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EARLY GROWTH OF MAIZE IN COMPACTED SOIL WITH FINE AND COARSE STRUCTURE*

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A b s t r a c t. We grew Zea mays in treatments with different compaction levels: a light bulk density (LC), 1.30 Mg m^{-3}; a moderate bulk density (MC), 1.45 Mg m^{-3}; and a severe bulk density (SC) 1.60 Mg m^{-3}. Each compaction level had treatments with coarse structure, as found in the field, and with fine structure, after passing the soil through a 2-mm sieve. All treatments had the same initial matric potential. We grew eight maize plants in each container for 28 d. At the end of the experiment, treatments were broken open and roots were counted. Permeability to air decreased and soil strength increased with soil compaction. At every compaction level, the permeability and strength were higher in the coarse- when compared to the fine-structured soil. Root densities decreased with increasing soil compaction especially for MC to SC. The penetration of roots in the most compacted soil was less inhibited in coarse-structured soil. Top growth was highest in MC and considerably lower in SC. In LC and MC, top growth was greater in the fine-structured soil, whereas in SC it was greater in the coarse-structured soil. We found an optimum crop response for the MC treatment when compared to treatments with either more or less compaction.

K e y w o r d s: maize, compacted soil, root responses

INTRODUCTION

Aggregate size affects soil properties, such as pore-size distribution, aeration, strength, root-soil contact and water and nutrient availability for crops [6,13]. These properties, in turn, affect the ability of roots to penetrate the soil. For example, Misra *et al.* [19], found higher penetrometer resistance and lower root growth within larger aggregates. Donald *et al.* [4], related the type of root to its response to aggregation. They showed that the main axes of seminal and nodal roots of maize were longer and secondary laterals shorter for a coarser aggregate system.

Root responses to physical conditions measured within different aggregate sizes have produced conflicting results. In a review, Braunack and Dexter [3] pointed out one such apparent conflict and its resolution. An increase in aggregate size does not include an overall increase in soil aeration. They noted that a fine aggregate provided better intra-aggregate aeration than a coarse aggregate (greater than about 9 mm). The cause of this was an anaerobic centre in the larger aggregate. Increases in aggregate size increase inter-aggregate aeration but decrease intra-aggregate aeration.

In another apparent contradiction, Boone and Veen [2] found fewer lateral roots with increased penetration resistance. Goss [7] and Schumacher and Smucker [17], working in artificial substrates, found increased lateral branching with increased penetration resistance. Differences in pore and aggregate

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structures may be responsible for this apparent contradiction.

The alteration of soil physical properties related to structure may depend on the level of compaction and on the size of the aggregates. Our objective was to compare the effect of different levels of compaction of finely and coarsely aggregated soils on selected soil physical properties and on the growth of maize.

MATERIALS AND METHODS

We obtained a loamy textured soil (12 % clay), an Orthic Luvisol, from a field near Lublin, Poland. One treatment, the coarse-structured treatment, used the disturbed soil as taken from the field. It had peds that were approximately 4 to 8 mm in diameter. The other treatment, the fine-structured treatment, was produced by pushing the soil through a 2 mm sieve, destroying much of the structure but retaining small, 2 mm or smaller, structural units. Four replicates of each treatment were compacted in 8 liter containers (0.2 m cube) using a hydraulic press. Soils were compacted lightly, moderately, and severely, to bulk densities of 1.30 Mg m^{-3} (LC); 1.45 Mg m^{-3} (MC) and 1.60 Mg m^{-3} (SC). These densities correspond to 81, 90 and 99 % of the reference bulk density as defined by Hakansson [8].

