Alleviating Soil Physical Constraints for Sustainable Crop Production through Tillage, Soil Amendment and Crop Residue Management

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Abstract: The alleviation of soil physical constraints limiting crop production is considered important to increase agricultural production and sustaining the productivity of soils. The results of several field experiments conducted during the last two and a half decades to identify soil physical constraints in the state of Haryana (India) and to generate different technologies for their management are discussed. The major soil physical constraints found to impair soil quality and hence reduce crop growth include high soil permeability, soil crusting, sub-surface mechanical impedance and soil hardening. Studies indicated that the compaction of highly permeable soils by six passes of 1,500 kg tractor driven iron roller reduced water and nutrient losses, increased moisture retention in the soil profile and reduced the irrigation requirements for crops. The yields of various crops were either increased or remained unaffected upon compaction. The application of farmyard manure (FYM) on seed lines at the rate of 4 t • ha^{-1} as mulch reduced the adverse effect of surface soil crusting on crop establishment and increased the yields of pearl millet and cotton quite significantly. High sub-surface mechanical impedance was found to affect plant growth more in legumes than in cereals. In these soils, deep tillage was found to be very effective in reducing the bulk density in sub-soil, increasing infiltration rate and yield of wheat. Incorporation of sesbania as green manure and the application of FYM were found to be useful in reducing the nitrogen requirement and improving the soil physical conditions of soils that set hard upon wetting and are under rice-wheat cropping system. The yield of both the crops were found to be higher where crop residues were burnt *in situ* followed by residue incorporation with 25 per cent extra nitrogen.
Keywords: soil physical constraints, compaction, crusting, soil management, mulching, tillage, residue management

1 Introduction

The enhanced soil productivity and the assured sustainability are the two major issues of concern in order to feed the increasing population of the world. Scientific planning and management practices for further enhancement and sustaining of the productive potential of soils, however, require a proper understanding of the factors limiting its productivity. There is growing realisation that the crop yields are now more often limited by the soil physical conditions rather than plant nutrient status in the soil. This envisages that for increasing crop production, soil must be maintained in such a physical condition so as to allow adequate crop growth.

The objective of this paper is to present the results of several field experiments conducted during the last two and a half decades in the state of Haryana (India) to identify soil physical constraints limiting crop production and different options for their management. The major emphasis for the development of management technology had been the manipulation of soil physical conditions through tillage, soil amendment and crop residue management, to improve crop growth and better utilisation of water and nutrients.

2 Study area

The state of Haryana is situated in the north-west of India and lies between the Thar desert in the south and Himalayas in the north at latitudes 27° 39′ to 30° 5′ 5″ and longitudes 74° 27′ 8″ to

77° 36′ 5″ E. Out of its total geographical area of 44, 222 km^2, about 82% area is net cultivated. It has a sub-tropical, semi-arid, continental monsoonal climate. Maximum temperature can be up to 49^{o}C in the month of May to June and minimum down to 1^{o}C in January. The average annual rainfall is <400 mm in south-west and >1000 mm in the north-east. The rainfall, however, is very erratic and over 70% is received during July to September. The texture of soils is mainly coarse to medium with illite and kaolinite as the dominating clay minerals. Most of the soils are alkaline and invariably have low organic carbon content.

The major soil physical constraints limiting the crop production studied are high permeability, surface soil crusting, sub-surface mechanical impedance and soil hardening (rice soils) which either restrict the crop growth or reduce the efficiency of basic inputs. General characteristics of these physically constraint soils (Agrawal *et al*., 1995) are described as under:

2.1 Highly permeable soils

Highly permeable coarse textured soils are characterised by low water retentivity, excessive permeability, and poor inherent fertility and prone to wind erosion. In these soils, the fertiliser use efficiency is very low and the nutrient losses are very high discouraging the use of high levels of inputs. These soils usually contain 5%—15% clay, nearly an equal amount of silt and about 60%—70% fine sand and 20%—30% coarse sand, retain about 5%—10% moisture at 10kPa tension and have high basic infiltration rates (up to 26 cm • hr^{-1}).

