International Journal of Food, Agriculture and Veterinary Sciences ISSN: 2277-209X (Online)
An Open Access, Online International Journal Available at http://www.cibtech.org/jfav.htm
2014 Vol. 4 (3) September-December, pp. 95-104/Singh and Hadda
Research Article

SOIL AND PLANT RESPONSE TO SUBSOIL COMPACTION AND SLOPE STEEPNESS UNDER SEMI-ARID IRRIGATED CONDITION

***Jagdish Singh and Hadda M.S.**
Department of Soil Science, Punjab Agricultural University, Ludhiana, Punjab, India -141004
**Author for Correspondence*

ABSTRACT
The present investigation was carried out with the objective to access the effect of subsoil compaction and slope steepness on soil physical properties, plant growth, yields and yield attributes of maize. The results revealed that the subsoil compaction significantly affected the bulk density, total porosity, infiltration rate and cumulative infiltration. However slope steepness did not shown significant effect on all these physical properties. The plant height, yield and cob length was significantly higher under lower level of subsoil compaction than that in higher degree of subsoil compaction, while cob barrenness and crop lodging was more under higher degree of subsoil compaction. The slope steepness significantly improved the grain yield and biological yield of maize by reducing the crop lodging as a result of high intensity rainstorm occurred during summer monsoon season. This study will encourage the fine tuning of existing technology to improve the crop yield under compacted subsoil conditions especially under rice-wheat cropping sequence.

Keywords: *Slope Steepness, Penetration Resistance, Porosity, Infiltration Rate, Maize Yield and Yield Attributes*

INTRODUCTION
The introduction of green revolution in the mid 1960's has helped in improving the income of farmers, that was possible only with the introduction of improved crop varieties, fertilizers, pesticides, assured irrigation and agricultural machinery. This has promised a better technology that is cost effective and time saving. The continuous use of agricultural machines such as tractor, harvester, etc for routine agricultural practices over the same piece of land resulted in the formation of hard pan below the surface of soil (Flower and Lal, 1998). This 'thick compacted layer' builds up in the root zone also as a consequence of poor tillage practices, primarily as a result of the farmer failing to vary the depth of ploughing over several years (Tursic *et al.*, 2008). The extent of the soil compaction problem is a function of soil type and water content, vehicle weight, speed, ground contact pressure and number of passes, and their interactions with cropping frequency and farming practices (Larson *et al.*, 1994; Chamen *et al.*, 2003). Soil degradation due to puddling also leads to development of subsurface compact layer. Compaction of soil affects nearly all soil properties and soil water-relations, which in turn affect the growth and productivity of plants. Compacted soils are characterized by high strength, high bulk density, and low hydraulic conductivity and air filled porosity (Soane and van Ouwerkerk 1994). Soil characteristics such as bulk density and mechanical impedance can be affected by tillage practices, and may markedly alter root growth and distribution (Russell, 1981). Soil with high strength impedes the growth, distribution, and function of roots. The magnitude of restriction to roots is closely related to the soil water content, because of the resulting increases in soil resistance due to decreasing soil moisture content (Gupta and Allmaras 1987; Raper 2005). With these restrictions, root systems develop superficially and, as a consequence, the roots exploit a smaller volume of soil and hence intercept a limited amount of water and nutrients. Reduced oxygen content in compacted surface soils, resulting in apart from reduced porosity and soil structure degradation, can in turn affect the transport, transformation (e.g., mineralization) and uptake of nutrients (Kemper *et al.*, 1971) and also restrict soil gas diffusion and water availability (Hansen *et al.*, 1993).

In the semi-arid tropical environment, as in Indian Punjab, erratic distribution of rainfall in time and space, and maize is mainly dependent on rainfall for its water requirement during summer. Maize growth is affected by rainfall characteristics especially during summer monsoon months. It has been observed under field conditions that most of high intensity storms arise in rainy season which cause damage to crop. Crop lodging took place due to combined effect of rainfall, wind storm also due to shallow root system of maize under subsurface compacted soils. It is proposed that if a slope is provides in maize field, lodging can be reduced and excess rainwater can be drained quickly from the field. In this field study, a broad approach to evaluate the integrated effects of subsurface compaction and slope steepness on crop growth, yield, yield attributes and soil physical properties of soil.