A 0.10 m deep container of loosely compacted soil was attached to the bottom of both the fine- and the coarse-structured soil samples (Fig. 1). We maintained the soil in this lower container at -35 kPa matric potential using the method of Lipiec *et al.* [14]. The loose soil was separated from the compacted samples by a 20 mm thick layer of 8 mm diameter gravel to avoid water movement between the two. The container was constructed in this way to allow us to measure root growth within the compacted zones, to observe which of the treatments had root penetration through the compacted zone, and to observe how quickly this occurred, as noted by water uptake from the bottom layer. It also simulated root growth through a hard layer into a subsoil.

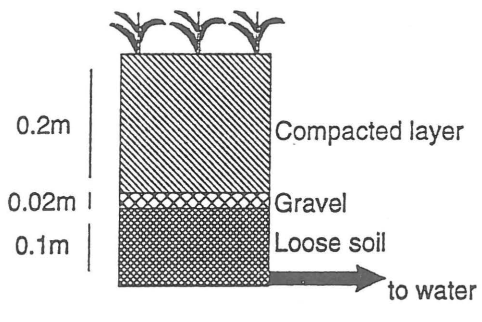

Fig. 1. Experimental set-up.

The initial soil water content in the top 0.2 m corresponded to field water capacity for each treatment. No water was added except for treatment SC where maize plants exhibited symptoms of water stress. For treatment SC, water (150 ml) was added on the 11th and 20th days after planting to avoid irreversible wilting. Withdrawal of water from the bottom soil layer was measured using the negative pressure circulation technique [14].

Containers were placed in a growth chamber with 14 h daytime temperatures of 25 °C and 10 h night-time temperatures of 18 °C for 28 days. Eight seedlings of maize (*Zea mays* L. cv KLG 22-10) were grown in each container.

We compacted a duplicate set of four replicates of each treatment. These duplicates were used to measurement soil strength, air permeability and oxygen diffusion rate (ODR). The duplicate samples had the same initial water contents as those used for maize growth. We measured soil strength with an INSTRON Machine using a 30° cone-shaped steel tip. The cone tip had a maximum diameter of 3.83 mm and a height of 3.1 mm. The cone-tip penetrated the sample to a depth of 0.1 m. Recorded values for the strengths of treatments were averages of measurements taken between 0.02 and 0.10 m depths. Core samples of 100 cm^3 volume, 5 cm diameter were taken from the bottom of the duplicate containers for measurements of air permeability. These measurements were made with an air-flow meter (Instrument Co., Wadowice, Poland).

The same cores were used to find the soil water characteristic curve. The characteristic curve was determined using the pressure cell apparatus and was used as the basis for the calculation of the pore-size distribution [11]. ODR measurements were made by the platinum electrode method [18] in the remaining undisturbed part of the bottom side of the 0.2 m deep containers. Leaf water diffusion was measured using an automatic porometer Mk 3 (Eijlkamp, The Netherlands).

Statistical analysis was performed using a split plot treatment design with levels of compaction as main plots and structure as splits. For these analyses, we used the ANOVA procedure of SAS [16].

RESULTS

Soil Physical Responses

Porosity

For the coarse aggregated treatment, total porosity decreased from 51.6 % for bulk density LC to 32.6 % for bulk density SC. For the fine aggregated treatments, it decreased from 48.9 % for bulk density LC to 31.0 % for bulk density SC. Most of the decrease was caused by the significant reduction of pores greater than 30 μm diameter (Table 1). This effect was even more pronounced in pores greater than 100 μm and was greater for the fine than the coarse structured treatment.

Porosity of the coarse-structured treatments was larger than the fine-structured treatment for pore sizes greater than 30 μm, less for the pores 6 to 30 μm, and the same for pores less than 6 μm. The percentage of pores smaller than 6 μm slightly increased with compaction from LC to MC and decreased slightly with further compaction both in coarse- and fine-structured treatments.

We had a limited view through the clear plastic front of the soil containers. The pore sizes that we could see were larger (up to 6 mm) for LC and MC than for SC (few pores up to 1 mm).

