Expl Agric. (2003), volume 39, pp. 341–348 © *2003 Cambridge University Press*
DOI: 10.1017/S0014479703001340 *Printed in the United Kingdom*

PERSISTENCE OF SUBSOIL COMPACTION EFFECTS ON SOIL PROPERTIES AND GROWTH OF WHEAT AND COTTON IN PAKISTAN

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(*Accepted 30 January 2003*)

SUMMARY

The residual effects of subsoil compaction (below 0.15 m depth) on soil properties, growth, yields and nutrient uptake by irrigated wheat (*Triticum aestivum*) and cotton (*Gossipium hirsutum*) are reported. The study was initiated during 1997 on a sandy clay loam soil in a semiarid region of Pakistan. Results showed that the adverse effects of subsoil compaction on bulk density, penetration resistance, total porosity and air-filled porosity of soil persisted for at least four years. In the third and fourth years after the imposition of treatments, compaction decreased yields of wheat by 12–18 % and by 7 % for cotton. The corresponding reductions in nutrient uptake by wheat were 11–16 % for N, 11–15 % for P and 5–10 % for K. For cotton, the values were 9 % for N, 3 % for P and 7 % for K. Subsoil compaction decreased nutrient use efficiency by 16 % in wheat and 5 % in cotton. The reductions in water use efficiency were estimated to be 11 % in wheat and 7 % in cotton. Wheat root length density was also decreased in the subsoil.

INTRODUCTION

Subsoil compaction of agricultural soils below the depth of normal tillage operations is a global concern (Soane and van Ouwerkerk, 1994) because of its adverse effects on crop yields and the environment. Traffic on agricultural land, inappropriate tillage and poor timing of field operations decreases aggregate stability and creates subsoil compaction (Oussible *et al*., 1992). Compaction causes unfavourable changes in soil bulk density and porosity, soil-water relationships, permeability and penetration resistance. The adverse effects can be cumulative and decrease crop productivity. In Pakistan, Ishaq *et al*. (2001a) reported that compacting a sandy clay loam soil to a density of 1.93×10^6 g m^{-3} below 0.15 m depth reduced grain yield of wheat (*Triticum aestivum*) by 12–38 %. Under extreme conditions of subsoil compaction, reductions in maize (*Zea mays*) grain yield may be up to 70 % (Gameda *et al*., 1994).

Adverse effects of compacted soil horizons on root growth and concomitant poor plant growth and yields have been reported (Oussible *et al*., 1992; Etana and Håkansson, 1994; Unger and Kaspar, 1994). Oussible *et al*. (1992) showed how compacting a clay loam soil to a density of 1.52×10^6 g m^{-3} below 0.1 m depth reduced the root elongation of wheat by 19–36 % within the compacted layer. A correlation coefficient of –0.93 was obtained between root length density and

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§ Corresponding author; Email: ishaque58@yahoo.com mechanical impedance. Ishaq *et al.* (2001b) reported similar negative correlations between root length and soil strength.

Compaction decreases water use efficiency (Ishaq *et al.*, 2001a), plant-available water reserves (Reeves *et al.*, 1990) and fertilizer use (Ishaq *et al.*, 2001a). Losses of N by denitrification are generally greater on compacted than uncompacted soils (Douglas and Crawford, 1993). Ishaq *et al.* (2001b) reported that subsoil compaction significantly decreased the uptake of N, P and K by wheat and sorghum (*Sorghum bicolor*). Other researchers have also reported reductions in crop yields due to soil compaction increasing resistance to root growth, and decreasing water and nutrient use efficiencies (Gameda *et al.*, 1994; Lal, 1996).

Subsoil compaction may persist for a decade or longer in cold regions despite the importance of freezing and thawing in the development of soil structure. For example, 11 years after compacting soils in Sweden, Etana and Håkansson (1994) found little change in soil density below tillage depth even though the soils froze to a depth of 0.4 m. Similar results were reported by Lal (1996), Sharratt *et al.* (1998) and Ishaq *et al.* (2001a).