MATERIALS AND METHODS

Location and experimental design

The experimental site is located at 30º54′ N latitude and 75º48′ E longitude with an altitude of 247 m above the MSL (mean sea level), at Research Farm, Department of Soil Science, Punjab Agricultural University, Ludhiana, in the central plain region of Punjab. The site has semi-arid climate with very hot and dry summer from April to June, hot and humid conditions from July to September, cold winters from November to January and mild climate during February and March. The site receives 75 per cent of the average annual rainfall in the July to September months. The soil was classified as alluvial, sandy loam in texture, calcareous, Typic Haplustept. The soil N, P, K and soil organic carbon content of experimental site were lied in medium category. The physio-chemical properties of soils are given in Table-1.

A split-plot design was laid out in three blocks with three subsoil compaction levels (main plot treatments) and three levels of slope steepness (subplot treatment). The subsoil compaction treatments were given by removing the surface 15-cm soil and then compacting the sub-surface layer with passes of tractor mounted roller to achieve the desired bulk density. After achieving the desired bulk density, surface soil was put back on the place. The soil compaction treatments were C_0- Control (bulk density, Db= 1.55-1.65 g/cm^3), C_1- Moderate compaction, (Db= 1.70-1.75 g/cm^3) and C_2- High compaction (Db>1.80 g/cm^3) at 15-30 cm depth. The slope steepness treatments were: S_0- flat leveled field, S_1- 0.5% slope and S_2-1.0% slope. The standard Proctor test (American Society for Testing Materials, 2000) was employed to establish the maximum soil bulk density that is 1.86 Mg m^{-3}, at an optimal water content (i.e., water content at which maximum compaction occurs) of 0.12 cm^3 cm^{-3}.

Cultural Practices

The maize was sown (June 27 during 2012 and June 22 during 2013) with row to row spacing of 60 cm and plant to plant spacing of 20 cm. Phosphorus, potassium and zinc sulphate were applied @ 60, 30 and 25 kg ha^{-1}, respectively. Entire quantity of P, K and Zinc Sulphate along with one third of N (as Urea 46 % N) was applied at the time of sowing and remaining N was applied in two equal splits i.e. at knee high and at pre-tasselling stages. The recommended cultural practices as per "PAU Package of Practices for *kharif* crops" were followed to ensure proper weed, insect and pest control.

Plant Observations

The plant height (cm) was recorded as average from randomly selected five plants at 30 DAS, 60 DAS and at harvesting stage. All the ears from each net harvested plot were sun dried for three days and shelled. Moisture content of grains from each plot was determined. The grain yield was adjusted to 15 per cent moisture level and expressed in t ha^{-1}. The cob length (cm) and cob bareness (%) and plant lodging (%) were recorded at the time of threshing. Unfilled portion of cobs selected for length was measured with scale and noted as percentage barrenness of the cob. The grain yield and biomass was recorded after sun drying and threshing of produce. The harvest index (HI) was calculated as the ratio of maize grain yield (t ha^{-1}) to the total biological yield (t ha^{-1}).

Soil Measurement

Replicated undisturbed soil samples were collected from the field at the depth of 0-15, 15-30, 30-45, 45-60, 60-90 cm and determinations were made for bulk density and saturated hydraulic conductivity. Total porosity was calculated from value of bulk density (D_b) and particle density (D_p) by equation as TP= (1-D_b/D_p). Hydraulic conductivity was measured with constant head permeameter method (Klute and Dirkson, 1986) using Darcy's equation. *Insitu* infiltration rate was measured using double metallic ring infiltrometers (Bouwer, 1986). Water was filled in both inner and outer rings and the fall of water level in the inner ring was recorded at different time intervals upto a cumulative time of 360 minutes from the start. Cumulative infiltration was worked out for each treatment and infiltration rate was calculated and expressed in cm hr^{-1}. Soil samples from various depths were collected at the time of sowing and harvesting to determine for gravimetric soil moisture content. The moisture content was determined gravimetrically by drying soil samples in the oven at 105 °C till the constant weight was achieved and the difference in wet and dry weights of samples was expressed as soil moisture content on dry weight basis. Penetration resistance was measured using cone peneterometer and expressed as KPa.

