Phyton (Austria)	Vol. 18	Fasc. 1–2	43–56	10. 6. 1977

Response of Wheat to Different Levels of Soil Compaction

By

Shadida Rashid and Khalid Hamid Sheikh *)

With 2 Figures

Received July 23, 1976

Summary

The work described here was carried out to study the effects of soil compaction on the growth and yield of Mexi-Pak wheat.

In one experiment air dried sandy loam soil was compacted manually to four different levels in pots of 20 cm ⌀. Porosity, bulk density, infiltration and permeability of the soils of these different treatments were determined. Mexi-Pak wheat plants were grown in these soils and two harvests were taken. Compaction of the soil up to the levels obtained (bulk density from 1.20 to 1.41 $g.cm^{-3}$) had no effect on the growth and yield of Mexi-Pak wheat when water supply was not the limiting factor.

In an another experiment Mexi-Pak wheat plants were grown in compacted and uncompacted sandy loam which was further subjected to full and half water holding capacity respectively. Relative water content was very much higher in the plants grown in compacted soil than in those grown in uncompacted soil. The growth of the plants in the compacted soil with full water holding capacity was significantly better than that of the plants of the other treatments and of the latter the plants grown in compacted soil with half water holding capacity even showed significanty better growth than those in uncompacted soil with full or half water holding capacity. Thus the compaction of the soil affected the growth of Mexi-Pak wheat plants mainly through its effects on moisture availability. Soil compaction, upto an acceptable limit, can be beneficial for the growth of wheat in areas with coarse-textured soil and relative paucity of water.

*) Ph. D., D. I. C. Shahida Rashid M. Sc. (after Hons.), Khalid Hamid Sheikh M. Sc., Department of Botany, Punjab University, New Campus, Lahore, Pakistan.

Zusammenfassung

Weizenpflanzen der Sorte Mexi-Pak wurden im Alter von 20 Tagen in Töpfe mit sandigem Lehm, der in standardisierter Weise künstlich bis 1,41 $g.cm^{-3}$ verdichtet worden war, verpflanzt. Geerntet wurde nach rd. 2 bzw. 6 Monaten. Solange das Wasser nicht begrenzender Faktor war, zeigte sich kein Einfluß der Bodenverdichtung auf das Wachstum und die Trockensubstanzproduktion. Wird jedoch der Bodenwassergehalt auf die volle oder die halbe Wasserkapazität eingestellt, so übersteigt der relative Wassergehalt der auf verdichtetem Boden gezogenen Pflanzen den der Kontrollen und Wachstum wie Trockensubstanz steigen mit der Verdichtung. Dieser Effekt geht offenbar auf die Menge des verfügbaren Wassers zurück, er könnte (innerhalb gewisser Grenzen) für das Wachstum auf grob strukturierten und relativ wasserarmen Böden von Bedeutung sein.

(Editor compil. et abbrev.)

Introduction

Excessive soil compaction is believed to decrease the productivity of many soils. Productivity of the compacted soil is affected by the increased mechanical impedance (Veihmeyer & Hendrickson 1948, Wiersma 1959), altered moisture availability and heat flux (Marshall 1954, Richards & Wadleich 1952), which result from increased soil density and reduced pore spaces. At any time, one or more of these factors may become critical. But it also depends upon the soil type, the climatic conditions, the plant species and possibly upon the stage of development of the plant when its roots encounter compact soil conditions (Rosenberg 1964).

Compaction may be due to genetically derived soil conditions (Winters & Simonson 1951) or a result of rapid oxidation of organic fraction and consequent loss of water stability in virgin soils when these are brought into cultivation. It has been shown that even the growing roots may temporarily compact the soil by reducing the root-free spaces (Barley 1954).

Vehicular traffic is considered to be a major cause of soil compaction. With the increased use of farm implements soil compaction is a factor which needs some attention. The compaction is caused mainly by the pressure of the heavy wheels of the tractors and other farm implements. However, this compaction is not uniform throughout a field. Nevertheless the compaction is likely to affect plant growth through effects on soil characteristics such as mechanical impedance, soil aeration, and soil moisture availability, etc.

The work described here was carried out to study the effects of different levels of soil compaction on the growth and yield of wheat (*Triticum vulgare* L. var. Mexi-Pak). In another experiment, the effects of soil compaction along with differential water levels on the growth of Mexi-Pak wheat were also investigated.