Air permeability and penetration resistance

Air permeability and penetration resistance were significantly influenced by level of compaction and by aggregation (Table 2). As expected, penetration resistance increased and air permeability decreased with increasing level of compaction. For all levels of compaction, air permeability and penetration resistance were higher in coarse- than in the fine-structured soil. The higher penetration resistance combined with the higher air permeability of the coarse structured samples imply that the larger aggregates were more compacted than the smaller aggregates with larger interaggregate spaces. This was partially verified by the fact that the coarse-structured treatments were also higher in porosity (Table 1). Higher penetration resistances within the larger aggregates have been shown by others [19].

ODR

Oxygen diffusion rates for all three levels of compaction were greater for the coarse- than for the fine-structured soil (Table 2). However, these differences were not statistically significant. Oxygen diffusion also decreased with increasing level of compaction; but was only significantly higher for treatment LC.

Root responses

Compaction significantly decreased total root length and altered root distribution (Table 3). We observed the largest root-length decrease with increasing soil compaction from MC to SC. This decrease was larger in fine- than coarse-structured soil. Differences in root growth between fine- than coarse-structured soil were not statistically significant at $P<0.05$. Increasing compaction resulted in root concentration near the soil surface. This effect was most pronounced for treatment SC. Here, most of the roots were in the top 0-5 cm layer. Only a small fraction of the roots penetrated deeper.

The penetration of roots in treatment SC was less inhibited in coarse-structured

Table 1. Pore size distribution as calculated from the water retention curve

Compaction level - bulk density (Mg m^{-3})	Pore size distribution (%)		
	Aggregation		
	fine	coarse	Mean[1]
	for pores > 100 μm		
LC - 1.30	14.90a	16.60a	15.70a
MC - 1.45	5.54b	8.32b	6.93b
SC - 1.60	3.06c	5.14c	4.10c
Mean[2]	7.82b	10.00a	
	for pores 100 - 30 μm		
LC - 1.30	5.74a	7.05a	6.40a
MC - 1.45	5.42a	6.49b	5.96b
SC - 1.60	1.45b	2.49c	1.97c
Mean	4.20b	5.34a	
	for pores 30 - 6 μm		
LC - 1.30	5.86b	4.98b	5.42b
MC - 1.45	8.86a	9.64a	9.25a
SC - 1.60	2.98c	2.48c	2.73c
Mean	5.90a	5.70b	
	for pores < 6 μm		
LC - 1.30	22.4c	22.9a	22.7b
MC - 1.45	25.1a	24.2a	24.6a
SC - 1.60	23.5b	22.5a	23.0b
Mean	23.7a	23.2a	
	for all pores		
LC - 1.30	48.9a	51.6a	50.2a
MC - 1.45	44.9b	48.7a	46.8b
SC - 1.60	31.0c	32.6b	31.8c
Mean	41.6b	44.3a	

[1] Means with the same letter in the column are not significantly different at the 5% level by the LSD test; [2] Means with the same letter in the row are not significantly different at the 5 % level by the LSD test.

soil although penetration resistance was higher (Tables 2 and 3). This implies the presence of pores larger than growing roots that allowed the roots to bypass the zones of high mechanical impedance. Ehlers *et al.* [5], Boone *et al.* [1], and Hatano *et al.* [10] reported similar observations.

Plant growth and water uptake

Plant height

Figure 2 shows growth as characterized by plant height and water extraction from the 20 to 30 cm layer. Throughout the experiment, treatment MC had the tallest plants. For treatment LC, plants were slightly shorter than for MC. For SC, plant height was considerably shorter. This difference was more pronounced in fine- than coarse-structured soil. Mean plant heights for the fine-structured soils (47.9 cm, at 28 days after planting) were only marginally higher than for the coarse-structured soils (45.7 cm).