Statistical Procedure

The analysis of variance (ANOVA) technique was employed using PROC GLM (SAS software 9.1, SAS institute Ltd., USA) as per the standard procedure given by Gomez and Gomez (1984) for split plot design. All mean comparisons were made using Duncan's multiple range test at p=0.05.

RESULTS AND DISCUSSION

Effect of Subsoil Compaction and Slope Steepness on Soil Physical Properties

The mean values of bulk density (D_b) are ranged from 1.49 to 1.61 Mg m^{-3} in 0-15 cm, 1.56 to 1.84 Mg m^{-3} in 15-30 cm, 1.51 to 1.74 Mg m^{-3} in 30-45 cm soil depth during the year the 2012 and 2013 (Table-2). The D_b of surface 0-15 cm soil layer was not significantly different among various treatments during the year the 2012 and 2013. However the D_b for 15-30 cm subsoil layer was significantly higher under C_2 treatment than that in C_0 and C_1 treatment during the year 2012 and 2013. The higher D_b under C_2 treatment was attributed to treatment effect, however slope steepness did not significantly affected the D_b during the period of study. The D_b of 30-45 cm subsoil layer followed almost similar trend as that of 15-30 cm subsoil layer, except the D_b under this layer was less than that in layer above.

The Penetration resistance (PR) of surface soil was less and it increased with depth (Table-2). The PR of C_2 treatment at 15-30 cm subsoil layer was significantly higher than that in C_0 and C_1 treatment, which reached to critical limit (ICPA, 1987) that negatively affected the root growth. The PR values averaged over 2 years at 30-45 cm soil depth were statistically different among themselves. The PR was higher under C_2 treatment than that in C_0 and C_1 treatment. The PR values were higher at 15-30 cm soil depth were higher than that in 0-15 cm surface layer. Kozicz (1996) also reported twice greater PR in subsoil layer than that in plough layer. Becher (2000) and Munkholm *et al.,* (2002) also observed higher soil strength under compacted zones due to cultivation.

The porosity was higher under lower D_b than that in higher D_b soil. The total porosity followed the similar trend as that of bulk density at all the soil depths, since it was calculated for D_b values (Table-3). Porosity was higher under C_0 treatment than that in C_1 and C_2 treatment at all depths during the year 2012 and 2013. The porosity values were significantly higher under C_0 treatment than that in C_1 and C_2 treatments at 15-30 cm and 30-45 cm soil depth.

The cumulative infiltration decreased with the increase in the subsoil bulk density (Fig 1 & 2). After 360 minutes of initiation of infiltration, cumulative infiltration was 25.10, 17.60 and 12.50 cm in C_0, C_1 and C_2 treatment, respectively during the year 2012, while it was 25.50, 18.80 and 11.30 cm in C_0, C_1 and C_2 treatment respectively during the year 2012 (Figure 1 & 2).

The infiltration rate also decreased with increase in the subsoil compaction level. After 360 minutes, infiltration rate was 4.18, 2.93 and 2.08 cm hr^{-1} C_0, C_1 and C_2 treatment respectively during the year 2012 and 4.25, 3.13 and 1.88 cm hr^{-1} C_0, C_1 and C_2 treatment respectively during the year 2013. There was 2.01 times and 2.26 times decrease in infiltration rate under C_2 than that in C_0 treatment during the year 2012 and 2013, respectively. The decrease in infiltration rate and cumulative infiltration had been resulted from decreased total porosity under higher level of subsoil compaction and entrapment of soil.

Effect of Subsoil Compaction and Slope Steepness on Plant Height

A significant effect of soil compaction was observed on plant height of maize (Table-4). Plant height decreased significantly with the increase in the soil strength of subsoil layer at 30, 60 DAS (days after sowing) and at harvesting stage.

