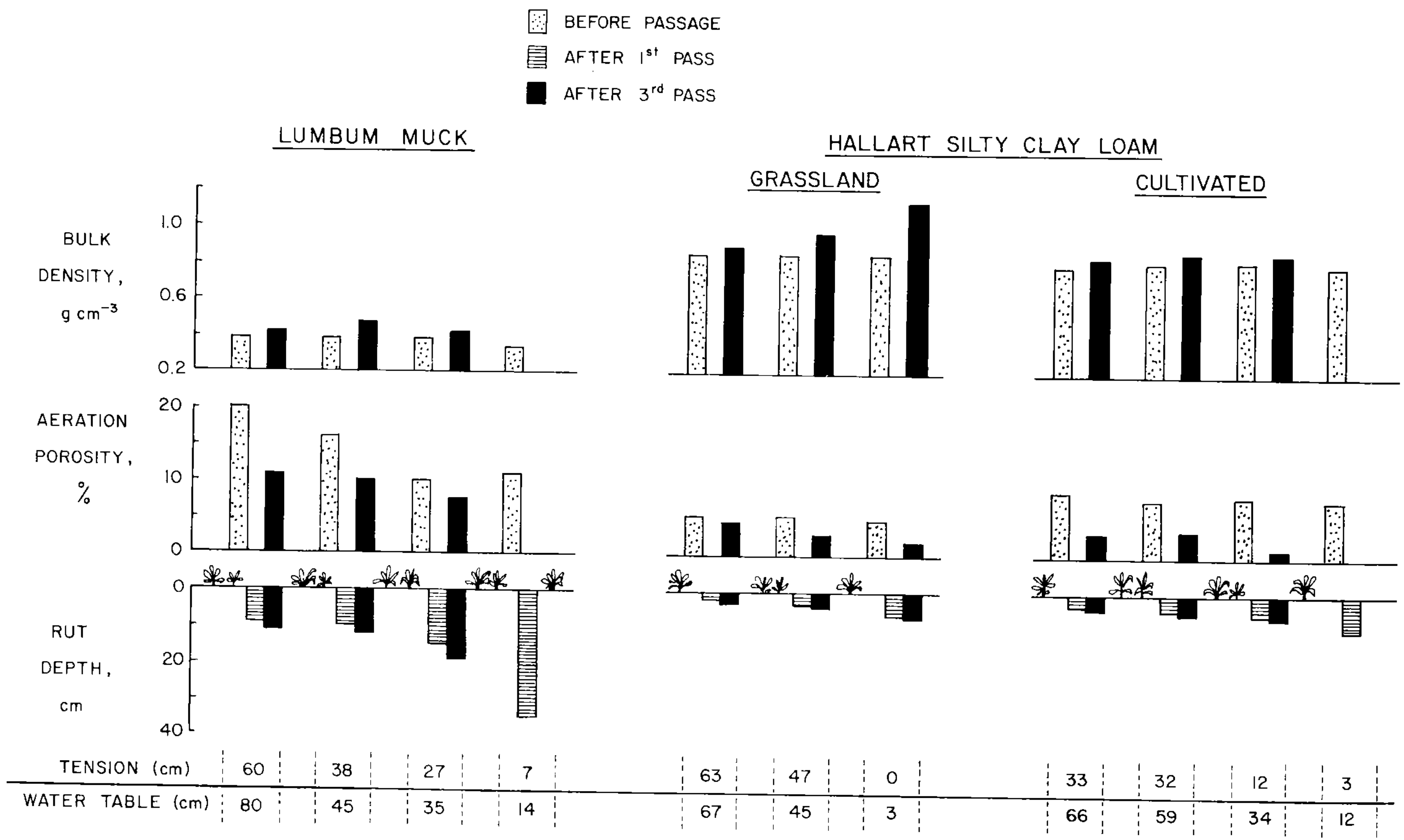

Fig. 4. Effects of traffic on soil physical conditions in the plough layer. Mean tension of 0- to 15-cm layer (above line) and water table depth (below line) within the test strips are shown at bottom of diagram.