Plant water use

Water use from the 20 to 30 cm layer started earlier in LC because roots, as viewed through the clear plastic front of the soil

Table 2. Soil and plant characteristics

Characteristics	Compaction level - bulk density (Mg m^{-3})			
	LC-1.30	MC-1.45	SC-1.60	Mean[1]
Penetration resistance (MPa)				
fine structure	0.650	1.60	4.08	2.11b
coarse structure	0.965	2.14	4.68	2.60a
Mean[2]	0.807c	1.88b	4.38a	
Air permeability ($10^{-8}m^2Pa^{-1}s^{-1}$)				
fine structure	40.5	32.4	4.48	25.8b
coarse structure	58.3	45.1	6.42	36.6a
Mean	49.4a	38.8a	5.45b	
Oxygen diffusion rate ($\mu g\ m^{-2}s^{-1}$)				
fine structure	67.8	44.2	32.5	48.2a
coarse structure	70.2	47.5	37.2	51.7a
Mean	69.0a	45.9b	34.9b	
Stomatal resistance (s cm^{-1})				
fine structure	15.4	15.3	27.1	19.3a
coarse structure	16.2	14.3	26.3	18.9a
Mean	15.8b	14.8b	26.7a	
Leaf area of 8 plants (cm^2)				
fine structure	656	719	219	531a
coarse structure	615	673	239	509a
Mean	636b	696a	229c	
Dry weight of 8 plants (g)				
fine structure	2.38	2.62	1.28	2.09a
coarse structure	1.94	2.03	1.35	1.77b
Mean[3]	2.16b	2.32a	1.32c	

[1] Means with the same letter in the column are not significantly different at the 10% level by the LSD test; [2] Means with the same letter in the row are not significantly different at the 5% level by the LSD test; [3] Means with the same letter in the row are not significantly different at the 10% level by the LSD test.

containers, grew there sooner than for treatment MC. Because it started earlier, water use for treatment LC from this layer was greater than MC over the entire growing period (Fig. 2). Mean water use from this layer for the coarse-structured soil (2.08 l) was 75 % of that for the fine-structured soil (2.79 l). No water was taken from the 20 to 30 cm layer for treatment SC, because its roots did not grow into that layer. Maize grown in treatment SC wilted, had higher stomatal resistance (Table 2), and had to be watered to keep it alive.

Between days 18 and 28, water use from the 20 to 30 cm deep layer per unit of plant height growth was significantly greater for fine (24.7 g cm^{-1}) than for the coarse (16.7 g cm^{-1})

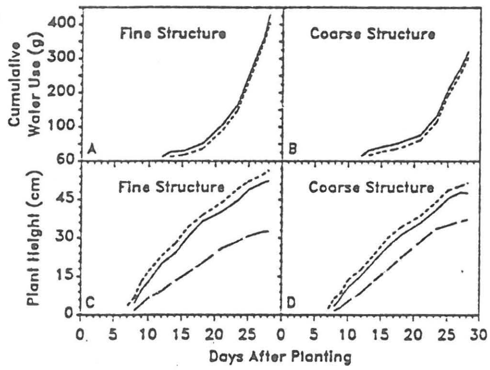

Fig. 2. Cumulative water use from the lower layer as shown in Fig. 1 (A and B) and plant heights (C and D) as a function of days after planting for both fine and coarse textured soils. Compaction level - bulk density (Mg m^{-3}): — LC - 1.30; - - - MC - 1.45; – – SC - 1.60.

Table 3. Root length density

Compaction level - bulk density ($Mg\ m^{-3}$)	Structure	Root length density ($m\ m^{-3}$)					
		Depth (cm)[1]					
		0 - 5	5 - 10	10 - 15	15 - 20	20 - 30	Mean
LC - 1.30	f	0.368	0.331	0.234	0.125	0.116	0.228a
	c	0.344	0.306	0.220	0.121	0.110	
MC - 1.45	f	0.381	0.288	0.246	0.092	0.089	0.221a
	c	0.374	0.338	0.227	0.095	0.081	
SC - 1.60	f	0.370	0.012	0.000	0.000	0.000	0.079b
	c	0.365	0.029	0.011	0.000	0.000	
Mean	-	0.367a	0.217b	0.156c	0.072d	0.066d	

[1] Means with the same letter within a row or column are not significantly different at the 5% level by the LSD test.

texture. There was no difference between treatments LC and MC. Treatment SC did not take water from this layer.

