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Effect of Compaction and Irrigation Regimes on Soil Physical Characteristics, Emergence, Growth and Productivity of Summer Moongbean

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ABSTRACT

Background: Soil compaction adversely affects mechanical and water transmission characteristics, thus hampering crop growth and productivity. However, under coarse-textured soils, compaction to a certain extent is beneficial concerning restricting water transmission, increasing water retention and improving productivity. The present study was aimed to investigate the effect of compaction and irrigation on soil physical characteristics and productivity of summer moongbean.

Methods: A field study was conducted on summer moongbean for two years in loamy sand soil at Punjab Agricultural University, Ludhiana, India. The treatments comprised three compaction levels *i.e.* no roller pass (C_0), one roller pass (C_1) and three roller pass (C_3) in main plots and in subplots three irrigation regimes ($I_{0.4}$, $I_{0.6}$ and $I_{0.8}$) with three replicates. Observations included soil bulk density and infiltration rate; seed emergence count, growth traits, yield and yield attributes.

Result: Soil bulk density of 5-10 cm depth increased from 1.53 at C_0 to 1.62 Mg m^{-3} at C_3. However, infiltration rate of water in soil decreased to 38% with an increase in compaction level from C_0 to C_3. Seed emergence count was deleteriously affected with increasing compaction level but at 15 DAS, it increased by 33 and 42% at C_1 and C_3 levels under $I_{0.8}$ regime as compared to $I_{0.4}$. Plant height was also minimal at C_3 irrespective of irrigation regimes. Compaction reduced the root length density in the surface layers but it increased in the sub-surface layers. Grain and straw yield increased by 15 and 13%, respectively in C_1 over C_3. An increase in irrigation regimes from $I_{0.4}$ to $I_{0.8}$, increased the mean straw and grain yield from 5.10 to 6.10 t ha^{-1} and 1.13 to 1.32 t ha^{-1} respectively. However, the irrigation water productivity decreased with an increase in irrigation frequency. These result suggest that compaction up to one roller pass with $I_{0.8}$ irrigation regime can be beneficial for enhancing grain yield of summer moongbean in loamy sand soil.

Key words: Compaction, Irrigation, Moongbean, Root length density, Water productivity.

INTRODUCTION

The unfavorable effects of compaction on soil health and crop productivity are much greater today than in the past because of immense increase in use of heavy farm equipments. Excessive use of heavy implements can cause deterioration of soil physical environment and structure. Soil compaction results in increased bulk density and penetration resistance and reduced infiltration. Mada *et al.* (2013) observed that compaction slowed down the rate of seed germination as it did not allow proper contact between seed and soil. Further it impeded the root growth, thus affecting the plant's ability to take up nutrients and water from subsurface soil (Bengough *et al.* 2006). Soil compaction reduces the crop growth and yield, by restricting root development as well as water and air movement in the soil (Alameda and Villar, 2009). Aase *et al.* (2001) reported that as cone index approaches 2.0 M Pa and moves above this value, root growth is restricted to varying degrees. Soil compaction can have adverse effect upon crops by increasing the mechanical impedance to the growth of roots; altering the extent and configuration of the pore space (Becerra *et al.* 2011; Chen and Weil, 2011; Li *et al.* 2012). Summer moongbean (*Vigna radiata* L.), cultivated in Punjab during mid-March to end June has a good potential under irrigated conditions due to high evapotranspiration rates and scarce water supply in this period. However, its growing season particularly the reproductive phase coincides with the harsh weather conditions and warrant attention for high yield realization. First irrigation at 15 days after sowing (DAS) and subsequent irrigation at weekly intervals recorded the highest plant height, plant dry matter, yield attributing characters and grain yield (Aulakh and Vashist, 2007). Yadav and Singh (2014) reported highest grain yield along with other growth attributes under more frequently irrigated water regimes. Furthermore, irrigation may reduce the impact of soil compaction (Vaz *et al.* 2013) as irrigation affects the pore structure of soil and water infiltration capacity by manipulation of hydraulic stresses (Peng *et al*. 2007).

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Therefore, it is required to specify optimum irrigation regime and its effect on compaction levels for achieving maximum productivity. Thus, the aim of the current investigation was to study the impact of soil compaction and different irrigation regimes on soil physical characteristics and growth and productivity of summer moongbean in loamy sand soil.