2.2 Crusting soils

Some soils are prone to form a hard crust on its surface on drying after rain showers due to reorientation of dispersed soil particles on wetting and differential sedimentation. The crust formation is a serious problem in sandy loam and loamy sand soils having low organic carbon content. The seedling emergence in crops like pearl millet, cotton, sorghum, mustard etc. is reduced drastically when rain showers occurs within one or two days of seeding.

2.3 Sub-surface mechanical impedance

Dense layer may develop either due to formation of a plough sole as in the case of rice fields on medium textured soil, use of heavy machinery on a moist soil or presence of kankar (calcium carbonate) layers. Presence of such layers at shallow depths affects the plant growth by restricting root penetration to sub-soil for their moisture and nutritional requirements. These layers are relatively impervious and as a result water may stagnate on the soil surface after heavy rainfall or irrigation causing oxygen stress to the crops. Thus, shallow root system makes the plant drought prone during dry spells and promotes lodging during unusually wet conditions.

2.4 Rice soils

In the state, rice is grown on fine loamy sand to clay soils with varying infiltration rates (0.2 cm • hr^{-1} to 1.8 cm • hr^{-1}). This moderate to high infiltration rate requires intensive soil puddling to reduce the percolation to an optimum level for rice cultivation. The intensive puddling deteriorates the soil structure and creates problem for subsequent crop. Invariably, wheat follows rice which needs different soil management practices.

3 Materials and methods

Field experiments at various locations with different soil physical constraints were conducted to generate technologies for their management. In highly permeable soils, experiments were conducted to evaluate the effect of compaction on water infiltration and retention, bulk density, nitrate movement and crop yields. The soil compaction was carried out by six passes of 1,500 kg tractor driven roller at moisture level attained within 24—48 hrs of sufficient rain or irrigation. In crust prone areas, the effect of the application of FYM @ 4 t • ha^{-1} on seed lines as mulch on soil moisture, soil temperature, seedling emergence and yields of pearl millet and cotton was studied. In sub-surface mechanical impedance soils, studies were carried out to see the effect dense sub-surface layer on penetration of roots by placing radioactive ^{32}P beneath the dense layer. Tillage operations with various implements (chiseller i.e. sub-soiler, disc harrow, mould board plough, country plough) were carried out for breaking such hard layers. Influence of the application of organic amendments (FYM, green manuring, burnt rice husk) and residue management of both paddy and wheat crops (burning, incorporation and incorporation with 25% extra nitrogen) in improving soil physical conditions and sustaining productivity of rice-wheat cropping system was studied in rice growing areas.

In all the experiments, measurements of soil physical properties were made using standard procedures/methods.

4 Results and discussion

4.1 Highly permeable soils

To reduce deep percolation losses and enhance soil moisture storage capacity of highly permeable sandy soils, application of bentonite clay, fine textured soils or pond sediments (Gupta and Nagarajarao, 1982) and placement of asphalt barrier at shallow depths (Gupta and Aggarwal, 1980) have been attempted. These treatments have, however, not been used on large areas due to practical difficulty. In these soils, the bulk density of sub-surface soil (10 cm—20 cm) is very important for irrigation water management as the surface soil is loosened by re-cultivation to facilitate the seeding operation. Field studies conducted at several locations on soil compaction revealed that the rolling increased the soil bulk density and decreased the hydraulic conductivity in 10 cm-20 cm soil depth (Table 1). Due to compaction of sub-soil layer, the infiltration rate decreased from 8.3 to 7.0 cm • hr^{-1}. The increase in soil moisture retention in 120 cm soil profile was about 1.7% in the compacted profile which reduced the irrigation water needed for wheat by 35% (Table 1). This reduced irrigation water requirement may also be attributed to the slow rate of infiltration and accelerated rate of water flow on the soil surface. In spite of reduced amount of irrigation water applied, the yield of various crops were either increased or not affected adversely (Table 2).

Table 1 Effect of soil compaction on some soil physical properties of coarse textured soils

Soil property	Control	Compacted
Bulk density [a] (Mg • m^{-3})	1.41	1.55
Hydraulic conductivity [a] (cm • hr^{-1})	2.74	0.77
Infiltration rate (cm • hr^{-1})	8.30	7.00
Gravimetric moisture content [b] (%)	10.4	12.1
Depth of irrigation [c] (cm)	9.93	6.42

[a] for 10 cm-20 cm depth; [b] for 120 cm deep soil profile; [c] average for the 10 locations.