Materials and Methods

On 7 December 1973 twenty-day old plants grown in the soil of Botanical Garden New Campus were used for transplantation to the pots. Uniform-sized plants were selected and from amongst these 4 plants were transplanted to each pot at random (128 in all for 32 pots). 24 plants were kept for initial growth measurements.

The pots were kept in a wire-house and their position was randomised once a fortnight. They were given an equal amount of water (500 ml) every alternate day. From 19 April 1974 onwards, in view of the markedly increased temperature, the pots were equally watered daily.

2 replicate pots of each treatment were kept for bulk density and soil porosity measurements described below.

Harvests: Two harvests were taken. Harvesting was done replicate by replicate — 4 replicates for each treatment at each harvest. The individual plants were cut with a sharp knife just above the soil surface while the soil containing the roots of all the four plants was washed in a sieve under a jet of water (only at Harvest I).

Soil analyses: The soil used for growing the plants was analysed. Texture was determined by the hydrometer method (Piper 1944). Water holding capacity of the soil was determined by the method described by Troeh & Palmer (1966). Soil pH was determined on a soil : water suspension (1 : 2) with a Karl Kolb pH meter. Soil organic matter content was determined by the chromic acid with sulphuric acid heat of dilution method (Jackson 1958). Electrical conductivity of the soil saturation extract (EC_{se}) was determined with a conductivity meter (U.S.D.A. 1954).

Soil porosity and bulk density: Porosity of the soils of the various treatments was determined by the moisture-tension method (Rutter & Sheikh 1962). The soil samples were obtained in metallic rings (5 cm deep, 10.5 cm ⌀) with a sharp cutting edge. A ring was driven into the soil using a block of wood and a heavy hammer. The ring was then dug up and using a bread knife the surface of the soil core in the ring was levelled off. Samples were taken from soil surface and a depth of 5 cm. 2 replicate samples were taken for each treatment. These soil cores were used for determining the soil bulk density.

Experiment I: Soil compaction and growth and yield of Mexi-Pak wheat

The four treatments of soil compaction were:

I. The pots were filled with soil in one go without any compaction;

II. The pots were filled with soil in two steps with half the soil added to the pot and compacted for 20 times and then the other half added and compacted in the same manner;

III. The pots were filled with soil in three steps and at each soil addition it was compacted for 40 times;

IV. The pots were filled with soil in three steps, as in treatment III, but the soil was compacted for 80 times at each step.

Compaction of the soil: Forty pots of 20 cm diameter (10 replicates for each treatment) were taken. Air dried soil of Botanical Garden New Campus was used for the filling of the pots.

An earthen pot (12.5 cm ⌀) was used to compact the soil when one-third of a pot was filled in treatments III and IV. Rest of the compaction was done with a cylindrical jar (15 cm long, 15 cm ⌀).

In treatments II, III and IV the compaction of the soil foı 20, 40 and 80 times at each soil addition, respectively, was done in a standardised manner, viz., the jar or the pot used for compaction was raised to a uniform height and then allowed to drop with a uniform force each compaction. The compaction of the pots of the various treatments was done with breathers in order that the tiredness of the worked could not lead to different applications of force.

Soil moisture content: The samples were taken from soil surface and depths of 5 and 10 cm for which a metal tube of 3.5 cm diameter with a sharped end was used. The soil was dried at 105° C to a constant weight.

Infiltration and permeability of soil: Infiltration was determined by the addition of 500 ml water to each pot (4 replicates for each treatment at Harvest II). All the cracks along the rim of the pot and on the soil surface were sealed with molten wax. The small pit formed at the time of sampling the soil for moisture content determinations (at 5 and 10 cm depths) was also closed with the tube of the same diameter, i. e., 3.5 cm ⌀. Molten wax was used to prevent the entry of water along the sides of the tube. The time taken for the complete infiltration of 500 ml water was noted. The pots were then broken and the maximum depth to which the water had penetrated through the soil was noted. From this soil permeability ($cm . min^{-1}$) was calculated.

Growth measurements:

Initial: Height of plant and dry weights of shoot and root (taken after drying the material at 80° C) of 20-day old plants, sampled at the time of transplantation to the pots, were determined to have a measure of the variability amongst them.

Harvest I: It was taken on 15 Februany 1974. The height of plant, number of tillers [1]), number of leaves, and dry weights of shoots and roots per plant were determined.

Harvest II: On 5 June 1974 for each plant its height, the number of ears, their dry weight and the number of grains, were determined.