MATERIALS AND METHODS

Experimental Site and Treatments

A field experiment was conducted at the Research farm of the Department of Soil Science, Punjab Agricultural University, Ludhiana, India (30°54′N, 75°48′E, 247 m above mean sea level) in 2017 and 2018 summer cropping seasons. The soil at experimental site was neutral, non-calcareous in nature and alluvial loamy sand in texture (*Typic ustochrept*) developed under hyper-thermic regime. Important soil physical and chemical characteristics are presented in Table 1. The groundwater level was more than 20 m deep. Weather information during the cropping seasons is given in Table 2. Total rainfall during the cropping seasons of 2017 and 2018 was 214.2 and 170.8 mm; while corresponding cumulative pan evaporation was 867.4 and 622.3 mm. Pan evaporation during both the cropping seasons was lower than the normal values; contrary to this rainfall was more. The actual rainfall during cropping duration in 2017 and 2018 was 118 mm and 145 mm. Mean maximum and minimum air temperatures during different growing seasons varied between 27.2-39.1°C and 12.-26.6°C.

Combinations of compaction levels and irrigation regimes were evaluated in a split-plot design with compaction in the main plot: three compaction levels *i.e.* zero (C_0), one (C_1) and three (C_3) roller passes and in the sub plots three irrigation regimes *i.e.* irrigation water (IW) to pan evaporation (E_p) ratios of 0.4 ($I_{0.4}$), 0.6 ($I_{0.6}$) and 0.8 ($I_{0.8}$) with three replications. The main plot size was 120 m^2 and sub plot size was 35.7 m^2. In no compaction plot, the sowing was done after seed bed preparations. While in single and three roller passes the crop was sown after seed bed preparations, thereafter different levels of compaction were accomplished with roller having weight 1000 kg; width 1.2 m and circumference 1.6 m. The cultivar SML-866 was sown in the last week of March @ 25 kg ha^{-1} with heavy pre-sowing irrigation for both the years. The seed was placed at 6 cm deep with a row spacing of 22.5 cm and plant spacing of 7 cm. Before seeding, the seed was treated with fungicide Captan @ 3 g kg^{-1} seed. The seed was inoculated with freshly prepared Rhizobium culture at the time of sowing. Nitrogen @ 12.5 kg ha^{-1} and phosphorous (P_2O_5) @ 40 kg ha^{-1} were applied through urea and single super phosphate, respectively as a basal dose. For both the years the number of post sowing irrigations (70 mm each measured with Parshall flume) applied in $I_{0.4}$, $I_{0.6}$ and $I_{0.8}$ regimes were three, four and five, thus, the amount of irrigation water applied was 210 mm, 280 mm and 350 mm, respectively. The crop was harvested in the last week of June.

Measurements

Undisturbed soil bulk density (ρ_b) was measured with the help of core having diameter and height of 5.0 cm at 0-5, 5-10, 10-15 and 15-20 cm depths with three replications at the time of harvest. The cores were dried in an oven at 105°C till the weight of the soil becomes constant. Soil bulk density

Table 1: Soil characteristics of experimental site.

Depth (cm)	pH	EC (dS m^{-1})	OC (%)	Sand (%)	Silt (%)	Clay (%)	FC (θ, %)	PWP (θ, %)
0-15	7.9	0.21	0.32	79.6	12.6	7.5	16.2	7.8
15-30	7.6	0.19	0.30	78.7	13..2	7.8	17.4	8.2
30-45	7.5	0.18	0.21	79.1	12.7	8.0	17.8	8.9
45-60	7.5	0.17	0.11	78.8	12.9	8.3	18.2	9.3
60-75	7.5	0.17	0.08	77.2	13.1	9.2	18.6	9.6
75-90	7.4	0.16	0.06	76.3	13.5	9.7	18.8	10.3

Table 2: Climatic data of the crop growing period.

Month	2017				2018				Normal value*			
	Max temp (°C)	Min temp. (°C)	Evaporation (mm)	Rain-fall (mm)	Max. temp. (°C)	Min. temp. (°C)	Evaporation (mm)	Rain-fall (mm)	Max temp. (°C)	Min temp. (°C)	Evaporation (mm)	Rain-fall (mm)
March	27.2	12.3	123.5	40.8	29.3	13.1	129.5	0.0	26.7	12.0	118.5	23.6
April	36.9	20.0	239.6	14.8	35.8	19.9	218.3	10.0	34.6	17.4	211.4	17.7
May	28.8	23.6	284.9	31.6	39.1	24.1	139.6	19.0	38.7	22.7	310.4	23.2
June	36.7	26.2	219.4	127.0	34.3	26.6	134.9	141.8	38.1	25.9	289.7	84.2
Total	-	-	867.4	214.2	-	-	622.3	170.8	-	-	930.0	148.7

*Normal values are average of 40 years.

(ρ_b, Mg m^{-3}) was calculated as the ratio of dry soil mass (M_s) and internal volume (V_t) of the core (Blake and Hartge, 1986).

$$\rho b = \frac{M_s}{V_t}$$

In-situ infiltration rate was measured by double-ring infiltrometer according to method described by Reynolds *et al.* (2002) at the time of harvest.