Table 2 Soil compaction and yield (t • ha^{-1}) of various crops of coarse textured soils

Treatment	Wheat (14) [a]	Pearl millet (4)	Cotton (3)	Mustard (2)
Control	3.64	1.58	1.49	0.81
Compacted	3.84	1.79	1.56	0.94
LSD at 0.05	NS	NS	NS	0.05

[a] Figures in parentheses are number of crop seasons/locations averaged.

In a column study, soil compaction decreased the infiltration rate and a greater amount of water and NO_3-N was retained in surface 20 cm soil layer. The NO_3-N content was 10 times higher or even more in surface compacted treatment than in the control (Table 3). The sub-surface compaction (10 cm—20 cm) was, however, less effective than surface compaction in NO_3-N leaching. Thus, soil compaction by roller can play an important role in the management of water and nutrients to enhance the productivity of highly permeable coarse textured soils.

Table 3 Infiltration, soil moisture and NO_3-N as affected by soil compaction of coarse textured soils

Treatment	Infiltration rate (cm • hr^{-1})	Moisture (v/v)[a]	NO_3-N (me $100g^{-1}$)[a]
Control	32.7	0.406	0.305
Sub-surface compaction	25.3	0.424	1.405
Surface compaction	22.2	0.461	3.524

[a] Average content in 0 cm—20 cm layer just after infiltration of 120 mm of water.

4.2 Crusting soils

The formation of the crust on the surface by rain showers within 2 hrs of seeding of pearl millet has been reported to reduce the seedling emergence to 40% and increase the seeding emergence from 42% to 67% when the soil moisture increased from 11.1% to 17.9% at seeding (Agrawal and Sharma, 1980). Thus, the low soil moisture at seeding increases the ill-effects of crust and reduces the seedling emergence. Application of FYM on seed lines as mulch increased the seedling emergence over the crusted soil by three and ten fold in pearl millet and cotton, respectively (Table 4). Upon mulching, the yield of pearl millet increased from 2.63 to 3.42 t • ha^{-1} whereas in cotton, the increase was from 0.35 to 1.49 t • ha^{-1}. Thus, FYM seed line mulch reduces the impact of rain drops and prevents the formation of the crust, improves the seedling emergence and yield of crops.

Table 4 Effect of FYM seed line mulch on seedling emergence and yield of pearl millet and cotton on sandy loam and loamy sand soils

Treatment	Seedling emergence (%)		Grain yield (t • ha^{-1})	
	Pearl millet	Cotton	Pearl millet	Cotton
Crusted	16.4	03.6	2.63	0.35
Uncrusted	48.2	35.5	3.26	1.47
Seed line mulch	43.1	20.2	3.42	1.49
CD at 5%	6.56	7.60	3.40	0.33

4.3 Sub-surface mechanical impedance

The presence of compacted layer below the tilled layer is a throttle to the process of infiltration and penetration of roots. The root penetration through compacted layer as measured by ^{32}P activity in wheat and chick-pea at different time intervals (Table 5) showed that wheat appears to be more tolerant to the sub-soil mechanical impedance than chick-pea. Tillage operations carried out with various implements indicated that the chiseller (Table 6) was effective in breaking the dense layer and reducing the bulk density of 10 cm—20 cm layer, and increasing the infiltration rate from 0.4 cm • hr^{-1} to 0.7 cm • hr^{-1}. The yield of wheat increased significantly by chiselling.