In Pakistan, the repeated use of tractor-driven cultivators has been known to create a hard pan at about 0.15 m depth that hinders the movement of water and air, and inhibits root growth (Hassan and Gregory, 1999). Despite the significance of subsoil compaction, most research in Pakistan has addressed only the deleterious effects of surface compaction on soil properties and crop growth. The available information on soil and crop responses to subsoil compaction under specific soil conditions in Pakistan is scanty (Ishaq *et al.*, 2001a,b). It is important, however, to describe the effects of tillage-induced hard pans on soil properties and crop growth. The objectives of this study, therefore, were to quantify the adverse effects of residual subsoil compaction on (i) soil physical properties, (ii) yields, (iii) nutrient uptake, (iv) water and nutrient use efficiencies by wheat and cotton, and (iv) root length density of wheat. The compaction effects on wheat and sorghum crops for the first two years following compaction were reported by Ishaq *et al.* (2001a,b). The residual effects on wheat and cotton are reported in this paper.

MATERIALS AND METHODS

Experiment background

The soil-compaction study was initiated in 1997 on the research farm of the Soil Chemistry Section, Ayub Agricultural Research Institute (AARI), Faisalabad, Pakistan. The soil, a sandy clay loam (fine-loamy, mixed, hyperthermic Typic Haplargids, USDA), is representative of about 21 % of the total cultivated area of Punjab province, Pakistan. Of 12.3×10^6 ha total cultivated area; about 2.52×10^6 ha is covered by Typic Haplargids and other soils of similar properties. The site is located in a semiarid region that is flood irrigated with canal water. During the study period, the mean annual rainfall was 380 mm and the pan evaporation was 4.6 mm per day. The top (0.15 m) soil had an electrical conductivity of 1.33 dS m^{-1}, pH of 8.2, organic carbon content of 3.8 g kg^{-1}, $CaCO_3$ concentration of 21.5 g kg^{-1}, cation exchange capacity of 6.0 cmol_c kg^{-1}, total N content of 0.41 g kg^{-1}, Olsen-P level of 7.3 mg kg^{-1} and ammonium acetate extractable K of 210 mg kg^{-1}. The proportions of sand, silt and clay were 545, 215 and 240 g kg^{-1} respectively.

In the laboratory, a Proctor density test was conducted to develop a relationship between soil water content and bulk density. Bulk soil was obtained from 0.15 to 0.30 m depths. Six soil water contents (0.03, 0.10, 0.12, 0.20, 0.25 and 0.32 by volume) were created. The moist soils were kept in plastic bags for 48 h for equilibration. Soils were compacted to their maximum value using the modified compacted mould (diameter of 0.15 m and length of 0.12 m with hammer of 4.54 kg fall) (BSI, 1975). Maximum compaction (bulk density 1.93×10^6 g m^{-3}) was attained at 0.20 volumetric water content.

In the field, continual shallow cultivation has been reported to create a hard pan below a depth of 0.15 m. The subsoil compaction protocol used here was selected to simulate the hard pan created by long-term ploughing of soil with a field cultivator, and the compaction treatments were imposed once at the start of the study period. The top 0.15 m soil was removed manually using a spade and the exposed soil was compacted at a water content of about 50 % of field capacity (0.20 m^3 m^{-3}). Compaction was achieved by a powered vibratory tamper with a weight of 60 kg, a base area of 0.3 × 0.3 m, a static pressure of 8.4 kPa, and operating at 80 strokes per minute. Thereafter the topsoil was replaced. Bulk density and penetration resistance of the uncompacted control (bulk density 1.65×10^6 g m^{-3}) and compacted (bulk density 1.93×10^6 g m^{-3}) plots from 0.00–0.15 m and 0.15–0.30 m depths were determined. Using a spade, both compacted and uncompacted plots were hoed manually to a depth of 0.15 m and levelled. The plots were arranged in a randomized complete blocks design with four replications of each treatment (control and compacted). Plots size was 3 × 3 m.