Seed emergence count (No. m^{-2}) was recorded at 5, 10, 15 and 20 days after sowing (DAS) in each plot. At harvest, five plants were selected randomly from each plot for recording plant height, number of pods $plant^{-1}$ and number of seeds pod^{-1}. From each plot weight of one thousand seeds was recorded and expressed as 1000-seed weight (g). The seed yield of each plot was recorded from the net area of 4 m^2 and expressed as t ha^{-1}. The straw yield was calculated by subtracting the seed yield from biological yield for each plot, recorded before the threshing of the crop, and expressed as t ha^{-1}. The irrigation water productivity was calculated by dividing the seed yield of corresponding treatment with the amount of irrigation water applied (mm) in particular treatment.

Soil cores for determining root growth were sampled at 55 DAS at 10 cm depth increments down to 70 cm soil depth with 5 cm diameter auger centred at 4 cm away from plant base (Gajri *et al.*1994). Roots from each sample were washed in net cloth, cleaned and length of roots was measured by a scanner (CI 202 model of CID Bio Science make USA). The root length density (RLD, cm cm^{-3}) was calculated from the total length of roots to internal volume of the core.

Treatment effects on various parameters were tested for their statistical significance using ANOVA for a split-plot design as prescribed by Cochran and Cox (1967) and adapted by Cheema and Singh (1991) in statistical package CPCS-I. The treatment mean comparisons were made at 5 percent level of significance. Standard deviations were computed for soil bulk density.

RESULTS AND DISCUSSION

Bulk density and infiltration rate

Among mechanical characteristics soil bulk density is mainly affected by compaction. The data regarding compaction effect on soil bulk density is presented in Fig 1. It revealed that with increase in compaction the soil bulk density increased. In 2017, for surface soil (0-5 cm) it varied from 1.50 at C_0 to 1.56 Mg m^{-3} at C_3. Similarly, at 5-10 cm depth it increased from 1.53 to 1.62 Mg m^{-3}. Similar trend was observed in 2018, bulk density increased by 4.6% for 0-5 cm and 6.5% for 5-10 cm at C_3 than C_0. Below this depth the difference in bulk density diminished due to soil compaction and it remained almost unchanged at 15-20 cm. Blanco-Canqui *et al.* (2004) also reported that wheel traffic increased bulk density by 6 per cent. Compaction increases bulk density by disrupting soil aggregates or by compression of soil aggregates forming restrictive layer and thus decreases soil volume (Badalıkova and Hruby, 2006).

The effect of compaction on infiltration rate of soil is presented in Fig 2. It decreased from 2.4 cm hr^{-1} at C_0 to 1.6 cm hr^{-1} at C_3 compaction level in 2017. Likewise in 2018, compaction affected infiltration rate with a decrease from

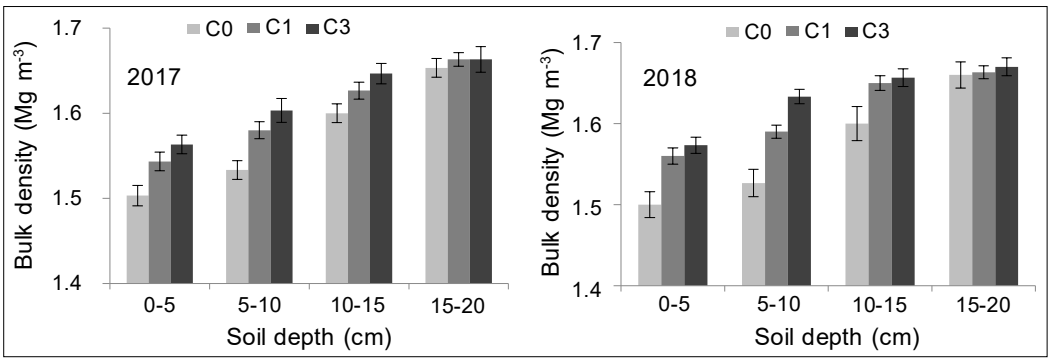

Fig 1: Effect of soil compaction on soil bulk density at harvest (Vertical bars represent standard deviation).