Maximum plant height (260.7 and 245.8 cm) was recorded at harvesting in plots with no subsoil compaction against minimum (239.9 and 214.3 cm) with higher subsoil compaction during the year 2012 and 2013 respectively.

The C_2 treatment resulted in reduced plant height by 13.29 and 7.48 per cent at 30 DAS, 8.4 and 4.4 per cent at 60 DAS and 7.9 and 12.6 per cent at harvesting than that in C_0 treatment during the year 2012 and 2013 respectively.

The reduced plant height in response to subsoil compaction may be attributed to restricted root growth under higher subsoil strength. Slope steepness had not significantly affected the plant height at 30, 60 DAS and at harvesting stage.

Effect of Subsoil Compaction and Slope Steepness on Yield

Subsoil compaction significantly affected the grain yield of maize during the years 2012 and 2013 (Table-5). The grain yield was higher under C_0 treatment than that in C_1 and C_2 treatments. Higher subsoil compaction level C_1 and C_2 resulted in yield reduction of 15.8 and 19.8 per cent, respectively than that in C_0 treatment during the year 2012.

The yield reduction of 5.6 and 17.2 per cent was recorded in C_1 and C_2 treatment respectively than that in C_0 treatment during the year 2013, although this difference was statistically non-significant. The yield reduction of maize due to subsoil compaction was reported by Gaultney *et al.*, (1980) and Canarache *et al.*, (1984). Siemens and Peterson (1997) reported an average yield reduction of 13 per cent due to compaction resulting from vehicular traffic.

The maize yield reductions under higher degree of subsoil compaction might be attributed to restricted root growth, limited oxygen and nutrient supply (Allmaras *et al*., 1988). Schuler and Lowery (1986) reported corn yield decreased up to 40%, partially due to subsoil compaction on silty clay soil.

Slope steepness treatment S_2 had improved maize yield by 10.2 per cent than that in S_o treatment, during year 2012.

While, non-significant affect of slope steepness was observed in the year 2013. The improvement in yield might be due to lesser water stagnation in the field after rainstorm and lesser plant lodging (Table-6) under higher slope steepness than that on flat land surface.

Biological yield of maize was significantly higher under C_0 than that in C_1 and C_2. The biological yield from treatments C_1 and C_2 were statistically at par among themselves during the year 2012 and 2013. The higher biological yield under C_0 treatment might be attributed to taller plants.

Unger and Kaspar (1994) also reported reduced plant growth, grain yield and biological yield as a result of compaction due to its effect on water infiltration, aeration and disease pressure. Slope steepness had significantly improved the biological yield of maize.

Biological yield was significantly higher under higher slope steepness that than in flat surface treatment. The better crop growth and lesser lodging could be the probable reason for this yield improvement.

Harvest index of maize was not significantly affected by the subsoil compaction and slope steepness during both the years (Table-5). However, slope steepness had shown significant negative effect on the harvest index of maize.

Table 1: Soil physico-chemical properties of experimental site

Parameter	Value
Sand (%)	64.8
Silt (%)	18.9
Clay (%)	16.3
Bulk density, (Mg m^{-3})	
0-15 cm depth	1.49
15-30 cm depth	1.67
pH	7.63
E C (dS m^{-1})	0.51
Plant available water (cm/180 cm profile)	21.8
Saturated Hydraulic conductivity (cm hr^{-1})	
0-15 cm depth	5.87
15-30 cm depth	1.95

The cob length was 14.1 and 9.4 per cent higher under C_0 treatment than that in C_2 treatment during the year 2012 and 2013 respectively (Table-6). However slope steepness showed non-significant affect on the cob length of maize during both the years.