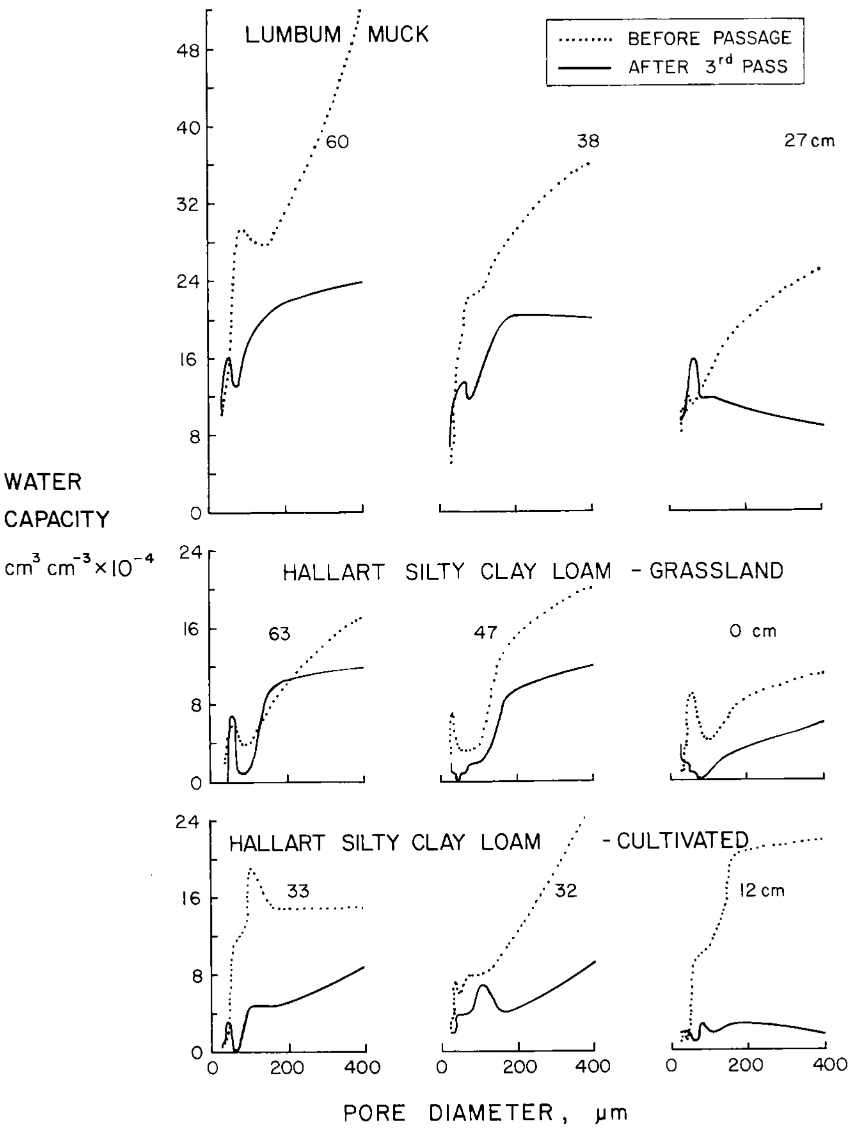

Fig. 5. Changes in pore size distribution due to traffic at different degrees of wetness. Numbers indicate mean soil water tension in 0- to 15-cm layer of test strips.

between 0 and 80 cm. The best fit was obtained for Lumbum muck (r^2 = 0.82) in which no water table depth greater than 80 cm was encountered during the sampling periods. Only fair fits were displayed by the mineral soils: r^2 (grassland) = 0.56; r^2 (cultivated) = 0.58.