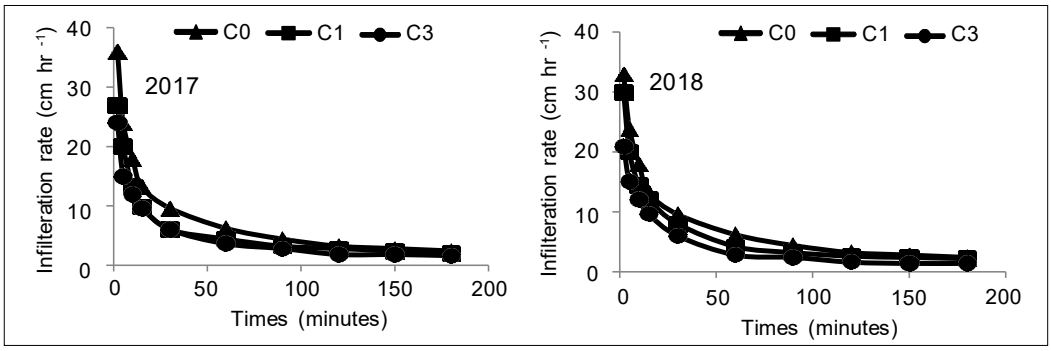

Fig 2: Effect of soil compaction on infiltration rate of soil at harvest.

2.4 cm hr^{-1} at C_0 to 1.6 cm hr^{-1} at C_3. Compaction of soil aggregates causes reduction in the pore space being occupied by water and air. In addition to pore space, pore size is also reduced which consequences in restricted water and air movement, thus affecting the hydraulic properties of soil (Vidinamo *et al.* 2010). Abo-Abda and Hussain (1990) also reported 30% reduction in infiltration of sandy soil due to compaction.

Emergence count

Uniform emergence of seed is a pre-requisite for attaining higher crop yields. The data on emergence count m^{-2} for 2017 and 2018 is presented in Table 3. Soil compaction had a significant effect on the seed emergence count of summer moongbean during both the years. In 2017, the emergence count was reduced by 84, 45.7, 18.7 and 17.7% at 5, 10, 15 and 20 DAS respectively. In 2018 also, compaction caused a reduction of 38.2-19.4% in emergence count from 5 to 20 DAS. On an average, maximum reduction was observed at 5 DAS, when emergence count of 22.4 m^{-2} in non-compacted plots (C_0) which was lowered by about 57% with compaction (C_3). On the other hand, irrigation had non-significant effect on emergence count till 10 DAS but at 15 DAS, a significant effect irrespective of the compaction was observed during both the cropping seasons; the corresponding increase in seedling count was 18.7 and 24.7% in $I_{0.8}$ as compared to $I_{0.4}$ due to irrigation water input in former regime. Compaction reduces porosity by moving soil particles close together, restrains air-water movement through soil and decreases water holding capacity of soils (Motavalli *et al.,* 2003) and amount of oxygen content required for energy metabolism during the process of germination (Masaka and Khumbula 2007), resulting in negative impact on the emergence count. The interactive effect of compaction and irrigation was observed in 2018 and average of two years. Irrigation regime $I_{0.8}$ might have provided the sufficient moisture to the seeds, thus resulting in significant increase in emergence count by 33.1 and 42% over $I_{0.4}$, at C_1 and C_3 compaction levels, respectively whereas at C_0, emergence count was at par in all the irrigation regimes.

Plant height

Plant height is an index of growth and development, representing the infrastructure build-up by the plant over some time. The data pertaining to plant height presented in Table 4 reveals reduction in plant height with an increase in soil compaction level during both years. Irrespective of irrigation regimes, plant height reduced significantly by 17.6 and 18.4% at C_3 than C_0 during 2017 and 2018 respectively. Amongst irrigation regimes, maximum plant height was observed in $I_{0.8}$ regime *i.e.* 47.6 and 46.4 cm in 2017 and 2018, respectively, while, the corresponding values for $I_{0.4}$ irrigation regime were 39.1 and 38.1 cm. Yadav and Singh (2014) observed an increase in plant height with an increase in the frequency of irrigations. Kirnak *et al.* (2016) also observed similar trend of decreasing plant height with increase in compaction level from low to high. Reduction in air filled porosity by compaction affects the oxygen content and may cause anaerobic conditions in soil. In addition, intermittent aerobic and anaerobic conditions during and between irrigation events in compacted soils may lead to enhancement of denitrification process or loss of nitrogen. Thus, impeded nitrogen content in soil along with reduced ability of roots to take up nutrients can be attributed to reduced plant height in compacted soils.

