

# Long Term Effect of Organic Cropping Systems on Hydraulic Properties of soils

## ABSTRACT

A field study on long term effect of five organic cropping systems viz. poplar + turmeric (CS<sub>1</sub>), sugarcane+ bottle gourd – broccoli (CS<sub>2</sub>), basmati – wheat (CS<sub>3</sub>), sugarcane fodder (CS<sub>4</sub>) and maize + summer moong - wheat (CS<sub>5</sub>) on soil hydraulic properties was conducted at Natural Agriculture Farm and Research Centre, Dharekot, Jandiala Guru, Amritsar, Punjab. The depth wise soil samples from these cropping systems were collected after *rabi* (2018-19) and *kharif* (2019) seasons. Maximum soil water retentivity (MWR) in CS<sub>2</sub> and CS<sub>5</sub> was significantly higher than CS<sub>1</sub>, CS<sub>3</sub> and CS<sub>4</sub>. In 15-22.5 cm soil layer MWR was significantly lower than 0-7.5, 7.5-15 and 22.5-30 cm soil layers. At 0.1, 0.3 and 0.5 bar matric potentials CS<sub>1</sub> and CS<sub>2</sub> has significantly higher soil moisture retention compared to CS<sub>3</sub>, CS<sub>4</sub> and CS<sub>5</sub> cropping systems. However CS<sub>4</sub> has significantly lower soil moisture at 0.1, 0.3, 0.5, 1 and 2 bar matric potential compared to CS<sub>5</sub>. Soil moisture retention was significantly lower in 15-22.5 cm depth compared to 0-7.5 and 7.5-15 cm depths at all matric potentials. Plant available water in CS<sub>1</sub>, CS<sub>2</sub> and CS<sub>5</sub> was significantly higher by 5.7, 4.9 and 2.9 percent, respectively compared to CS<sub>3</sub> and by 5.5, 4.7 and 2.7 percent, respectively compared to CS<sub>4</sub>. Soil infiltration rate and cumulative infiltration were significantly higher in CS<sub>4</sub> compared to all other cropping systems. Saturated hydraulic conductivity (SHC) was significantly lower in CS<sub>3</sub> than all other cropping systems. In CS<sub>1</sub> and CS<sub>2</sub> SHC was at par but these cropping systems have significantly lower SHC than CS<sub>4</sub> and CS<sub>5</sub>. Irrespective of cropping systems SHC of 22.5-30 cm layer was significantly lower than other soil depths. In different cropping systems unsaturated hydraulic conductivity (K<sub>ψ</sub>) was significantly higher in CS<sub>4</sub> and CS<sub>5</sub> compared to CS<sub>1</sub>, CS<sub>2</sub> and CS<sub>3</sub>. Soil drainage rate was significantly higher in CS<sub>4</sub> by 8.6, 19.3, 30.2 and 67.3 percent compared to CS<sub>5</sub>, CS<sub>2</sub>, CS<sub>1</sub> and CS<sub>3</sub>, respectively.

*Keywords: cropping systems, soil moisture retention, plant available water, infiltration rate, saturated and unsaturated hydraulic conductivity*