Table 2: Bulk density and Penetration resistance as affected by subsoil compaction (average of 2 years). Different letters in each column of experimental factors show significant differences at 0.05 probability level

Treatment	Bulk Density (Mg m^{-3})			Penetration resistance (KPa)		
	Soil depth			Soil depth		
	0-15 cm	15-30 cm	30-45 cm	10 cm	22 cm	45 cm
C_0	1.57a	1.601c	1.523c	1008.7a	1889.8c	1588.6b
C_1	1.55a	1.732b	1.648b	993.7a	2098.1b	1640.7b
C_2	1.56a	1.824a	1.727a	1043.3a	2562.2a	1852.8a
P-value subsoil compaction	0.76	<0.0001	<0.0001	0.15	<0.0001	0.0005
S_0	1.56a	1.70a	1.591b	1037.3a	2165.0a	1683.1a
S_1	1.55a	1.72a	1.63ab	985.8a	2146.9a	1678.3a
S_2	1.57a	1.73a	1.64a	1022.7a	2238.2a	1720.7a
P-value Slope steepness	0.66	0.14	0.06	0.13	0.21	0.66
P-value C X S	0.18	0.43	0.53	0.17	0.23	0.30

Table 3: Total porosity (v/v) as affected by subsoil compaction (average of 2 years). Different letters in each column of experimental factors show significant differences at 0.05 probability level

Treatments	Soil Depth		
	0-15 cm	**15-30 cm**	**30-45 cm**
C_0	0.410a	0.379a	0.398a
C_1	0.407a	0.341b	0.368b
C_2	0.409a	0.308c	0.337c
P-value subsoil compaction	0.15	<0.0001	<0.0001
S_0	0.413a	0.356a	0.370a
S_1	0.410a	0.332ab	0.366a
S_2	0.403a	0.341a	0.365a
P-value Slope steepness	0.13	0.07	0.69
P-value C X S	0.17	0.20	0.73

Table 4: Plant height (cm) of maize under different subsoil compaction and slope steepness treatments. Different letters in each column of experimental factors show significant differences at 0.05 probability level

	30 DAS		60 DAS		At harvesting	
Treatments	**2012**	**2013**	**2012**	**2013**	**2012**	**2013**
C_0	65.73a	54.89a	223.44a	218.56a	260.73a	245.81a
C_1	61.09b	50.56a	210.00ab	217.67a	253.00a	230.36b
C_2	56.99b	50.78a	203.78b	208.78a	239.99b	214.32c
P-value subsoil compaction	0.003	0.20	0.04	0.27	0.004	<0.0001
S_0	59.73a	51.22a	205.44a	207.89b	253.23a	225.04a
S_1	61.38a	54.67a	217.00a	214.22ab	250.18a	233.03a
S_2	62.71a	50.33a	214.78a	222.89a	250.31a	232.42a
P-value slope	0.36	0.24	0.26	0.09	0.79	0.16
P-value C X S	0.97	0.20	0.56	0.23	0.11	0.64

Table 5: Grain yield, biological yield and Harvest Index of maize under different subsoil compaction and slope steepness treatments. Different letters in each column of experimental factors show significant differences at 0.05 probability level

Treatments	**Grain yield (t/ha)**		**Biological yield (t/ha)**		**Harvest Index**	
	2012	**2013**	**2012**	**2013**	**2012**	**2013**
Subsoil compaction levels						
C_0	5.98a	4.86a	18.71a	15.30a	0.30a	0.32a
C_1	5.03b	4.59ab	16.00b	13.13b	0.31a	0.35a
C_2	4.79b	4.02b	14.65b	12.82b	0.34a	0.31a
P-value subsoil compaction	0.0003	0.06	0.001	0.001	0.35	0.19
S_0	5.08b	4.52a	15.39b	12.32b	0.32a	0.37a
S_1	5.12b	4.26a	15.87b	13.42b	0.33a	0.31b
S_2	5.60a	4.69a	18.09a	15.11a	0.30a	0.30b
P-value slope	0.056	0.43	0.01	0.0003	0.11	0.038
P-value C X S	0.14	0.65	0.37	0.62	0.47	0.78

Table 6: Growth and yield attributing characters of maize under different subsoil compaction and slope steepness treatments. Different letters in each column of experimental factors show significant differences at 0.05 probability level