Yield attributing traits

The data pertaining to yield attributing traits *viz.* number of pods $plant^{-1}$, number of seeds pod^{-1} and 1000-seed weight is presented in Table 4. Considering the main factor compaction levels, number of pods $plant^{-1}$ was maximum at C_1 (27.4 and 24.9) followed by C_0 (22.3 and 20.3) and C_3 (17.1 and 16.2) during both the years respectively. While considering irrigation levels, number of pods $plant^{-1}$ increased significantly with increase in frequency of irrigations from 19.8 ($I_{0.4}$) to 24.9 ($I_{0.8}$) in 2017 and from 17.2 ($I_{0.4}$) to 23.1 ($I_{0.8}$) in 2018. The number of seeds pod^{-1}, is considered an important factor as it deals with the potential yield recovery in leguminous crops. The highest number of seeds pod^{-1} *i.e.*, 10.2 and 9.1 was observed in C_1 compaction level during 2017 and 2018 respectively. However, corresponding values recorded at C_0 (9.1 and 8.3) and C_3 (8.6 and 7.9) compaction level were at par but significantly lower than C_1. The number of seeds pod^{-1} was highest in $I_{0.8}$ regime (9.9 and 9.3), which was statistically at par with irrigation schedule $I_{0.6}$ regime (9.1 and 8.8) but, was significantly higher than $I_{0.4}$ irrigation regime (8.9 and 7.2) in 2017 and 2018, respectively. Similar pattern was observed for 1000-seed weight with significantly higher values (41.9 and 40.4 g) observed under C_1 compaction level as compared to C_0 (39.5 and 36.2 g) and C_3 (38 and 35.1 g) compaction levels during both the cropping seasons. 1000-seed weight was 8.1 and 14% higher in the respective crop seasons, when irrigated with $I_{0.8}$ regime as compared to $I_{0.4}$. The positive response of yield attributing traits to one roller pass (C_1) can be attributed to the effect of compaction on water holding capacity of sandy loam soils. Also, higher number of pods under $I_{0.8}$ might be due to better moisture regime, while in $I_{0.6}$ and $I_{0.4}$, moisture stress conditions might have led to flower drop, thus reducing the number of pods. Our results are in corroboration with the findings of Yadav and Singh (2014) who also reported an increase in the number of pods per plant with an increase in a number of irrigations.

Root length density

The data depicting the effect of compaction levels on root length density is presented in Fig 3. It reveals that with increase in soil compaction level though the root length density decreased at the surface layer, it increased at subsurface soil layers. In no compaction plots, maximum root length density 1.35 and 1.31 cm cm^{-3} was recorded in the surface soil layer which decreased to 1.12 and 1.16 cm cm^{-3}

Table 3: Effect of soil compaction and irrigation regimes on seed emergence count m^{-2} in summer moongbean.

Irrigation regimes	Compaction level															
	C_0	C_1	C_3	Mean	C_0	C_1	C_3	Mean	C_0	C_1	C_3	Mean	C_0	C_1	C_3	Mean
	5 DAS				10 DAS				15 DAS				20 DAS			
								2017								
$I_{0.4}$	22.3	17.3	11.7	17.1	35.7	29.0	25.0	29.9	44.0	38.3	34.3	38.9	44.7	39.0	34.3	39.3
$I_{0.6}$	20.7	15.7	12.0	16.1	37.3	31.3	26.0	31.6	43.0	37.0	36.3	38.8	46.7	41.7	41.0	43.1
$I_{0.8}$	24.0	17.0	12.7	17.9	36.0	30.3	23.7	30.0	48.0	45.7	43.0	45.6	48.0	45.7	43.0	45.6
Mean	22.3	16.7	12.1		36.3	30.2	24.9		45.0	40.3	37.9		46.4	42.1	39.4	
LSD (< 0.05)	C= 1.33; I= NS; C×I= NS				C= 1.26; I= NS; C×I= NS				C= 4.94; I= 2.76; C×I= NS				C= 4.59; I= 2.62; C×I= NS			
								2018								
$I_{0.4}$	23.3	20.3	16.7	20.1	41.7	36.3	32.3	36.8	48.0	35.3	34.0	39.1	48.7	37.3	35.0	40.3
$I_{0.6}$	20.7	18.3	16.3	18.4	40.0	33.3	33.3	35.6	46.3	35.3	34.0	38.6	48.0	41.3	40.3	43.2
$I_{0.8}$	23.3	19.0	15.7	19.3	42.3	34.0	32.3	36.2	51.0	47.0	48.3	48.8	51.0	47.0	48.3	48.8
Mean	22.4	19.2	16.2		41.3	34.6	32.7		48.4	39.2	38.8		49.2	41.9	41.2	
LSD (< 0.05)	C= 1.97; I= NS; C×I = NS				C= 2.02; I= NS; C×I= NS				C= 2.95; I= 3.01; C×I= 5.2				C= 3.16; I= 2.74; C×I= 4.75			
								Average of two year								
$I_{0.4}$	22.8	18.8	14.2	18.6	38.7	32.7	28.7	33.3	46.0	36.8	34.2	39.0	46.7	38.2	34.7	39.8
$I_{0.6}$	20.7	17.0	14.2	17.3	38.7	32.3	29.7	33.6	44.7	36.2	35.2	38.7	47.3	41.5	40.7	43.2
$I_{0.8}$	23.7	18.0	14.2	18.6	39.2	32.2	28.0	33.1	49.5	46.3	45.7	47.2	49.5	46.3	45.7	47.2
Mean	22.4	17.9	14.2		38.8	32.4	28.8		46.7	39.8	38.3		47.8	42.0	40.3	
LSD(< 0.05)	Y= NS; C= 0.99; I = NS; Y×C= 1.4; Y × I= NS; C×I = NS; Y×C × I= NS				Y= 3.33; C= 0.99; I= NS; Y×C= NS; Y×I= NS; C×I = NS; Y×C×I= NS				Y= NS; C= 2.39; I= 1.93; Y×C= 1.4; Y x I= NS; C×I = 3.34; Y×C×I= NS				Y= NS; C= 2.31; I = 1.79; Y×C= NS; Y×I=NS; C×I = 3.11; Y×C×I=NS			