## 1. Introduction

In the Indo-Gangetic plains (IGP) of India, adoption of intensive agriculture, imbalanced use of chemical fertilizers and decreased use of organic manures have lead to depletion of soil organic carbon and deterioration of soil physical properties (Jat *et al* 2017). Organic farming has been suggested as a more sustainable alternative to conventional high-input agriculture (Ram *et al* 2014). Organic farming combines traditional farming methods such as natural pest management, rotating crops, and organic fertiliser application with modern technologies including biological control and reduced tillage (Reganold and Wachter, 2016; Peigne *et al.*, 2016). Organic management involves the use of cover crops and organic amendments (legumes or manure), which results in more stable soil structure, better soil fertility and greater soil organic matter content than conventional systems relying on inorganic fertilizers (Ghabbour *et al.*, 2017; Papadopoulos *et al.*, 2014). The use of crop rotations favours a more efficient use of soil nutrients by plants. Crops with different root lengths and densities are able to mobilize and extract nutrients and water from deeper layers. However, these roots also create biopores in the soil profile. Organic systems, due to the higher content of organic matter and the presence of cover crops would offer more favourable soil structure which can be quantified from soil hydraulic properties (Abdollahi *et al.*, 2014; Naveed *et al.*, 2013). There is ample scientific evidence that organic farming improves soil quality and soil fertility compared to conventional agriculture (Wheeler *et al.*, 2015; Reganold and Wachter, 2016; Di Prima *et al.*, 2018). The impact of organic farming on soil properties could also improve ecosystem water relations. The characteristic of soil water retention is affected by soil organic carbon (SOC) content and porosity, which are significantly influenced by organics and cropping systems (Zhou *et al.* 2008). Soil water retention at field capacity (FC) and permanent wilting point (PWP) are important to estimate the irrigation water depth. Understanding the relation between water storage capacity and cropping systems is important in determining the flow properties of water in soil. Soil hydraulic properties are important to understand the water transmission properties and water balance in soils. In particular, soil water retention (SWR) is a function of the distribution of pore sizes and the saturated hydraulic conductivity reflects movement of water through connected macropores (Koestel *et al.*, 2018).

Furthermore, having information on SWR permits estimation of various soil physical quality indicators that are of agronomic importance, such as plant-available water and air-filled porosity (Reynolds et al., 2009). Organically managed soils have a greater soil organic matter content (Gattinger et al., 2012), which directly improve soil structure and water holding capacity of soils (Abdi et al., 2018), increases water infiltration (Kundel et al. 2020) and ecosystem water relations under drought conditions (Sun et al., 2022). Cropping systems have an important effect on the soil hydraulic characteristics (Bormann and Klaassen 2008). However, less is known about the effects of organic cropping systems on the physical characteristics of soil structure (Papadopoulos et al., 2014), and its impact on water retention and infiltration (Williams et al., 2017). Spatial variability of soil hydraulic properties of different soil layers add complexity to the prediction of soil water redistribution and availability in time and space (Vereecken et al., 2014; Bonfante and Bouma, 2015; De Jong van Lier and Wendroth, 2016). The current need for improvements in the water use efficiency by organic cropping systems requires a holistic assessment of the hydraulic functioning of cropped soils for efficient soil and water management. Therefore, the objective of present study was to characterize the hydraulic properties of soils under different long term organic cropping systems.

## 2. MATERIAL AND METHODS

### 2.1 Description of the study area

The research work was conducted at *Bhagat Puran Singh Natural Agriculture Farm and Research Centre*, Dherekot, Jandiala Guru, Amritsar ( $31^{\circ} 34' 24''$  N,  $75^{\circ} 03' 58''$ E) situated at an altitude of 236 m above mean sea level. The total area of the organic farm is 12 ha. The impact of long term five organic cropping systems viz. agroforestry (poplar + turmeric as intercrop (CS<sub>1</sub>)), vegetables (sugarcane+bottle gourd – broccoli (CS<sub>2</sub>)), basmati – wheat (CS<sub>3</sub>), sugarcane fodder (CS<sub>4</sub>) and maize + summer moong (cover crop) – wheat (CS<sub>5</sub>) was studied on soil hydraulic properties. The farm has a herd of *Sahiwal* cows. In all these cropping systems, none of chemical fertilizer, herbicide and pesticide was used. Instead different crops were grown with the application of locally prepared compost, *jeeva amrita*, *bijamrita* (Badwal et al., 2019) and mulching to supply nutrients. Other important principles for crop growth were intercropping of legumes and use of local species of earthworms. The pest management was done through the use of *agniastra*, the *brahmastra* and the *neemastra* (Badwal et al., 2019).