Experiment II: Soil compaction, differential water levels and growth of Mexi-Pak wheat

The treatments were:

A Uncompacted soil (compaction I of Experiment I) with full water holding capacity

B Uncompacted soil (compaction I of Experiment I) with half water holding capacity

C Compacted soil (compaction IV of Experiment I) with full water holding capacity

D Compacted soil (compaction IV of Experiment I) with half water holding capacity.

Compaction of soil: The air dried soil used was the same as in Experiment I. A smooth-surfaced piece of brick was used to compact the soil. 16 earthen pots of 12.5 cm diameter were used — 8 replicates for each level of compaction. Two pots out of 8 for each level of compaction were kept for soil porosity and bulk density measurements. Empty and soil-filled pots were weighed in order to calculate the amount of soil used in each pot.

Differential water levels: Water holding capacity of the soil used in the pots was determined. Soil moisture content was determined and this helped to calculate the dry weight of the soil used in each pot. Using this data the soils were maintained at full water holding capacity and half water holding capacity by adding the calculated amount of water.

On 5 March 1974 three-day old, uniform-sized, seedlings of Mexi-Pak wheat were transplanted to the pots at random at the rate of 2 seedlings per pot. The pots were daily weighed and the total weight of a pot was maintained by the addition of water to it. They were kept on the laboratory bench and were provided with artificial light. The experiment was a completely randomised design and randomisation was done twice a week.

Soil porosity and bulk density: These were determined in the same way as in Experiment I, but smaller metal rings (5 cm deep and 3 cm diameter) were used for taking the soil samples.

---

[1]) The number of tillers being less than 10, the method suggested by Cochran (1938) was applied to remove the skewness of the data. The formula used was $\sqrt{n + 1/2}$ where n = the number of tillers.

Infiltration and permeability of soil: These were determined as in Experiment I but, because of the smaller size of the pots, only 100 ml water was used.

Relative water content of leaf: It was determined by following the procedure described by LAWLOR (1967). 1.5 cm long pieces of 2nd lea from above on a plant (2 replicates for each plant) were used for this determination.

Growth measurements: The plants were harvested on 4 April 1974. The growth measurements made were the height of plant, number of tillers, number of leaves, and shoot dry weight.

Results

The soil used in this work was a neutral, non-saline, sandy loam with a moderate water holding capacity (Table I).

Table 1
Analysis of the soil used for growing the plants
(Means of 2 replicates)

Soil texture:	Sand	55,2±1,0%
	Silt	30,0±0,2%
	Clay	14,8±1,1%
Textural class	Sandy loam	
Water holding capacity		28,5±0,4% dry weight
Organic matter		1,72±0,01% dry weight
Electrolytic conductivity		1,82 mmhos.cm^{-1}
pH		7,2

Experiment I: Soil compaction and growth and yield of Mexi-Pak wheat

Initial growth measurements: Measurements of 20-day old plants used for transplantation showed that they were reasonably uniform in size (variability, on the average, less than 5 per cent).

Soil porosity measurements: Air-filled porosity of surface soil was highest in treatment I, lowest in treatment IV, with treatments II and III falling in between them (Fig. 1). At a depth of 5 cm the porosity was highest in treatment I, treatments III and IV were equally lowest whereas the soil of treatment II had intermedicte porosity between these two groups (Fig. 1).

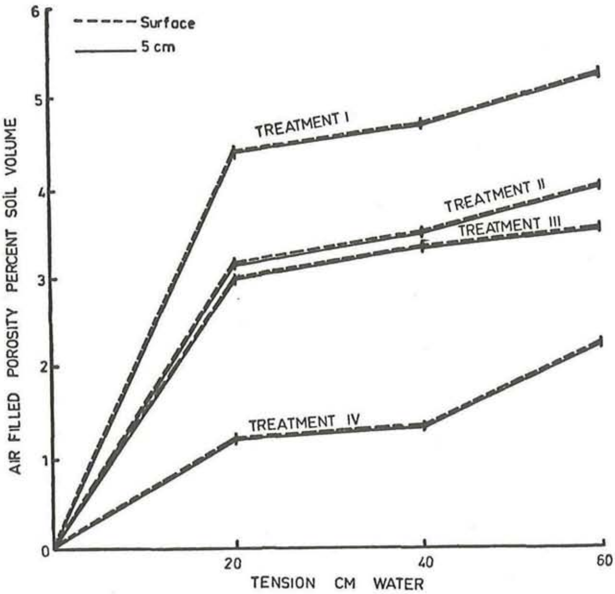

Fig. 1. Mean air-filled porosity, at different moisture tensions, of the soils of the different treatments of Experiment I

Bulk density and soil water content: The data of Table 2 reinforces the values of Fig. 1. The bulk density progressively increased from treatments I to IV. The amount of water lost at 60 cm tension (= water content at saturation — water content at 60 cm tension) progressively decreased from treatments I to IV. This was due to the decreasing air-filled porosity from treatments I to IV.

