INTRODUCTION

Soil compaction affects the suitability of a soil for its intended use — crop production. Compaction reduces permeability to water, reduces aeration, and increases mechanical strength of the soil — all effects that may reduce the quality and quantity of the crop produced.

Compaction is caused by forces applied by machines and animals resulting from natural phenomena. Before compaction can be predicted and controlled, these forces will have to be described by accurate behaviour equations. Soil forces are the equation inputs, and are difficult to measure, change in compactness is the equation output and can be more easily expressed, usually as the absolute volume. However, such equations are not available, though considerable work has been done. Simple loading devices and test methods established that the largest principal stress is not uniquely related to compaction (7). More elaborate tests using pressure transducers in the soil (7), and a triaxial apparatus (7), (3), failed to formulate accurate behaviour equations. Soil strength values measured by mechanical seedlings were 3 to 7 times the values predicted by the Terzaghi rupture theory model (5).

Similarly, accurate behaviour equations representing plant response to soil compaction do not exist. A review paper (2) concluded that mechanical resistance influences growth of roots and underground shoots in many situations, rather than merely becoming a limiting factor only in unusually strong soils. The same review suggested that forces required to deform soil can be estimated by classical soil mechanics theories if plastic and elastic zones of action and modes of failure are recognized and separated. Modes of soil failure due to plant forces are tension, shear without compression, and shear with compression. In other investigations, cotton seedlings extended thrusts of up to one pound (5), and increased pressure on corn seedlings reduced growth (8).

While the search for behaviour equations continues, with progressively more discerning methods, empirical measurements of soil compaction and crop response can supply parameters for better tillage and traction machinery design. Numerous studies have been made, but only some of the more relevant ones will be mentioned here. Gill and Vanden Berg (7) reported that, at equal weight and pull, a tire caused more compaction than a track, partly due to greater slippage of the tire. Increased compaction decreased root penetration and reduced water infiltration rate. Rosenberg (14) reported that crop growth was related to bulk density, penetrometer resistance and oxygen diffusion rate. Tomatoes were more sensitive to soil compaction than corn, though tomatoes were affected by surface treatments, while corn yield correlated with subsurface treatments (17). Minimum tillage improved crop response due to reduced machine traffic (15). In north Dakota (9), overwintering reduced traffic pans. Domier (4) initiated studies to deal with soil compaction problems in Manitoba. Plots were packed by superimposed passes with a tractor. Compared to check plots, the treatments reduced yield on early seeded plots, but some treatments improved yield on late seeded plots. There were no differences between plots seeded with a discer and those seeded with a double disc drill. In general, post-seeding treatment yields were less than pre-seeding treatment yields.

In addition to the results reported by Domier (4), the following problems have been observed on Manitoba clay soils:

1. The emerging crop is often poorer in wheel paths made during harrowing. It is not generally known whether these effects carry through to crop maturity.
2. In some cases, initial crop growth appears better in wheel tracks.
3. With a discer, the path of the left tractor wheel remains visible even after the operation. There is no experience as to whether its effects are harmful or not.
4. Harmful effects increase as soil moisture content increases.

The object of this study, therefore, was to examine pre-seeding and post-seeding soil compaction on a wet clay field during seeding activities by characterizing the soil conditions and determining the crop response.

PROCEDURE

The Treatments

The experiment was carried out on a three-acre plot of Scanterbury, Morris and McTavish clay soil (moderately drained) on the Glenlea Research Station, University of Manitoba. Soil moisture content was 26% (0 to 3-inch depth) during preseeding treatments and 32% (0 to 1½-inch depth) to 37% (2 to 3-inch depth) during post-seeding treatments. Pre-seeding compaction treatments were performed while seeding the plot, in one direction, with a tractor and discer equipped with seeding and fertilizer attachments. Manitou wheat was seeded at 77 lbs. per acre, with 11-48-0 fertilizer applied at 73 lbs. per acre. The following day, post-seeding compaction treatments were added at right angles to the direction of seeding at the same time as the plot was harrowed. In this way, pre-
seeding compacted, post-seeding compacted, and non-compacted areas were specifically located over the entire plot. The non-compacted areas, providing comparisons to evaluate treatment results, received both tillage operations but no wheel traffic, so represented the intended soil environment.