In CS<sub>1</sub>, the poplar + turmeric as intercrop is practiced in cycle since fifteen years. Every year turmeric is being sown as inter crop in the poplar during the month of April and harvested by the end of December. Before sowing of turmeric two preparatory tillage operations with rotavator were done. Two rows of turmeric were sown on 37.5 cm wide beds with plant to plant spacing of 18 cm. Paddy straw mulch was applied @ 9 t ha<sup>-1</sup> after the first irrigation. No other chemical fertilizer was added to this cropping system. Irrigation was applied through flooding in the rows as and when required. In CS<sub>2</sub>, sugarcane (Co J 85 var.) was sown as two rows (in 4') and 12' inter row spacing in the North-South direction. The inter row spacing (12') was used for sowing of vegetables since 15 years. Preparatory tillage with cultivator followed by rotavator was done before sowing of bottle guard and broccoli in the inter row spacing. Bottle gourd was sown during the month of March and harvested in September. Broccoli was transplanted in the month of October after bottle gourd and harvested in December to February. Only organic manures (added through compost @ 5 t ha<sup>-1</sup> + *Jeeva Amrita*) were used to raise vegetables and sugarcane. In CS<sub>3</sub>, basmati (Pusa Basmati 1121 var.) was transplanted in the month of July and harvested in October. After incorporation of basmati straw with discing+ rotavator, wheat (Sona Moti var) was sown as 8 rows on 120 cm beds and furrows of 30 cm. In CS<sub>4</sub>, sugarcane fodder (KRFo93-1 var.) was sown on 75 cm beds at 75 cm plant to plant spacing during 2016 (after preparatory tillage with cultivator) and it was a 3 year ratoon crop during 2019. During three years no any tillage operation was carried out in sugarcane fodder. In CS<sub>5</sub>, maize (var. local) was sown (after one preparatory tillage with rotavator) in the month of April after harvesting of wheat at a 60 cm row to row spacing and two rows of summer moong (SML 668 var.) were sown as inter/cover crop in maize during April every year. After maize, wheat was sown (after preparatory tillage of one discing+rotavator) in October as 8 rows on the beds (120 cm width and 30 cm furrow).

### 2.2 Soil sampling and analysis

The soil samples were taken from four sites and four depths (0-7.5, 7.5-15, 15-22.5 and 22.5-30 cm) under each cropping system after the harvest of *rabi* (2018-19) and *kharif* crops during 2019. The collected soil samples were dried, grounded and passed through 2-mm sieve for analysis. The maximum water holding

capacity (MWHC, per cent) was determined using Keen's box (Richards, 1954) with its internal diameter 5.6 cm and height 1.6 cm. The soil moisture characteristics curve was prepared for each sample collected from different depths and cropping systems using pressure plate apparatus (Richards, 1949) with application of 10, 30, 50, 100, 200, 300 and 1500 kPa pressure. The plant available water (PAW) was calculated from the soil moisture characteristic curve as:

$$PAW = FC - PWP$$

Where, PAW is the plant available water (cm), FC is the soil moisture storage (cm) at field capacity (30kPa), PWP is the soil moisture storage (cm) at permanent wilting point (1500 kPa). The infiltration of water into the soil was measured in-situ, after the harvest of crops in the month of May 2019 and December 2019 in all cropping systems using double ring infiltrometer (Reynolds *et al.*, 2002). Saturated hydraulic conductivity of undisturbed soil cores from different soil depths were taken from different cropping systems with the help of core sampler to measure saturated hydraulic conductivity. Then the saturated hydraulic conductivity of soil was calculated using Darcy's equation as given below and detailed by Reynolds *et al.*(2002).