Table 4: Effect of soil compaction and irrigation regimes on plant height, number of pods plant^{-1}, number of grains pod^{-1} and thousand grain weight in summer moongbean

Irrigation regimes	Compaction level															
	C_0	C_1	C_3	Mean	C_0	C_1	C_3	Mean	C_0	C_1	C_3	Mean	C_0	C_1	C_3	Mean
	Plant height (cm)				Number of pods plant^{-1}				Number of grains pod^{-1}				Thousand grain weight (g)			
2017																
$I_{0.4}$	42.2	39.3	35.7	39.1	19.3	25.3	14.7	19.8	8.7	9.7	8.3	8.9	37.4	39.8	36.7	38.0
$I_{0.6}$	47.3	43.1	38.6	43.0	22.3	27.0	17.3	22.2	9.0	10.3	8.0	9.1	40.2	42.1	38.3	40.2
$I_{0.8}$	50.7	47.5	44.7	47.6	25.3	30.0	19.3	24.9	9.7	10.7	9.3	9.9	40.8	43.7	38.9	41.1
Mean	46.7	43.3	39.7		22.3	27.4	17.1		9.1	10.2	8.6		39.5	41.9	38.0	
LSD (< 0.05)	C= 1.98; I = 2.02; C×I= NS				C= 2.99; I= 2.39; C×I = NS				C= 0.73; I = NS; C×I = NS				C= 1.69; I= 1.50; C×I= NS			
2018																
$I_{0.4}$	41.7	38.4	34.2	38.1	16.3	20.7	14.7	17.2	7.3	7.7	6.7	7.2	33.2	37.8	32.5	34.5
$I_{0.6}$	46.1	42.0	36.8	41.6	21.3	25.7	16.3	21.1	8.3	9.7	8.3	8.8	36.6	40.9	35.7	37.7
$I_{0.8}$	48.6	46.5	44.1	46.4	23.3	28.3	17.7	23.1	9.3	10.0	8.7	9.3	38.7	42.6	37.1	39.5
Mean	45.5	42.3	38.4		20.3	24.9	16.2		8.3	9.1	7.9		36.2	40.4	35.1	
LSD (< 0.05)	C= 2.23; I= 1.76; C×I = NS				C= 3.30; I = 1.70; C×I = NS				C= 0.62; I = 1.06; C×I = NS				C= 1.74; I = 1.41; C×I= NS			
Average of two year																
$I_{0.4}$	41.9	38.9	35.0	38.6	17.8	23.0	14.7	18.5	8.0	8.7	7.5	8.1	35.3	38.8	34.6	36.2
$I_{0.6}$	46.7	42.6	37.7	42.3	21.8	26.3	16.8	21.7	8.7	10.0	8.2	8.9	38.4	41.5	37.0	39.0
$I_{0.8}$	49.7	47.0	44.4	47.0	24.3	29.2	18.5	24.0	9.5	10.3	9.0	9.6	39.8	43.1	38.0	40.3
Mean	46.1	42.8	39.0		21.3	26.2	16.7		8.7	9.7	8.2		37.8	41.1	36.5	
LSD (< 0.05)	Y= NS; C= 1.24; I= 1.27; Y×C= NS; Y×I= NS; C×I= NS; Y×C×I= NS				Y= 0.32; C= 1.85; I= 1.39; Y×C= NS; Y×I= NS; C×I = NS; Y×C×I= NS				Y= NS; C= 0.40; I= 1.06; Y×C= NS; Y×I= NS; C×I= NS; Y×C×I= NS				Y= 0.41; C= 1.01; I= 0.97; Y×C= NS; Y×I =NS; C×I = NS; Y×C×I = NS			

in C_3 plots during 2017 and 2018, respectively. While comparison at 20 cm depth reveals that root length density was higher in C_1 plots (1.32 and 1.28 cm cm^{-3}) in comparison to C_0 (1.17 and 1.09 cm cm^{-3}) in 2017 and 2018 respectively. Abu-Hamdeh (2003) also reported that compacted plots had greater concentration of roots near the base of the plants in comparison to zero-load plots. Compaction increased bulk density, added to soil strength along with the retention of soil moisture for crop use, thus confining the roots almost entirely to the top 60 cm of soil (Laboski *et al.* 1998). RLD values were at par for the three irrigation regimes.