We measured stomatal resistance on 19th day after planting (Table 2). It was lowest for treatment MC, although only significantly lower than treatment SC.

Plant growth

Table 2 shows some plant characteristics for the three compaction levels and for both types of structure. Leaf area and plant dry weight were highest in MC irrespective of soil structure. These characteristics decreased for LC and markedly decreased for SC.

In LC and MC, leaf area and plant dry weight were higher in the fine- and lower in the coarse-structured soil (Table 2). In SC they were higher in coarse-structured soil.

DISCUSSION

Treatment MC displayed an optimum crop response to soil compaction for leaf area and plant dry weight. Plant height for treatment MC was also higher than for treatments LC and SC. There was no indication of mechanical impedance or low aeration for either treatments LC or MC. Some investigators [9,14] attribute less growth in lower bulk density treatments to lower unsaturated hydraulic conductivity and less water flow to the roots. This was partially verified here by our pore size distribution (Table 1). Treatment MC had a significantly higher pore volume for pore sizes 30 μm. Higher water flow to the roots for moderate levels of compaction was also partially verified by the stomatal resistance data. Treatment MC had the lowest stomatal resistance although it was only statistically significantly lower than treatment SC.

Root-soil contact can also help explain an optimum crop-soil compaction response [20]. Kooistra *et al.* [12], using thin sections, showed that the root-soil contact was 60 % in a loose sandy loam of bulk density 1.08 $Mg\ m^{-3}$. It increased to 72 % for a bulk density of 1.32 $Mg\ m^{-3}$ and 87 % for a bulk density of 1.50 $Mg\ m^{-3}$. However, an increased root-soil contact area does not necessarily mean increased water uptake. Although slow, water transfer can take place through the vapour phase [9].

The poor growth of maize in treatment SC can be related to its small root length density (Table 3) caused by excessive mechanical impedance and, consequently, less available water. This was verified by the wilting that we observed, by the lack of root growth into the 20 to 30 cm deep layer, and by the high value of stomatal resistance (Table 2). Poor root growth for treatment SC could also be a result of oxygen deficiency. ODR values were 34.9 $\mu g\ m^{-2}\ s^{-1}$ for treatment SC, a value reported to be limiting for root growth of most plants [6].

The effect of fine or coarse structure on crop response was dependent on the level of soil compaction. In treatments LC and MC, crop growth was better in fine-structured soil while in treatment SC growth was better in coarse-structured soil. Donald *et al.* [4], and Logsdon *et al.* [15], reported similar results for loose soil. A result similar to treatment SC was noted in a moderately compacted clay soil with high penetration resistance (2 to 2.5 MPa). The pores larger than the roots in a coarse-structured treatment resulted in deeper, faster root growth and greater water use from a deeper layer [13]. In treatment SC, crop growth was dramatically reduced both in coarse- and fine-structured soil. A few large inter-aggregate pores in the coarse-structured soil allowed some roots to grow deeper (Table 3). But this did not significantly affect top growth (Table 2).

CONCLUSION

This study showed an interrelationship among level of compaction, aggregation, and plant root and shoot growth. The moderately compacted treatment had the greatest leaf area, plant dry weight, and water use. It also had a slightly lower root length density than the least compacted treatment. We obtained the best crop response with the medium-compacted, fine-structured soil. The worst was with the most compacted, fine-structured soil. In low- and medium-compacted soils, plant growth and water use were greater in fine-structured soil. In a severely compacted soil, plant growth was greater in the coarse-structured soil. This research and the early findings [13] on a clay soil suggest that there are considerable differences in crop responses to soil structure and compaction based on soil type.

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