$$K_s = (Q \times L) / At (H+L)$$

where Q is the volume of water percolated (cm<sup>3</sup>), A is the cross-sectional area of the core (cm<sup>2</sup>) 't' is time of percolation in minutes, L is the length of core (cm), H is the height of water above soil surface in the core (cm). The unsaturated hydraulic conductivity of 0-7.5, 7.5-15, 15-22.5 and 22.5-30 cm soil depths in different cropping systems was estimated from the soil moisture retention data using a computer programme developed by Jalota and Khera (2001) using Millington and Quirk (1961) method. The drainage rate was measured from a plot of size 2 x 2 m<sup>2</sup> bunded on all sides saturated completely for 2 days and covered with polythene sheet in the different cropping systems. Soil samples were taken continuously from 3<sup>rd</sup> day upto 16<sup>th</sup> day in the depth increments of 0-7.5, 7.5-15, 15-22.5 and 22.5-30 cm two times a day (i.e morning at 10 am and evening at 5 pm) with the help of screw auger to calculate soil moisture storage. Deep drainage was estimated by employing the equation as suggested by Ogata and Richards (1957) between equivalent depth of water in a soil profile (W, cm) as function of drainage time (T, days) by following the mathematical expression as listed below:

$$W = AT^B \dots\dots\dots 1$$

where A- water amount (W) at T = 1 and B- slope of W versus T plotted on a log-log scales. Differentiating equation 1 with respect to T (time) yields  $dW/dT = AB(T)^{B-1}$

The drainage rate (dW/dT) is expressed as a function of time (T).

### 3. RESULTS AND DISCUSSION

**3.1 Maximum water retentivity:** The pooled data pertaining to maximum water retentivity in different cropping systems at different depths is presented in Table 1. Irrespective of seasons and depths, CS<sub>3</sub> (basmati-wheat) has significantly lower maximum water retentivity (MWR) than all other cropping systems. MWR was at par in CS<sub>2</sub> and CS<sub>5</sub> but these cropping systems have significantly higher MWR than CS<sub>1</sub> and CS<sub>4</sub>. Irrespective of cropping systems MWR of 15-22.5 cm depth was significantly lower than other soil depths. However, no significant difference in MWR was observed among 0-7.5, 7.5-15 and 22.5-30 cm depths.

**Table 1. Effect of different cropping systems on maximum water retentivity (% v/v)**

Soil depth (cm)	Cropping systems					Mean
	CS <sub>1</sub>	CS <sub>2</sub>	CS <sub>3</sub>	CS <sub>4</sub>	CS <sub>5</sub>	
0-7.5	45.0	46.1	43.0	45.2	46.9	45.3 <sup>a</sup>
7.5-15	45.3	47.2	42.4	44.8	47.3	45.4 <sup>a</sup>
15-22.5	42.7	43.0	40.9	44.7	46.8	43.6 <sup>b</sup>
22.5-30	45.9	48.0	44.9	44.2	46.8	45.9 <sup>a</sup>
Mean	44.7 <sup>a</sup>	46.1 <sup>b</sup>	42.8 <sup>c</sup>	44.7 <sup>a</sup>	46.9 <sup>b</sup>	

Means followed by different letters are significantly different at  $p < 0.05$  by Tukey's honest significant difference

The reduction of MWR in CS<sub>3</sub> cropping system may be due to reduction in total porosity of the soil due to puddling in basmati. CS<sub>5</sub> has significantly higher MWR than CS<sub>1</sub>, CS<sub>3</sub> and CS<sub>4</sub>. This may also be due

to more total porosity in CS<sub>5</sub> compared to other cropping systems. Similar results have been observed by Suwara *et al.* (2016). However no significant difference in MWR was observed among CS<sub>1</sub>, CS<sub>2</sub> and CS<sub>4</sub>. Irrespective of cropping systems MWR of 15-22.5 cm depth was significantly lower than other soil depths. However, no significant difference in MWR was observed among 0-7.5, 7.5-15 and 22.5-30 cm depths. Similarly higher MWR has also been reported with addition of organics in surface soils by Siddika and Jeyamangalam, (2017).

### 3.2 Soil water retention characteristics

The pooled data pertaining to soil water retention characteristics of different cropping systems at different depths after *rabi* and *kharif* seasons is presented in Table 2.