The magnitude of soil compaction was quantified by measuring soil bulk density, penetration resistance, total porosity and air-filled porosity. These soil parameters were determined at the start of the study and again four years later, in 2001. The bulk density was measured using the core method (Blake and Hartge, 1986), and the penetration resistance by cone penetrometer (30° cone tip angle, 9.2 mm diameter). At the same time, soil samples from the respective depths (0.00–0.15 m and 0.15–0.30 m) were taken to determine soil water contents. These observations were made between crop rows. Soil cores collected for bulk density measurements were used to determine the gravimetric and volumetric water contents, total porosity and air-filled porosity by following the techniques described by Lowery *et al*. (1996).

Wheat was sown during the third week of November each year from 1997 to 2000, and cotton during the second week of May in 2000 and 2001. The seeding rate was 100 kg ha^{-1} for wheat, and 25 kg ha^{-1} for cotton. A basal application of 120 kg N as urea, 40 kg P as single superphosphate and 42 kg K ha^{-1} as muriate of potash was applied to wheat; and 170 kg N, 37 kg P and 50 kg K ha^{-1} to cotton. Weeding was done manually as and when necessary. The wheat was harvested manually from a 2.80 × 2.80 m area in each plot. Similarly, the seed cotton yield was recorded in each plot. Fertile tillers in a 1-m row of wheat were recorded at four random sites. Plant

Table 1. Residual effects of subsoil compaction on soil physical properties after four years during 2001 at AARI, Faisalabad, Pakistan.

Depth (m)	Treatment	Bulk density ($\times 10^6$ g m^{-3})	Total porosity (m^3 m^{-3})	Air-filled porosity (m^3 m^{-3})	Penetration resistance (MPa)	Volumetric water (m^3 m^{-3})
0.00–0.15	Compacted	1.51	0.43	0.24	0.62	0.20
	Control	1.49	0.44	0.26	0.64	0.18
	s.e.	0.03	0.01	0.02	0.08	0.02
0.15–0.30	Compacted	1.92	0.28	0.05	1.74	0.23
	Control	1.67	0.37	0.17	0.94	0.21
	s.e.	0.15	0.05	0.07	0.45	0.01

height was measured at maturity. Total dry matter, grain and straw yields, and 1000-grain weight were also measured. Nutrient use efficiency was calculated by dividing the yield by the amount of nutrients applied. The estimated water use efficiency was calculated by dividing the crop yield by the amount of irrigation water used during the crop-growing season. The consumptive water use of wheat and cotton (ET) was assumed to be 353 and 756 mm respectively (PARC, 1982).

Nutrient uptake was computed for each plot — concentration (%) × yield (kg ha^{-1}). Using a sampling core (0.15 m long and 0.08 m in diameter), the root length of wheat was measured at anthesis (flowering) from soil samples collected from in between the rows. Root samples were taken at 0.00–0.15 and 0.15–0.30 m depths from both sides of the row. The roots were separated from the soil and other residues by gentle washing under a flow of swirling water. Root length was measured following the techniques of Tennant (1975). The root length density (mm cm^{-3}) was calculated by dividing the root length (mm) by the volume (cm^3) of the sampling core. Data were statistically analysed for the analysis of variance (Gomez and Gomez, 1984) and the comparisons among the treatment means were made by calculating standard error of the mean values (Duncan, 1955).

RESULTS

Soil physical properties

The residual effects of subsoil compaction on soil physical parameters after growing six crops (four wheat and two cotton) are depicted in Table 1. While the physical properties of the surface layer were similar in both the compacted and uncompacted treatments, compaction had a drastic effect on physical properties of the subsoil. Soil bulk density (BD), penetration resistance (PR), total porosity (TP), air-filled porosity (AP) and volumetric water (WC) content in the compacted zone were adversely and significantly affected compared with those of the control treatment. At the start of the experiment (1997), the compacted layer had a BD of 1.93×10^6 g m^{-3}, TP of 0.27 m^3 m^{-3}, AP of 0.06 m^3 m^{-3}, PR of 4.83 MPa and WC of 0.22 m^3 m^{-3}. The data showed that the adverse effects of subsoil compaction on all the soil physical parameters persisted for at least four years.