Soil moisture content at harvests: Harvest I: In treatment I soil moisture content increased from surface to a depth of 10 cm. In treatments II and III the amount increased at a depth of 5 cm as compared to that at soil surface but decreased at a depth 10 cm. In treatment IV the amount of moisture progressively decreased from surface to a depth of 10 cm (Table 2). The amount of moisture in the uncompacted soil (treatment I), both at surface and 5 cm depth, was very much lower than that of the compacted soils (treatments II, III and IV).

Harvest II: In treatments I, II and III the amount of moisture remained almost the same from surface to 5 cm depth but decreased at a depth of 10 cm. In treatment IV the amount increased at a depth of 5 cm but considerably decreased at a depth of 10 cm (Table 2).

Infiltration and permeability of soil: The time taken by water to infiltrate the soil increased from treatment I to IV (Table 3). The permea-

Table 2

Bulk density and water content of the soils of the different treatments

Treatment	I	II	III	IV
Bulk density $g.cm^{-3}$				
Surface	1,27 ± 0,01	1,31 ± 0,00	1,34 ± 0,00	1,34 ± 0,00
5 cm	1,26 ± 0,01	1,31 ± 0,04	1,41 ± 0,00	1,36 ± 0,00
Water content % dry weight				
at saturation [1])				
Surface	35,7 ± 16,3	33,6 ± 3,6	32,8 ± 2,9	29,5 ± 0,0
5 cm	36,5 ± 4,6	33,5 ± 3,6	28,2 ± 0,0	30,0 ± 4,6
at 60 cm tension [1])				
Surface	31,2 ± 0,1	30,5 ± 0,5	30,1 ± 0,8	27,8 ± 0,4
5 cm	30,9 ± 0,0	29,8 ± 1,0	27,0 ± 0,2	28,6 ± 0,8
at Harvest I [2])				
Surface	12,2 ± 1,6	19,9 ± 3,7	18,0 ± 4,7	23,4 ± 3,7
5 cm	16,0 ± 2,7	22,8 ± 2,7	22,5 ± 5,8	21,2 ± 2,1
10 cm	18,2 ± 3,6	18,0 ± 7,1	18,7 ± 4,5	17,0 ± 5,0
at Harvest II [2])				
Surface	14,6 ± 0,8	11,2 ± 0,9	13,1 ± 0,6	11,9 ± 0,9
5 cm	14,3 ± 0,7	10,1 ± 1,4	13,6 ± 0,7	14,1 ± 2,9
10 cm	12,1 ± 2,2	9,4 ± 2,1	9,0 ± 2,8	5,7 ± 1,7

[1]) Means of 2 replicates; [2]) Means of 4 replicates.

bility of the soil was highest in treatment I, lowest in treatment IV, treatments II and III being intermediate between them in this regard.

Permeability of the soil with unsealed cracks was about 8 times more than that of the soil with sealed cracks (Table 3).

Growth measurements: Harvest I: Significant differences were found amongst the treatments only for the heigt of plant and the number of leaves. But there were no significant differences amongst the treatments for the other measures of growth (Table 4).

The roots of the plants of treatments III and IV were growing more often on the periphery of the soil block. No differences were found between the plants of different treatments for the rooting depth and root dry weight. Therefore, root studies were not made at Harvest II.

Harvest II: Although the plants of treatments I and IV were comparatively better in their growth and yield than those of treatments II and III, yet no statistically significant differences were found between the treatments for any of the parameters measured (Table V4).