**Table 2 Effect of different cropping systems on soil water retention (percent v/v)**

Soil matric potential (bars)	Cropping systems					LSD (0.05)	Soil depth (cm)				LSD (0.05)
	CS <sub>1</sub>	CS <sub>2</sub>	CS <sub>3</sub>	CS <sub>4</sub>	CS <sub>5</sub>		0-7.5	7.5-15	15-22.5	22.5-30	
0.1	26.9	26.1	20.8	19.9	22.9	1.98	25.0	24.6	21.1	22.6	2.83
0.3	20.3	20.1	16.0	15.5	18.3	1.47	19.4	18.6	16.3	17.8	2.03
0.5	17.6	17.7	14.4	13.7	16.1	1.44	17.1	16.7	14.4	15.3	1.75
1.0	14.5	14.9	13.1	11.7	14.1	1.32	14.5	14.6	12.2	13.2	1.30
2.0	12.5	12.6	11.7	10.2	11.6	1.33	13.0	12.2	10.5	11.2	1.08
3.0	10.7	10.7	10.3	9.2	9.5	NS	11.5	10.9	8.7	9.4	1.06

Pooled data of cropping systems showed that soil moisture retention in CS<sub>1</sub> and CS<sub>2</sub> was at par at all matric potential values but these both cropping systems have significantly higher moisture retention at 0.1, 0.3 and 0.5 bar matric potential than all other cropping systems. This may be due to more aggregation in CS<sub>1</sub> and CS<sub>2</sub> (Kaur and Singh 2023) which favours moisture retention at lower suctions. Similar results were reported by Guber *et al.* (2004) where soil water retention can be predicted from soil aggregation. CS<sub>4</sub> has significantly lower soil moisture at 0.1, 0.3, 0.5, 1 and 2 bar matric potential compared to CS<sub>1</sub>, CS<sub>2</sub> and CS<sub>5</sub>. The lower soil moisture at different matric potentials in CS<sub>4</sub> may be due to lighter soil texture and less organic carbon (Kaur and Singh 2023). Similar results have been reported by Nath (2014). Soil moisture retention was significantly lower in 15-22.5 cm depth compared to 0-7.5 and 7.5-15 cm depths at all matric potentials. The lower moisture retention in 15-22.5 cm depth may be due to more compaction as indicated by significantly higher bulk density of this layer. Similar results have been reported by Singh *et al.* (2009) where moisture retention was significantly low in 15-22.5 cm depth compared to all other depths. However, at all matric potentials, no significant difference in soil moisture retention was observed among 0-7.5, 7.5-15 and 22.5-30 cm soil depths. There was also no significant difference in soil moisture retention between 15-22.5 and 22.5-30 cm depths.

### 3.3 Plant available water

The data pertaining to water available to plants in different cropping systems at different depths in two seasons is presented in Fig 1. Pooled plant available water (PAW) in CS<sub>1</sub> and CS<sub>2</sub> was at par but significantly higher than CS<sub>3</sub>, CS<sub>4</sub> and CS<sub>5</sub>. In CS<sub>1</sub>, CS<sub>2</sub> and CS<sub>5</sub> PAW was significantly higher by 5.7, 4.9 and 2.9 percent, respectively compared to CS<sub>3</sub> and by 5.5, 4.7 and 2.7 percent, respectively compared to CS<sub>4</sub>. Similarly Eden *et al.* (2017) also reported that plant available water generally improves after addition of organic wastes due to more aggregation and organic carbon. Overall, PAW in 15-22.5 cm depth was significantly lower than 0-7.5, 7.5-15 and 22.5-30 cm by 1.1, 1.3 and 0.8 percent. Plant available water was at par in 0-7.5, 7.5-15 and 22.5-30 cm depths. This decrease may be due to reduction in porosity of this layer.