Table 2. Residual effects of subsoil compaction on wheat yield and related components at AARI, Faisalabad, Pakistan.

Season	Treatment	Yield (kg ha^{-1}) Grain	Straw	Total	1000-grain weight (g)	Plant height (m)	Fertile tiller (m^{-1} length)
1999/2000	Compacted	2780	5790	8570	32.0	0.90	89
	Control	3400	5935	9330	33.2	0.93	94
	s.e.	357	586	630	0.7	0.04	14
2000/2001	Compacted	3050	5025	8070	36.2	0.91	92
	Control	3420	5190	8610	37.4	0.93	103
	s.e.	218	112	323	1.1	0.02	7.5

Table 3. Residual effects of subsoil compaction on nutrient uptake, nutrient and water use efficiencies by wheat at AARI, Pakistan.

Season	Treatment	Nutrient uptake (kg ha^{-1}) N	P	K	Nutrient use efficiency (kg grain ha^{-1} kg^{-1} nutrient applied)	Water use efficiency (kg grain ha^{-1} mm^{-1} ET)
1999/2000	Compacted	88	11.6	114	13.8	7.9
	Control	105	13.7	126	16.5	9.4
	s.e.	9.6	1.3	8.9	1.7	1.0
2000/2001	Compacted	94	11.0	110	15.1	8.6
	Control	104	12.4	115	16.9	9.6
	s.e.	6.1	0.8	3.7	1.1	0.6

Crop yield

Subsoil compaction had adverse effects on wheat yield and its related components (Table 2) and seed cotton yield (Table 4). During the 1999/2000 season, subsoil compaction decreased 1000-grain weight, the number of productive tillers and the grain yield of wheat (Table 2). However, subsoil compaction did not affect the total biomass and plant height. During the 2000/2001 season, the negative effect of compaction was observed on all yield components except total biomass and the 1000-grain weight. The reduction in grain yield due to subsoil compaction was 11 %. An adverse effect of subsoil compaction was also observed on the yield of cotton in one out of two seasons (Table 3). During 2000, compaction significantly decreased the seed cotton yield by 5 % compared with the control. However, seed cotton yield was relatively unaffected by compaction in 2001.

Nutrient uptake, water and nutrient use efficiencies

Subsoil compaction effects on nutrient uptake (NU), nutrient use efficiency (NUE) and water use efficiency (WUE) by wheat and cotton are depicted in Tables 3 and 4 respectively. Compaction decreased the uptake of N, P, and NUE and WUE by the wheat crop compared with the control (Table 3). However, the uptake of K was not affected by subsoil compaction. In 1999/2000 reductions in uptake due to compaction were about 16 % for N, 15 % for P and 10 % for K compared with the control treatment. In the second year, uptake decreased by 11 % for N, 11 % for P, and 5 % for K. A similar trend was observed in the case of WUE. The NUE and WUE by

Table 4. Residual effects of subsoil compaction on yield, nutrient uptake, and nutrient and water use efficiencies by cotton at AARI, Faisalabad, Pakistan.

Year	Treatment	Seed cotton (kg ha^{-1})	Nutrient uptake (kg ha^{-1}) N	P	K	Nutrient use efficiency (kg seed cotton ha^{-1} kg^{-1} nutrient applied)	Water use efficiency (kg seed cotton ha^{-1} mm^{-1} ET)
2000	Compacted	1390	32	5.8	16	5.4	1.8
	Control	1455	35	5.9	17	5.7	1.9
	s.e.	45	0.7	0.19	0.53	0.18	0.06
2001	Compacted	1560	37	5.6	19	6.1	2.1
	Control	1670	40	6.5	20	6.5	2.2
	s.e	80	2.3	0.40	0.87	0.31	0.11

Table 5. Residual effect of subsoil compaction of root length density of wheat at AARI, Faisalabad, Pakistan.