Straw yield

The data on effect of different irrigation and compaction level on straw yield is presented in Table 5. The straw yield under C_1 compaction level was found to be significantly higher as compared to C_3 (14.6 and 16.6%) and C_0 (8.3 and 8.7%) during both the years respectively. Straw yield of moong was significantly influenced by different irrigation schedules. Irrigation regime of $I_{0.8}$ produced maximum straw yield (6.21 and 5.91 t ha^{-1}) being significantly higher than $I_{0.6}$ (5.63 and 5.37 t ha^{-1}) and $I_{0.4}$ (5.20 and 4.89 t ha^{-1}) irrigation regimes. The reason for increased biomass yield under more frequently irrigated regimes might be due to more efficient photosynthesis as the evapo-transpirational demands were fulfilled better under this and the plants produced more dry matter, leaf area and ultimately higher biomass yield (Trivedi *et al.* 1994). The interaction of compaction and irrigation was significant in 2018 with maximum straw yield (6.37 t ha^{-1}) in C_1 under $I_{0.8}$ regime. There were about 17 and 30% increase in straw yield under $I_{0.8}$ regime as compared to $I_{0.4}$ in C_1 and C_3 compaction levels respectively.

Grain yield

The data regarding summer moongbean grain yield as affected by compaction level and irrigation scheduling is presented in Table 5. The data reveals that grain yield was higher in 2017 than 2018 though difference was non-significant. Among different compaction levels, maximum grain yield was recorded at C_1 *i.e.* 1.38 and 1.27 t ha^{-1} in 2017 and 2018 respectively while the minimum grain yield was observed at C_3 compaction level *i.e.* 1.22 and 1.08 t ha^{-1} in the respective years. The mean grain yield decreased up to 6.9 and 16% in C_3 as compared to C_0 and C_1 respectively. The highest grain yield obtained under C_1 might be due to a higher number of pods per plant, seeds per pod and 1000-seed weight as compared to C_3 and C_0 compaction. Kirnak *et al.* (2013) also reported yield loss up to 45% with high compaction levels. Considering the effect of irrigation on grain yield, highest yield (1.36 t ha^{-1}) was recorded under $I_{0.8}$ irrigation regime, which was statistically higher by 22% than $I_{0.4}$ and 14% than $I_{0.6}$ irrigation regime. So, it is apparent that increased moisture availability of soil increased grain yield. Yadav and Singh (2014) also observed a similar trend in seed yield with increase in irrigation frequency.

Irrigation water productivity

Irrigation water productivity (IWP) is the measure of economic yield of crop obtained per unit amount of irrigation water used by the crop. The data on irrigation water

Table 5: Effect of soil compaction and irrigation regimes on straw yield, grain yield and irrigation water productivity (IWP) of summer moongbean.