	Cob length (cm)		**Cob barrenness (%)**		**Lodging (%)**	
Treatments	**2012**	**2013**	**2012**	**2013**	**2012**	**2013**
Subsoil compaction levels						
C_0	17.01a	18.07a	11.39a	9.46b	7.24c	9.10c
C_1	15.77ab	17.06ab	12.51a	10.95ab	8.90b	10.76b
C_2	14.61b	16.36b	13.24a	14.25a	10.4a	13.39a
P-value subsoil compaction	0.004	0.03	0.29	0.042	<0.0001	<0.0001
S_0	15.90a	17.45a	11.49a	12.19a	10.22a	12.70a
S_1	15.73a	17.24a	13.21a	11.82a	9.19b	11.62a
S_2	15.77a	16.80a	12.44a	10.65a	7.55c	9.01b
P-value slope	0.95	0.52	0.34	0.64	<0.0001	0.0003
P-value C X S	0.96	0.20	0.76	0.057	0.065	0.167

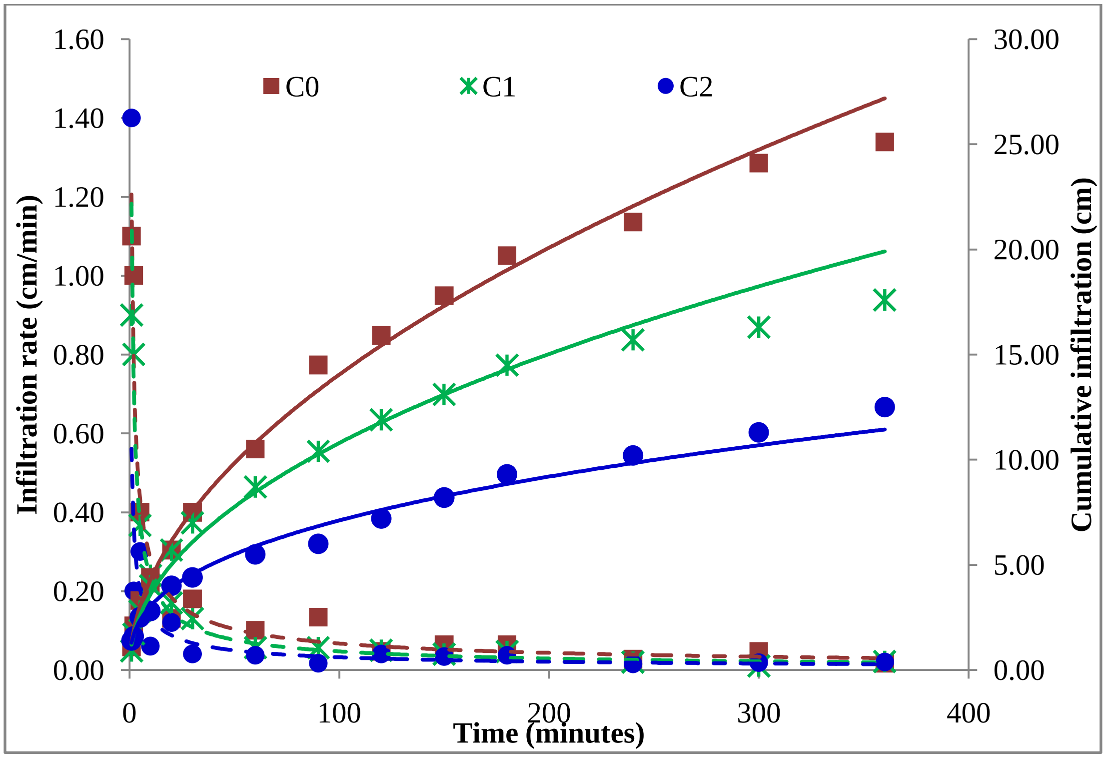

Figure 1: Cumulative infiltration (straight line) and infiltration rate (dotted) as influenced by subsoil compaction during the year 2012.