DISCUSSION

Soil Structural Indices as Criteria for Trafficability

In this discussion trafficability is oriented toward soil structure and not traction efficiency. It is difficult in this context to interpret results on an absolute basis. Critical values for soil structural indices for adequate plant growth, such as bulk density, porosity and pore-size distribution, have not been established for all species of plants growing in all conditions. In fact, such an undertaking would be extremely difficult, if not impossible. However, it seems that ρ_b becomes limiting for plant growth at about 1.20–1.50 g $\cdot$ cm^3 (Soane 1970). A number of papers dealing with critical aeration porosities for plant growth (Viehmeyer and Hendrickson 1948; Flocker et al. 1959; Meredith and Patrick 1960; Soane 1970) indicate a wide range of aeration porosities (0–15%) which may limit growth depending

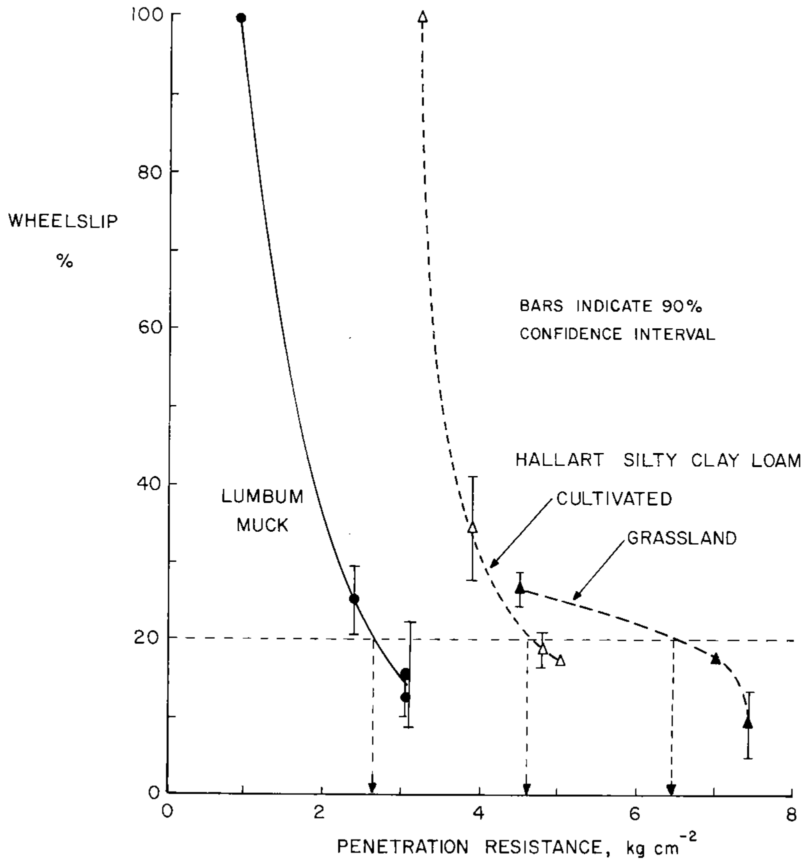

Fig. 6. Effect of soil strength (before traffic) on wheelslip during the first pass. A wheelslip of 20% was used as a critical value for traction efficiency.