Irrigation regimes	Compaction level											
	C_0	C_1	C_3	Mean	C_0	C_1	C_3	Mean	C_0	C_1	C_3	Mean
	Straw yield (t ha^{-1})				Grain yield (t ha^{-1})				IWP (kg ha^{-1} mm^{-1})			
						2017						
$I_{0.4}$	5.27	5.70	4.63	5.20	1.15	1.33	1.11	1.20	5.49	6.35	5.30	5.71
$I_{0.6}$	5.54	5.98	5.37	5.63	1.28	1.35	1.16	1.26	4.58	4.81	4.13	4.51
$I_{0.8}$	6.08	6.61	5.94	6.21	1.41	1.46	1.38	1.42	4.04	4.18	3.95	4.06
Mean	5.63	6.10	5.32		1.28	1.38	1.22		4.70	5.11	4.46	
LSD (< 0.05)	C= 0.19; I= 0.16; C×I= NS				C= 0.77; I= 0.97; C×I= NS				C= 0.23; I= 0.35; C×I= NS			
						2018						
$I_{0.4}$	4.96	5.45	4.27	4.89	1.05	1.19	0.94	1.06	5.00	5.68	4.49	5.06
$I_{0.6}$	5.32	5.66	5.14	5.37	1.17	1.26	1.07	1.17	4.19	4.51	3.83	4.18
$I_{0.8}$	5.78	6.37	5.58	5.91	1.28	1.36	1.22	1.29	3.67	3.90	3.50	3.69
Mean	5.36	5.83	5.00		1.17	1.27	1.08		4.29	4.70	3.94	
LSD (< 0.05)	C= 0.26; I= 0.11; C×I= 0.18				C= 0.13; I= 0.71; C×I= NS				C= 0.48; I= 0.31; C×I= NS			
						Average of two year						
$I_{0.4}$	5.12	5.58	4.45	5.05	1.10	1.26	1.03	1.13	5.25	6.02	4.90	5.39
$I_{0.6}$	5.43	5.82	5.26	5.50	1.23	1.31	1.12	1.22	4.39	4.66	3.98	4.34
$I_{0.8}$	5.93	6.49	5.76	6.06	1.35	1.41	1.30	1.36	3.85	4.04	3.72	3.87
Mean	5.49	5.96	5.16		1.23	1.33	1.15		4.50	4.90	4.20	
LSD (< 0.05)	Y=0.22; C=0.13; I= 0.09; Y×C= NS; Y×I= NS; C×I= 0.16; Y×C×I= NS				Y=0.34; C=0.06; I= 0.06; Y×C= NS; Y×I= NS; C×I= NS; Y×C×I= NS				Y= 0.12; C= 0.22; I= 0.22; Y×C= NS; Y×I= NS; C×I= NS; Y×C×I= NS			

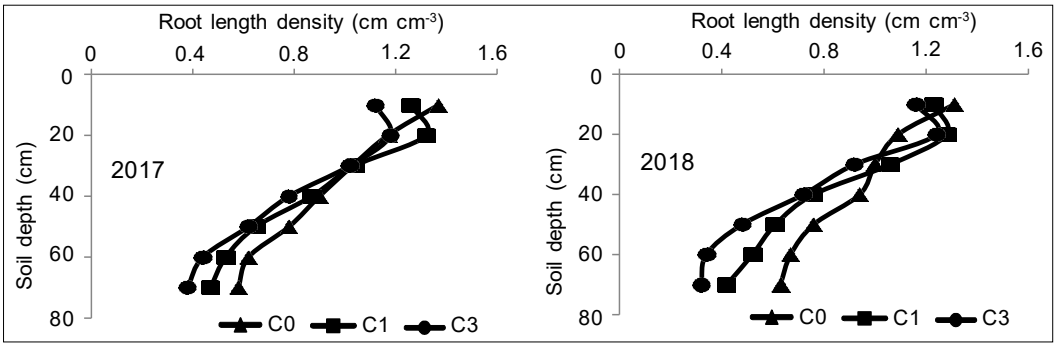

Fig 3: Effect of soil compaction on root length density at 55 days after sowing.

productivity of moongbean is presented in Table 5. The data reveals that during 2017 and 2018, maximum IWP *i.e.* 5.11 and 4.70 kg ha^{-1} mm^{-1}, respectively was recorded at C_1 compaction level irrespective of irrigation regimes. The corresponding values at C_0 were 4.70 and 4.29 kg ha^{-1} mm^{-1} while at C_3, 4.46 and 3.94 kg ha^{-1} mm^{-1}. On an average of two years IWP was higher at C_1 (4.90 kg ha^{-1} mm^{-1}) followed by C_0 (4.50 kg ha^{-1} mm^{-1}) and C_3 (4.20 kg ha^{-1} mm^{-1}). Higher water productivity with C_1 level resulted from significantly higher grain yield as compared to other levels. Among irrigation regimes, highest value of IWP (5.4 kg ha^{-1} mm^{-1}) was obtained under $I_{0.4}$ irrigation regime. This can be attributed to efficient use of applied water and relatively more grain yield per unit water applied. The water productivity decreased with increase in irrigation level. The lowest water productivity (4.4 and 3.8 kg ha^{-1} mm^{-1}) was recorded in $I_{0.6}$ and $I_{0.8}$ irrigation regime, respectively because the proportionate increase in grain yield was lower. These results are in similarity with the findings of Soni and Gupta (1999) and Yadav and Singh (2014).

CONCLUSION

The results indicated that maximum grain yield and yield attributes were recorded at C_1 compaction level. Amongst irrigation regimes $I_{0.8}$ recorded maximum yield. As expected, the irrigation water productivity was highest in $I_{0.4}$ irrigation regime. This study suggested that C_1compaction *i.e,* one roller pass in loamy sand soil with $I_{0.8}$ irrigation regime may be useful for achieving higher productivity in summer moongbean.

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