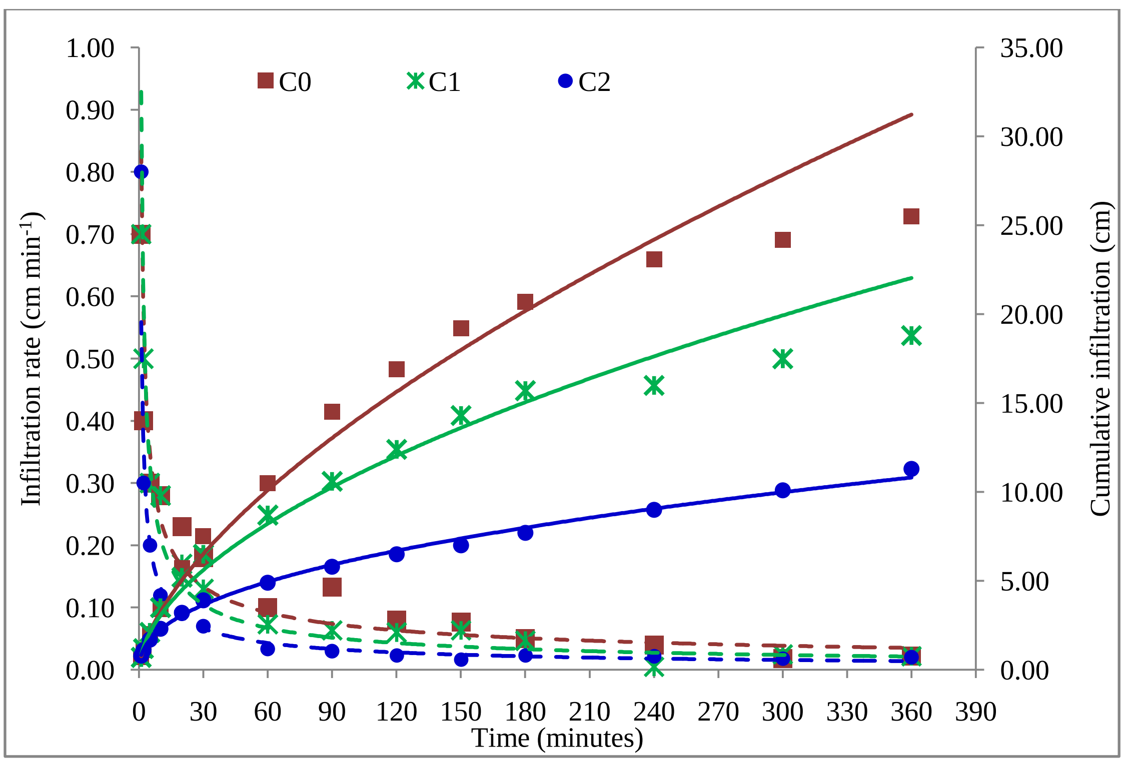

Figure 2: Cumulative infiltration (straight line) and infiltration rate (dotted) as influenced by subsoil compaction during the year 2013.

Subsoil compaction and slope steepness significantly affected cob barrenness. The barrenness was 13.97 and 33.6 per cent higher under C_2 treatment than that in C_0 treatment during the year 2012 and 2013, respectively (Table-6). Cob barrenness was 16.24 and 50.6 per cent higher under C_2 treatment over C_1 treatment during the year 2012 and 2013, respectively. The higher barrenness under C_2 treatment might be attributed to poor dry matter accumulation and translocation of photosynthetes. The cob barrenness was lower by 14.4 per cent in S_2 than that in S_0 during the year 2013. The reduced cob barrenness was attributed to the higher vegetative growth, dry matter accumulation and its role in reproductive functioning of plant.