Table 3

Infiltration and Permeability of the soils of the different treatments at Harvest II (Means of 4 replicates)

Treatment	I	II	III	IV
Time taken by 500 ml of water to infiltrate min				
Cracks sealed	16,8 ± 4,4	21,0 ±4,5	19,8 ±4,3	26,5 ±0,1
Cracks unsealed	4,0 ± 2,8	[1])	[1])	[1])
Permeability cm.min^{-1}				
Cracks sealed	0,43± 0,15	0,30± 0,03	0,26±0,04	0,20±0,07
Crack unsealed	3,50± 0,37	[1])	[1])	[1])

[1]) not determined

Experiment II: Soil compaction, differential water levels and plant growth

Soil porosity: Fig. 2 shows that in the soil samples from surface and 5 cm depth the uncompacted soil (compaction I) had higher air-filled porosity than the compacted soil (compaction IV).

Table 4

Plant growth measurements at Harvests. Means of 4 replicates

Growth measure	Harvest I Treatments I	II	III	IV	LSD (P = 0,05)	Harvest II Treatments I	II	III	IV	LSD (P = 0,05)
Plant height cm	37,1	39,8	42,4	39,2	3,6	50,0	50,8	49,4	50,5	NS [1])
Number of tillers	1,9	2,2	2,0	2,1	NS	—	—	—	—	—
Number of leaves	14,4	17,3	17,3	18,5	2,7	—	—	—	—	—
Shoot dry weight g	1,32	1,49	1,62	1,42	NS	—	—	—	—	—
Root dry weight g	5,17	6,26	6,84	5,85	NS	—	—	—	—	—
Number of ears	—	—	—	—	—	1,4	1,3	1,3	1,4	NS
Number of grains	—	—	—	—	—	56,6	51,4	50,3	56,9	NS
Ears dry weight g	—	—	—	—	—	2,84	2,43	2,78	2,91	NS

[1]) NS = not significant

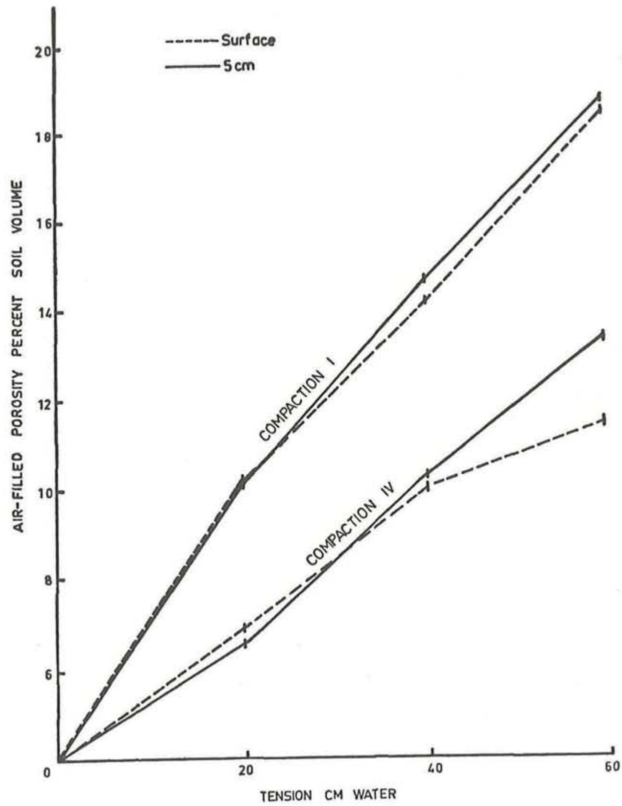

Fig. 2. Mean air-filled porosity, at different moisture tensions, of the soils of the different treatments of Experiment II

Bulk density and water content of soil: Soil bulk density was lower in compaction I whereas it was higher in compaction IV (Table 5). At a depth of 5 cm the relative values of bulk density were higher than those for the surface samples. Much water was lost by the soil at 60 cm tension in compaction I (showing high air-filled porosity) than that in compaction IV. At saturation the water content of soil of compaction I was also higher than that of compaction IV (Table 5).

Infiltration and permeability of soil: Infiltration of water into the soil was slow in compaction IV as compared to that in compaction I. Permeability of soil of compaction I was twice that of compaction IV (Table 5).

Relative water content of leaf: Relative water content of 2nd leaf from above of the plants of treatments A and B was about 70 and 60 percent, respectively, of that of treatments C and D while the latter two had it almost equal (Table 6).