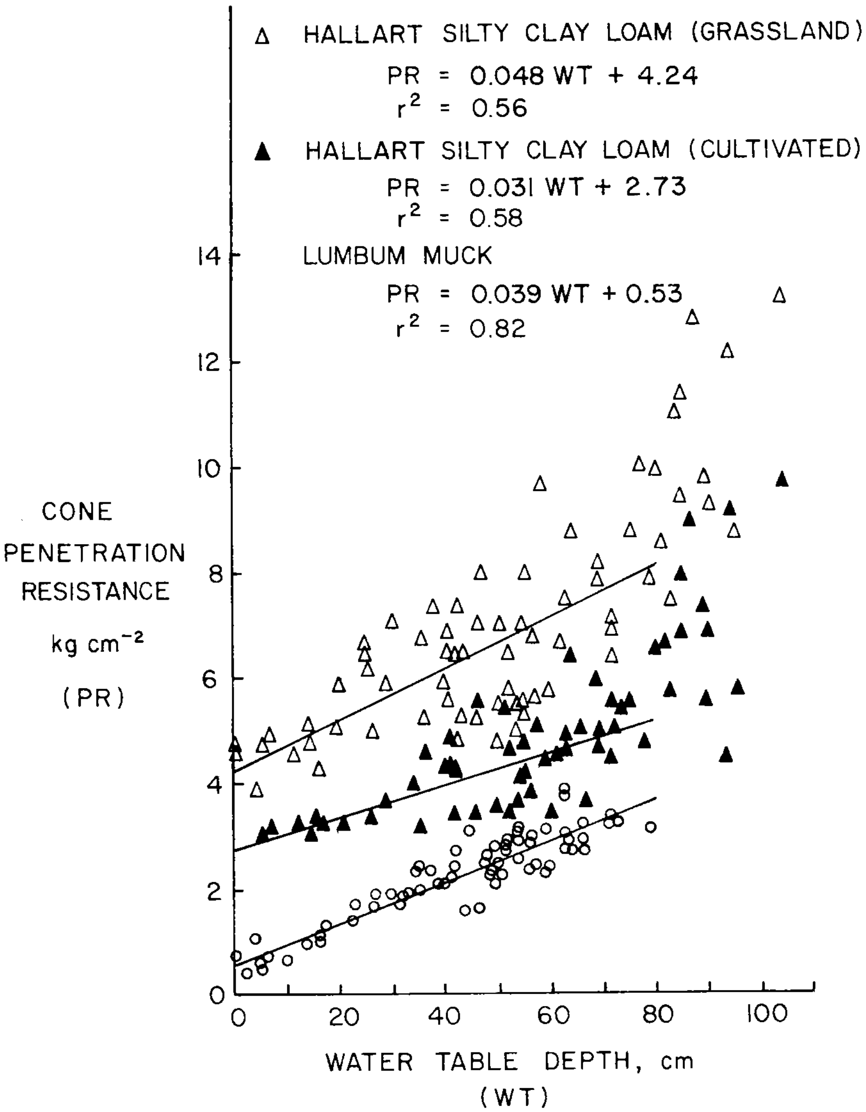

Fig. 7. Effect of water table depth on soil strength of 0- to 15-cm layer. Regression lines are for water table depths between 0 and 80 cm.

upon other growth factors. Meredith and Patrick (1960) observed active sudangrass root growth in a clay loam having an aeration porosity, determined at 60-cm tension, to be as low as 0%. The tension at which aeration porosity is determined is not standard but varies from 40 to 300 cm. This makes direct comparisons of reported values difficult.

In light of the foregoing, data from the present experiment (Fig. 4) indicated that on the basis of ρ_b and aeration porosity Lumbum muck was trafficable at small values of tension and water table depth. However, there is an obvious disadvantage in using ρ_b (and possibly aeration porosity) as a critical limit in organic soils. Results of rut depth seemed more meaningful. Therefore, solely on the basis of a 10-cm rut depth being excessive, it appeared that this soil was trafficable at tensions greater than 38–60 cm. The water table depths corresponding to this tension range in the test strips were 45–80 cm.

In the grassland and cultivated fields of Hallart SiCL, and especially in the former, aeration porosity levels were surprisingly low (<8%) even before passage of the vehicles. Only broad conclusions could be made with respect to structural damage by traffic in these fields. No limiting values of ρ_b or rut depth were encountered except in the 3-cm tension test strip of the cultivated field where rut depth was excessive. However, extremely low aeration porosity (<3%) was encountered after three passes in grassland test plots at tensions less than 47 cm (water table <45 cm from Fig. 4). The same was true in the cultivated field when the tension was less than 33 cm (water table <60 cm).