Conclusion

The increased usage of heavy machinery for field cultivation had resulted in the formation of compacted layer just below the plough layer. This layer found to reduce the water infiltration rate as a result water stagnation over the surface posing a risk of crop lodging due to increase in risk of soil erosion during monsoon season, that receive rainstorms with high intensity. Thus the present study was initiated to access the effect of subsoil compaction and slope steepness on the growth, yield and yield attributes of maize and on the physical properties of the soil. The subsoil compact layer exhibited higher soil strength that resulted in higher bulk density, higher penetration resistance, lower total porosity and lower cumulative infiltration and infiltration rate. Thus the compacted subsoil layer negatively affected the soil plant water relations than that in uncompacted subsoil. A significant grain and biological yield reduction in response to the higher level of subsoil compaction was observed. The slope steepness helped in the safe drainage of excess water during monsoon season. It further helps in significantly reducing the crop lodging even under higher degree of subsoil compactness. The present study will help in fine tuning the existing technology for enhancing crop production under adverse environmental conditions.

REFERENCES

American Society for Testing Materials (ASTM) (2000). Standard test methods for laboratory compaction characteristics of soil using standard effort (600 kN-m m^{-3}), Designation D 698-00a. ASTM, West Conshohocken, PA.

Canarache A, Trandafirescu T, Colibas I, Colibas M, Horobeanu I, Patru V and Simota H (1984). Effect of induced compaction by wheel traffic on soil physical properties and yield of maize in Romania. *Soil Tillage Research* **4** 199-213.

Chamen T, Alakukku L, Pires S, Sommer C, Spoor G, Tijink F and Weisskoff P (2003). Prevention strategies for field traffic induced subsoil compaction: a review, Part 2. Equipment and field practices, *Soil Tillage Research* **73** 161–74.

Flowers M and Lal R (1998). Axle load and tillage effect on soil physical properties and soybean grain yield on a mollic ochraqualf in Northwest Ohio. *Soil Tillage Research* **48** 21-35.

Gaultney L, Krutz GW, Steinhardt GC and Liljedahl (1980). Field and laboratory tests to determine effects of subsoil compaction on corn yield. *ASAE* paper no 80-1011, ASAE St. Joseph, MI, USA.

Gomez KA and Gomez AA (1984). *Statistical Procedures for Agricultural Research* (John wiley and sons, Inc) U K.

Gupta SC and Allmaras RR (1987). Models to assess the susceptibility of soils to excessive compaction. *Advances Soil Science* **6** 65-100.

Hansen S, Mzhlum JE and Bakken LR (1993). N_2O and CH_4 fluxes in soil influenced by fertilization and tractor traffic. *Soil Biology and Biochemistry* **25** 621-30**.**

Kemper WD, Stewart BA and Porter LK (1971). Effects of compaction on soil nutrient status. In: *Compaction in Agricultural Soils*, edited by Barnes KK, Charleton WM, Taylor HM, Throckmorton RI and Vanden GE (Berg.) *American Society of Agricultural and Biological Engineers*, St. Joseph, Michigan 178-189.

Klute A and Dirksen C (1986). Saturated hydraulic conductivity and diffusivity; laboratory methods. In 'Methods of soil analysis, Part 1 *Physical and Mineralogical Methods* edited by Klute A, (American Society of Agronomy-Soil Science Society of America: Madison, WI) 687- 732.

Larson WE, Gupta SC, and Useche RA (1980). Compression of agricultural soils from eight soil orders. *Soil Science Society America Journal* **44** 450–57.

Raper RL (2005). Agricultural traffic impacts on soil. *Journal of Terramechanics* **42** 259-280.

Russell RS (1981). Root growth in relation to maximizing yields. In: "*Agricultural Yield Potentials in Continental Climates"*. *Proceedings of Colloquium International Potash Institute, l6th, Poland. 1981*. Warsaw International Potash Institute, Bern, Switzerland 23-47.

Schuler RT and Lowery B (1986). Long term compaction effects on soil and plant growth. ASAE Paper 86-1048. *American Society of Agricultural and Biological Engineers*, St. Joseph, MI.

Soane BD and Van Ouwerkerk C (1994). Soil compaction problems in world agriculture. *In*: *Soil Compaction in Crop Production*, edited by Soane BD and Van Ouwerkerk C (Elsevier) Amsterdam 1-22.

Tursic I, Husnjak S and Zalac Z (2008). Soil compaction as one of the causes of lower tobacco yields in the republic of Croatia. *Cereal Research Communication* **36** 687-90.