Table 5

Bulk density, water content, infiltration and permeability of the soils with different levels of compaction

Compaction level		I	II
Bulk density, $g.cm^{-3}$ [1])	Surface	1,36±0,00	1,51±0,07
	5 cm	1,45±0,00	1,55±0,00
Water content % dry weight [1])			
at saturation	Surface	48,9 ±1,6	41,2 ±1,1
	5 cm	44,7 ±0,0	39,5 ±0,0
at 60 cm tension	Surface	35,4 ±0,3	33,5 ±0,7
	5 cm	31,9 ±0,0	30,9 ±0,0
Time taken by 100 ml water to infiltrate [2]) min		7,6 ±0,5	11,5 ±0,7
Permeability [2])		0,66±0,02	0,32±0,03

[1]) Means of 2 replicas; [2]) Means of 3 replicas

Growth measurements: The plants of treatment C showed significantly better growth than those of the other treatments. Of the latter, the plants of treatment D had significantly more shoot dry weight than those of the treatments A and B (Table 6).

Table 6

Relative water content of 2nd leaf from above, and the growth measurements of plants at harvest. Means of 3 replicates

Treatment	Relative water content %	Plant height cm	Number of tillers	Number of leaves	Shoot dry weight mg
A	57,3±6,7	27,1	1,2	2,5	62,0
B	49,2±9,8	24,8	1,2	2,4	60,0
C	86,3±2,1	30,1	1,2	2,7	96,0
D	84,9±3,7	24,5	1,2	2,5	66,0
LSD (P = 0,05)	—	1,1	NS	NS	2,7

Discussion

In the sandy loam soil used the air-filled porosity, water retaining ability at saturation and the amount of water lost at 60 cm tension decreased with the increasing level of compaction whereas the values of bulk density increased with it (Fig. 1, Table 2).

At Harvest I the plants of different treatments differed significantly only in their height and leaf number but these were not important as the dry weights of plants did not differ significantly (Table 4). Moisture content at a depth of 10 cm at this Harvest was about the same in the soils of the different treatments and there were no differences amongst them in the depth of root penetration. At Harvest II the moisture content of the soil of treatment IV at a depth of 10 cm was greatly reduced (Table 2). Nevertheless, the lack of significant differences amongst plants for their growth and yield in the different treatments (Table 4) indicated that sufficient water was available to them for their growth even in treatment IV. Thus compaction of soil, combined with the application of adequate amount of water, did not affect the growth and yield of Mexi-Pak wheat.

At Harvest I (15 February, 1974) the moisture content of soils of the various treatments was higher than that at Harvest II (5 June 1974) because of the lower temperature at Harvest I which must have resulted in lesser evaporation.

The direct effect of compaction is considered to be on root penetration. The effects of this mechanical impedance have been discussed by LUTZ (1952). The values of bulk density which exclude root penetration differ according to the soil type used, and for clays a density of 1.6 to 1.7 $g.cm^{-3}$ is the critical limit for root penetration (VEIHMEYER & HENDRICKSON 1948). It has been reported that corn roots would not penetrate Fincastle silty clay loam compacted to a bulk density of 1.5 $g.cm^{-3}$ (BERTRAND & KOHNKE 1957). Rooting of sugarcane was restricted in a Grey Hydromorphic clay at a bulk density of 1.75 $g.cm^{-3}$ (TROUSE & HUMBERT 1961). ZIMMERMAN & KARDOS (1961) found that a bulk density of 1.9 to 2.0 $g.cm^{-3}$ could only exclude root penetration into Hublersbury sandy loam and sandy clay loam. In the present work the sandy loam with bulk density values of up to 1.41 $g.cm^{-3}$ in the different treatments of Experiment I did not check the penetration of roots into the soil. It must be pointed out here that the compaction of soil in an enclosed space, such as pot in the present work, encouraged the roots to grow along the periphery of the compacted soil block and this may explain the lack of significant differences in the growth of the plants. However, the compaction of soil in a large field, to the levels employed in this work, may affect the growth of plants, at least those growing in the centre of the compacted area. This emphasizes the care which need be exercised while translating the results obtained in pot experiments to the field conditions.

In Experiment II higher air-filled porosity, bulk density, greater moisture content at saturation and higher water loss at 60 cm tension were observed in the uncompacted soil (compactionI) than in the compacted soil (compaction IV). The values obtained for these characteristics in Experiment II were higher than those in Experiment I. The soil used in both the Experiments was the same but the pot size, the amount of soil used in the pots and the implement used for compaction were different. These differences ultimately manifested themselves in their air-filled porosity and bulk density, etc. (cf. Figs. 1 and 2, Tables 2 and 5).