Table 5 Effect of sub-surface compaction of medium textured soils on uptake of radioactive ^{32}P from beneath the dense layer by wheat and chick-pea (^{32}P count g^{-1} 10 min^{-1})

Days after	Bulk density (Mg • m^{-3})			C.D. at	Bulk density (Mg • m^{-3})			C.D. at
Germination	1.4	1.6	1.8	5%	1.4	1.6	1.8	5%
		Wheat				Chick-pea		
17	3233	784	474	621	2035	128	166	343
45	7512	5212	4164	212	4066	1275	1120	162
52	3685	2265	1641	19	3407	2179	1716	18
73	786	453	407	10	1064	730	551	7

Table 6 Effect of tillage with different implements on soil bulk density, infiltration rate and yield of wheat in an alluvial sandy loam soil with a compacted sub-soil

Tillage implement	Bulk density(Mg • m^{-3}) Depth (cm)			Infiltration Rate (cm • hr^{-1})	Yield (t • ha^{-1})
	0-10	10-20	20-30		
Country plough	1.32	1.51	1.58	0.4	3.23
Disc harrow (twice)	1.37	1.54	1.59	0.5	3.31
Mould board plough +disc harrow	1.35	1.42	1.57	0.5	3.18
Chiseller+ disc harrow	1.28	1.39	1.61	0.7	3.68
C.D. at 5%					0.27

4.4 Rice soils

Sustaining productivity of soils under rice-wheat cropping system is a major problem as continuous such cultivation has deteriorated the soil health as is evident by diminishing agricultural returns and increased use of various inputs (Kumar and Yadav, 1993; Agrawal *et al*., 1994). The field experiments conducted to sustain the productivity of rice soils by application of organic amendments and crop residue management suggested that the organic amendments significantly increases the yield of rice and wheat due to enhanced nutrients supply and improvement in soil physical conditions (Beri *et al*., 1989; Joshi *et al*., 1994). The result of a study (Table 7) showed that application of 80 kg • N • ha^{-1} along with the green manuring with sesbania gave 8.12 t • ha^{-1} rice yield which was significantly higher than that in control at 160 kg • N • ha^{-1}. Rice yield declined at 120 and 160 kg • N • ha^{-1} in green manuring. At N_o level, the increase in rice yield was 22%, 71% and 113% with burnt rice husk, FYM and green manuring treatments, respectively, over control. Progressive increase in yield was obtained at N_{80}, N_{120} and N_{160} kg • N • ha^{-1} in all the amendment treatments except in green manuring where the rice yield decreased after N_{80} kg • N • ha^{-1}. The yield of both the crops were found to be higher where crop residues were burnt *in situ* followed by residue incorporation with 25 per cent extra nitrogen (Table 8).The productivity of rice-wheat rotation can be sustained by organic amendments with reduced level of fertiliser input. Experiments are still on for the development of better management options of rice based cropping system.

Table 7 Effect of different organic amendments and nitrogen levels on rice yield (t • ha^{-1})

Amendments	N level (kg • ha^{-1})				
	0	80	120	160	Mean
Control	3.10*	6.16	7.30	7.80	6.09
Burnt rice husk	3.77	6.60	7.68	8.17	6.55
FYM	5.27	7.32	8.27	8.34	7.30
Green manure (susbania)	6.58	8.12	7.88	7.66	7.56
C.D. (0.05) Amendment (A) = 0.200, Nitrogen (N) = 0.196, A × N = 0.31					

* Each figure is an average over four years.

Table 8 Effect of crop residue management on yield ($t \cdot ha^{-1}$) of rice and wheat

Crop	Residue treatment				C.D. at 5%
	Control	Burning	Incorporation	Incorporation+25%extraN	
Rice	6.97*	7.23	7.01	7.17	0.23
Wheat	4.65	4.84	4.43	4.52	NS

* Each figure is an average over four years.

5 Conclusions

Soil compaction with six passes of 1,500 kg tractor driven roller was found to be effective in water and nutrient retention, and the yield of various crops in highly permeable sandy soils. Application of FYM on seed lines at the rate of 4 $t \cdot ha^{-1}$ as mulch was very helpful in reducing the ill-effects of surface crust on seedling emergence and crop establishment in crust prone sandy loam and loamy sand. Tillage operations with chiseller was effective in breaking the high bulk density sub-soil layer and resulted in increased water entry and crop yields. Burning of the residues of rice and wheat gave higher yields of both the crops in rice-wheat cropping system. Use of sesbania as a green manure was found to be helpful in sustaining the productivity of this system with reduced fertiliser inputs.

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