Depth (m)	Treatment	Root length density (mm cm^{-3}) 1999/2000	2000/2001
0.00–0.15	Compacted	5.5	6.9
	Control	5.7	6.8
	s.e.	0.5	0.6
0.15–0.30	Compacted	1.3	1.6
	Control	2.6	3.1
	s.e.	0.8	0.8

wheat decreased by 16 % during the first year and by 11 % in the second year due to subsoil compaction. Similarly, the uptake of N and K, and NUE and WUE by cotton, were reduced, but there was no effect on P uptake during 2000 (Table 4). However, these parameters were not affected during 2001. Cotton assimilated 5 % more applied nutrients in uncompacted compared with compacted plots in 2000 and 7 % more in 2001.

Root length density of wheat

Similar root length densities were observed in the top 0.15 m depth for both compacted and uncompacted treatments (Table 5). However, subsoil compaction significantly decreased the root length density of wheat below that depth compared with that of the control plots during both years.

DISCUSSION

While physical properties of the surface layer were similar in both compacted and uncompacted treatments, the compaction treatment had drastic effects on the physical properties of the subsoil (Table 1). Compaction increased soil bulk density and penetration resistance and decreased porosity and permeability. The effects of compaction treatments on soil physical parameters persisted for at least four years.

The compaction treatments had negative effects on yield and yield components of wheat (Table 2). The reduction in grain yield during both years was associated with the reduction in fertile tillers (Ishaq *et al*., 2001a). This decrease in tiller development could have been due to nutritional deficiency, especially low nitrogen uptake (Table 3). Oussible *et al*. (1992) concluded that reductions in the grain yield of wheat in response to subsoil compaction were due to a reduction in spike number. Compaction also reduced the root length density of wheat confining roots mostly to within the top 0.15-m layer (Table 5). Cotton plants in compacted plots had more secondary roots (as observed by up digging the roots) compared with control plots in the 0–0.15 m layer indicating that the cotton plant can exhibit a remarkable degree of developmental plasticity to soil strength. Root channels and fissures created by the previous crop may also have facilitated root penetration in the compacted layer (Coelho *et al*., 2000). Overall, the adverse effects of subsoil compaction treatment on the yield and yield components of wheat have persisted for at least four years. Oussible *et al*. (1992) reported that compacting a clay loam soil to a density of 1.52×10^6 g m^{-3} below 0.1m depth reduced grain and straw yields of wheat and the residual effects of compaction persisted for up to one year in a clay loam soil.

Because root length was severely reduced, NU, NUE and WUE by wheat (Table 3) were also less in compacted than uncompacted soils. Both WUE and NUE are probably over estimated by this method, which assumes that the consumptive water use is the same in both treatments. Compaction reduced the root length density, thereby limiting the volume of soil exploited by the roots for nutrient and water uptake (Ishaq *et al*., 2001b). The effect of subsoil compaction on root growth may be directly related to high soil strength and/or indirectly to soil oxygen depletion and nutrient availability plus reduced soil water (Coelho *et al*., 2000). These conditions could have directly restricted mass flow of NO_3^- to roots. In fact, the root system was concentrated mainly in the top 0.15-m layer overlying the compacted layer, thereby indicating limitation of the volume of soil exploited by the roots. The values of air-filled porosity that limit root growth range from 0.08 to 0.15 m^3 m^{-3} (Smucker and Erickson, 1989). Subsoil compaction decreased the air-filled porosity from 0.17 m^3 m^{-3} in the uncompacted control plots to 0.05 m^3 m^{-3} in the compacted treatments, thereby decreasing growth, yields and nutrient uptake by both wheat and cotton. Although the severity of subsoil compaction artificially created in this experiment may not occur in traditional small-scale farming practices, the potential of severe subsoil compaction in alluvial soils exists with progressive increases in mechanization of farm operations in the Punjab and elsewhere in South Asia.

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