In summary, attempts to use soil structural indices as criteria for trafficable conditions were only partly successful. The reasons for this were twofold. Firstly, critical soil physical limits for plant growth have not been established with any degree of certainty. Secondly, bulldozing of soil out of ruts complicated interpretation of the results. The broad conclusions made here might be supportive to the establishment of a trafficability criterion oriented toward traction efficiency by determining for each soil the relationship between its strength and traction efficiency measured by wheelslip.

Traction Efficiency as a Criterion for Trafficability

There is general agreement among researchers that maximum traction efficiency is achieved at a wheelslip of about 20% (Gill and Vanden Berg 1968; Kilgour 1976). Using 20% slip as a critical value for traction efficiency, the critical soil strength values of the 0- to 15-cm layer for efficient traction were 2.6, 6.4, and 4.6 kg $\cdot$ cm^{-2} for Lumbum muck, Hallart SiCL (grassland) and Hallart SiCL (cultivated), respectively (Fig. 6). Differences between these values are possibly related to differences in mechanisms governing the soils' interactions with the moving vehicles.

These values can be used for establishing drainage design criteria from known relationships between soil strength and hydrologic properties. For example, from the strength-tension relationships presented by Paul and de Vries (1979) critical soil water tension for trafficability was 48, 35, and 27 cm for Lumbum muck, Hallart SiCL (grassland) and Hallart SiCL (cultivated), respectively. Why the cultivated silty clay loam had a lower critical tension than the grassland is not clear. The added bearing strength provided by a relatively dense plough pan observed at approximately 25 cm below the surface only in the former field is one possible reason. Further research on the effects of a plough pan on soil trafficability is worthy of consideration.

EFFECT OF WATER TABLE DEPTH ON TRAFFICABILITY. By applying the linear equations of Fig. 7 to the critical strength levels obtained in Fig. 6, it was possible to establish critical water table levels for trafficability. These were 53, 45, and 60 cm for Lumbum muck, Hallart SiCL (grassland), and Hallart SiCL (cultivated), respectively. These results receive good support from the broad conclusions made in earlier discussions on the effects of traffic on soil physical properties. In those discussions it appeared that "critical" water table levels might be 48–80 cm for the muck, and 45 cm and 66 cm for the grassland and cultivated fields, respectively.

Of interest here is the work of Steinhardt and Trafford (1974) who recommended water table depths of 50–60 cm as being necessary to minimize structural damage of clay soils in England; also, the findings of Schothorst (1970) who showed that adequate bearing strength was obtained in peat grassland in the Netherlands when the water table was deeper than 30 cm.

Even after taking into account the averaging method used to express tension in the 0- to 15-cm layer there seems to be a mismatch between the critical values of tension and water table depth in the cultivated silty clay loam. A perched water table caused by the plough pan in this field could have decreased the slope of the strength-water table relationship without interfering with the strength-tension relationship established above the pan.

CONCLUSIONS

Significant changes in soil structural properties were recorded when farm equipment was run on three wet lowland areas.

Attempts to use bulk density, aeration porosity and rut depth as criteria for trafficable conditions were only partly successful. Bulldozing of soil out of ruts complicated interpretation of the data.

Critical levels of soil strength for efficient traction of typical farm vehicles were found from trafficability tests to be 2.6, 6.4, and 4.6 kg $\cdot$cm^{-2} for Lumbum muck, Hallart silty clay loam (grassland) and Hallart silty clay loam (cultivated), respectively. Corresponding critical soil water tensions of 48, 35, and 27 cm were obtained from known strength-tension relationships.

Soil strength in the plough layer was linearly dependent upon water table depths between 0 cm and 80 cm. Critical water table depths for trafficability obtained by way of this dependency were 53, 45, and 60 cm for the muck, silty clay loam (grassland), and silty clay loam (cultivated), respectively.

A plough plan in the cultivated field appeared to influence soil water-strength relations and further investigations into this influence seemed necessary.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the help of the Engineering Branch of the British Columbia Ministry of Agriculture. Financial support from the British Columbia Ministry of Agriculture and the University of British Columiba is also gratefully acknowledged.

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