The left wheel of the tractor pulling the discer during seeding accomplished the pre-seeding compaction treatments. Treatment levels were obtained by varying the rear tractor wheel slip rate between 7 and 30 percent. The low slip level was attained by pulling the discer alone. For increased slip, the required drawbar pull was obtained by hitching a load tractor to the drawbar of the head tractor in addition to the discer. A cable was used for hitching, to allow the load tractor to travel to the right of the discer.

A two-wheel trailer, fitted with special tires (9.00 x 15 treadless racing slicks) and loaded with cast iron weights applied the post-seeding compaction. A tractor towed the trailer, and the trailer, in turn, towed a set of spike tooth harrows. The tractor's swinging drawbar was pinned to one side so that the racing tires on the trailer did not follow the tractor wheels.

The racing slicks provided the most practical means of applying a known, uniform packing pressure. With such a low ply, flexible tire pressure distribution applied to the soil was quite uniform and essentially equal to the inflation pressure (7), (18). Three treatment levels of 15, 27 and 40 psi were chosen. These approximate the range of contact pressures measured on the lug face of a powered tractor tire (16). Trailer load was changed along with inflation pressure of the racing tires according to the manufacturer's load and inflation pressure recommendations.

Characterization of the Soil Conditions

The soil conditions resulting from the treatments were characterized by measuring four types of soil parameters. These were bulk density, shear strength, penetrometer resistance, and oxygen diffusion rate.

Dry bulk density, measured by the sand cone method, was used as a direct measure of soil compactness. For each observation, a small excavation was dug between the one- and two-inch levels, below the soil surface. The excavation volume was measured, using uniform Ottawa sand, and the oven dry weight of the excavated soil was obtained.

A 2-inch square shear box, imbedded and pulled horizontally with a small spring scale, provided the means of measuring cohesion. Cohesion is the remaining component of shear strength when normal force is zero, according to the well known Mohr-Coulomb Theory. The measurements were made at one depth in the soil, approximately midway between the seed and the surface. This parameter was chosen for measurement since compaction can increase soil strength, impeding shoot emergence and root growth (2), (7).

Penetrometer measurements were made with a 30-degree cone lowered or raised by a hand crank. The soil force resisting the cone was counteracted by an automotive valve spring. Through a linkage to the pen holder, penetration moved the pen vertically and spring deflection moved it horizontally, relative to the stationary paper holder. A nylon tip pen recorded the locus. The force-deflection curve was established and converted to a cone index-deflection curve. Cone index is the resisting force per unit cone end area. The penetrometer, used by many other researchers (1), (6), (9), (13), (17), provided a quick and easy device to obtain relative comparisons of different conditions. However, no correlation with any physical soil property has been established.

The oxygen diffusion rate apparatus used was quite similar to that described in detail by other reports (10), (11). Potential was applied across a porous cup and the platinum electrodes, all in the soil, and the resulting current recorded. The magnitude of the current depends upon the rate of oxygen flux at the electrode surface. This, in turn, is related to the rate of oxygen diffusion through the soil to the electrodes that represent plant roots. Since compaction reduces porosity, oxygen availability is a separate factor influencing plant growth that should be measured when assessing soil compaction.

Determination of the Crop Response

Crop response was measured by the oven dry weight of above ground growth, and plant population. This information was obtained from random samples made approximately every two weeks as weather permitted. Vegetative growth provides an earlier evaluation than grain yield and potentially a more accurate measure of response by considerably reducing the time available for intervening weather effects. Vegetative growth rate measurements have been described by Loomis (12).

RESULTS AND DISCUSSION

Pre-Seeding Compaction Treatments

Crop growth was approximately the same across all slip rates (Figure 1), showing no evidence that slip rate influenced crop growth. Similarly, slip rate did not influence plant population, with the number of plants approximating the theoretical number of seeds planted (22 to 25 plants per ft²). This could be expected, since none of the four soil parameters (bulk density, cohesion, penetration resistance and oxygen diffusion rate) could detect any differences in soil compactness between the different slip rates. (Plant population and soil parameter data are not shown). If the tractor wheel slippage affected compaction, it seems that the discer destroyed these effects.