Relative water content of leaves of the plants grown in treatments C and D (compaction IV) did not differ in spite of the different amount of water given to the soil (Table 6). Thus sufficient water must have been available to the plants even whan the soil was maintained at half water holding capacity (treatment D). This means that the compaction of soil resulted in a greater availability of water to the plants grown in it. In the uncompacted soil (compaction I) the relative water content was higher in the leaves of the plants of treatment A (full water holding capacity) than those of treatment B (half water holding capacity).

The significantly greater dry weight of the shoots of the plants of treatments C and D than those of treatments A and B (Table 6), also indicated that a given amount of water was more available to the plants grown in a compacted sandy loam (treatments C and D) than in the uncompacted sandy loam (treatments A and B).

Permeability of the soil with unsealed cracks was considerably higher than of that with the sealed cracks (Table 3). During the course of this work the cracks on the soil surface, and between the soil and the rim of the pot (though very small), were unsealed. The cracks are very important in the compacted soil as through these roots and water can penetrate into it to greater depths. Nevertheless in the work described here the differences in bulk density and the amount of water retained at different soil depths were there as a result of the different levels of soil compaction in the different treatments.

The soil used in this work was a sandy loam. Had a clayey soil been compacted, these levels of compaction might have given different results. When a sandy loam is compacted, because of the greater proportion of coarse particles, some pores are still left through which roots can penetrate, water can move and gaseous exchange can take place. On the other hand, when the same amount of force is applied to a clay soil, the compaction obtained is likely to be greater due to the greater proportion of fine particles and the resultant low air-filled porosity (= effective porosity).

It the light of the results obtained here it can be stated that in areas where a sandy loam soil is compacted, comparitively less water is needed for plant growth, per unit soil volume, than that required in an uncompacted sandy loam. Thus compaction, up to an acceptable limit, can be beneficial for growth of wheat in areas where soils are coarse-textured and water is not available in sufficient quantities. The compaction of soil by farm implements, or through other means, cannot affect the growth and yield of Mexi-Pak wheat in a sandy loam with bulk density values of upto 1.51 $g.cm^{-3}$.

References

BARLEY K. P. 1954. Effects of root growth and decay on the permeability of a synthetic sandy loam. — Soil Sci. 78: 205—210.

BERTRAND A. A. R. & KOHNKE H. 1957. Subsoil conditions and their effect on oxygen supply and the growth of corn roots. — Soil Sci. Soc. Am. Proc. 21: 135—140.

COCHRAN W. G. 1938. Some difficulties in the statistical analysis of replicated experiments. — Emp. J. exp. Agric. 6: 170—175.

JACKSON M. L. 1958. Soil Chemical Analysis. — London.

LAWLOR D. W. 1967. The relation of growth to leaf and soil water potentials in some *Gramineae*. — Ph. D. thesis, University of London.

LUTZ J. F. 1952. In: SHAW B. T. (Ed.) Soil physical conditions and plant growth. — New York.

MARSHALL T. J. 1959. Relations between water and soil. — Commonwealth Agricultural Bureau, Tch. Comm. 50, Bucks. England.

PIPER C. S. 1944. Soil and plant Analysis. — Adelaide.

RICHARDS L. A. & WADLEIGH C. H. 1952. In: SHAW B. T. (Ed.) Soil physical conditions and plant growth. — New York.

ROSENBERG N. J. 1964. Plant response to soil compaction. — Adv. Agron. 16: 181—195.

RUTTER A. J. & SHEIKH K. H. 1962. A survey of the vegetation of wastelands round Lahore and its relation to soil conditions. — Biologia 8: 91—121.

TROEH F. R. & PALMER R. G. 1966. Introductory soil science laboratory manual. — Iowa.

TROUSE A. C. Jr. & HUMBERT R. P. 1961. Some effects of soil compaction on the development of sugarcane root. — Soil Sci. 91: 208—217.

U. S. D. A. 1954. Diagnosis and improvement of saline and alkali soils. Handbook 60. — Washington.

VEIHMEYER F. J. & HENDRICKSON A. H. 1948. Soil density and root penetration. — Soil Sci. 65: 487—493.

WIERSMA D. 1959. The soil environment and root development. — Adv. Agron. 11: 43—51.

WINTERS E. & SIMONSON R. W. 1951. The sub-soils. — Adv. Agron. 3: 1—92.

ZIMMERMAN R. D. & KARDOS L. T. 1961. Effect of bulk density on root growth. — Soil Sci. 91: 280—288.