The difference observed on the pre-seeding compaction treatments was earlier emergence, compared to non-compacted locations. As shown in Figure 1, this meant more growth; the pooled mean dry weight of growth on the pre-seeding treatments, for the second growth sampling, exceeded the mean of the non-compacted observations by over 40%. Observations...
of local farmers' fields confirmed generally earlier emergence in depressions due to pre-seeding wheel tracks. This occurrence seems to be one source of the observation that some wheel tracks result in beneficial crop response.

The reason for earlier emergence was shallower seed coverage in the path of soil displaced by the discer from the pre-seeding wheel track. To illustrate, seedlings from adjacent areas were compared 10 days after seeding. The treatment area seedling started one inch below ground, and grew a total of 4½ inches, while the noncompacted area seedling started 2½ inches below ground, and was only 3¾ inches long. It seems that less soil was available in the wheel track for coverage due to vertical compaction and lateral displacement of the soil by the tractor tire.

**Post-Seeding Compaction Treatments**

The penetrometer results and oxygen diffusion rates showed that compactness increased for each increment in tire-soil contact pressure for the post-seeding treatments. At a depth of 1½ inches, each 15 psi increment in contact pressure increased the cone index by 8 or 9 psi (Figure 2). The same increments in contact pressure reduced oxygen diffusion rate by $3 \times 10^{-8}$ to $5 \times 10^{-8}$ gm/cm² sec (Figure 3). The first increment in pressure increased cohesion by 0.7 psi (Figure 4), but there was no evidence of any differences in cohesion between the medium and high pressure treatments. Bulk density measurements (Figure 5) were not sensitive enough to detect any differences in the mean densities for the three compaction levels. All four soil parameters reflected greater differences between non-compacted and low pressure (15 psi) treatments than between the low and high (40 psi) pressure treatments.

Increasing soil-tire contact pressure reduced the weight of vegetative growth produced. The reduction was due to both slower growth rate (Figure 6) and fewer plants (Figure 7). The plant populations on the 27 psi and 40 psi treatments were less than on the lower pressure treatment (Figure 7) and on the noncompacted area (shown as 0 psi), and less than the assumed seeding rate. The mean population on the 40 psi treatment was about 15 plants per ft.² compared to nearly 20 on the 15 psi treatment. The final sampling, taken eight weeks after seeding when the plants had headed out shows that growth on the high pressure treatment was approximately 15 gm/ft.² less than on the 15 psi treatment and that growth increased by 55% on the 15 psi treatment, but only 33% on the 40 psi treatment, between July 22 and 28 (Figure 6).

With one exception, there was no evidence of different mean growth or plant populations between the low pressure treatment and the non-compacted location. There was more dry weight on the non-compacted areas on the third sampling (July 22, Figure 6).
When the third growth sampling was taken, additional observations were made in the wheel tracks of the tractor towing the post-seeding compaction equipment. This provided an opportunity to compare the effects of common farm tires with the treatment effects. The tractor was equipped with 18.4-34 tires, inflated to 16 psi. The data are not shown, but growth in the tractor wheel paths was equivalent to that in the 27 and 40 psi treatments.

CONCLUSIONS

1. Pre-seeding compaction, above the seed depth, due to rear tractor wheel slip rates up to 30%, apparently was destroyed by the discer. The main result of the wheel track was a strip of shallower seed cover, likely due to the wheel compressing and laterally displacing enough soil to reduce the effective depth of the discer blades in its path. Under the conditions of this test, the reduced seed depth gave early emergence and the best plant growth; response under drier conditions would need investigating.

2. Post-seeding traffic increased soil compactness as applied pressure was increased. Contact pressures exceeding 15 psi decreased emergence and growth rate of wheat on clay soil just dry enough for field operation. The growth differences remained evident long after the period of immediate growth response. Further investigations to establish the effects at other moisture contents, limiting soil moisture contents and contact pressures could eventually be established that would minimize crop damage.

3. This study and others point out the need for more precise information on the ideal soil environment required by various plants. More effort could be expended in this direction.

4. Of the soil parameter measuring devices, the penetrometer was the most useful for determining relative soil compactness. Field data was quickly and easily obtained. Automatic recording, continuous with depth, was a distinct advantage. Modifications to improve accuracy and establishment of the effects of soil conditions and soil moisture contents are needed.

5. Plant growth and plant population were good measures of crop response. However, the presumption that yield correlates with vegetative growth was not clearly verified in the literature.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the financial support provided by the Canada Department of Agriculture for this project.

REFERENCES