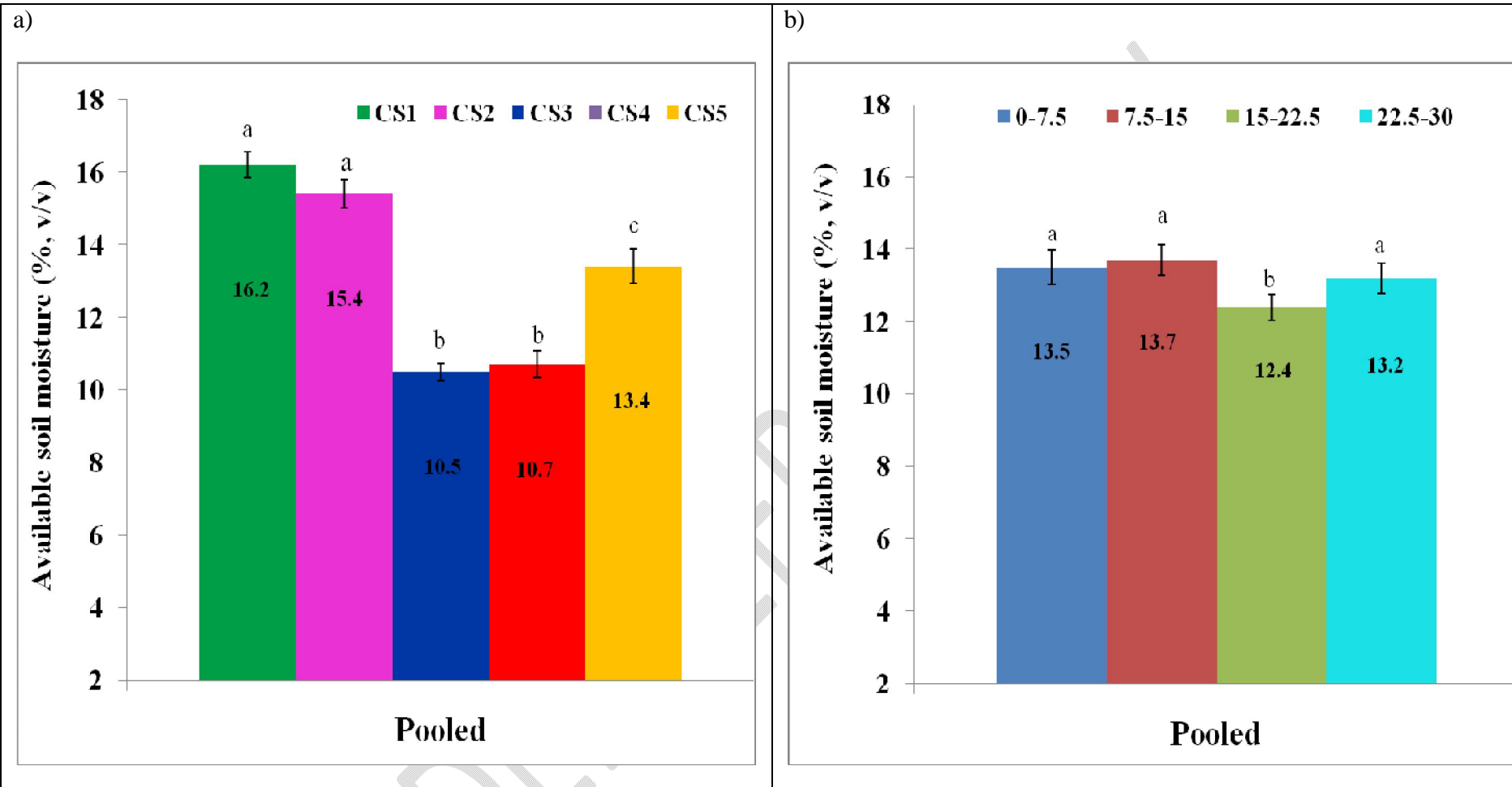
### 3.4 Infiltration

#### 3.4.1 Infiltration rate

The data pertaining to infiltration rate in different cropping systems in two seasons is presented in Fig 2. Generally infiltration rate was more after *rabi* than *kharif* season. This may be due to lower initial moisture after *rabi* than *kharif* season. After *rabi* season the initial infiltration rate was 1.2, 0.4, 0.3, 0.25 and 0.1 cm

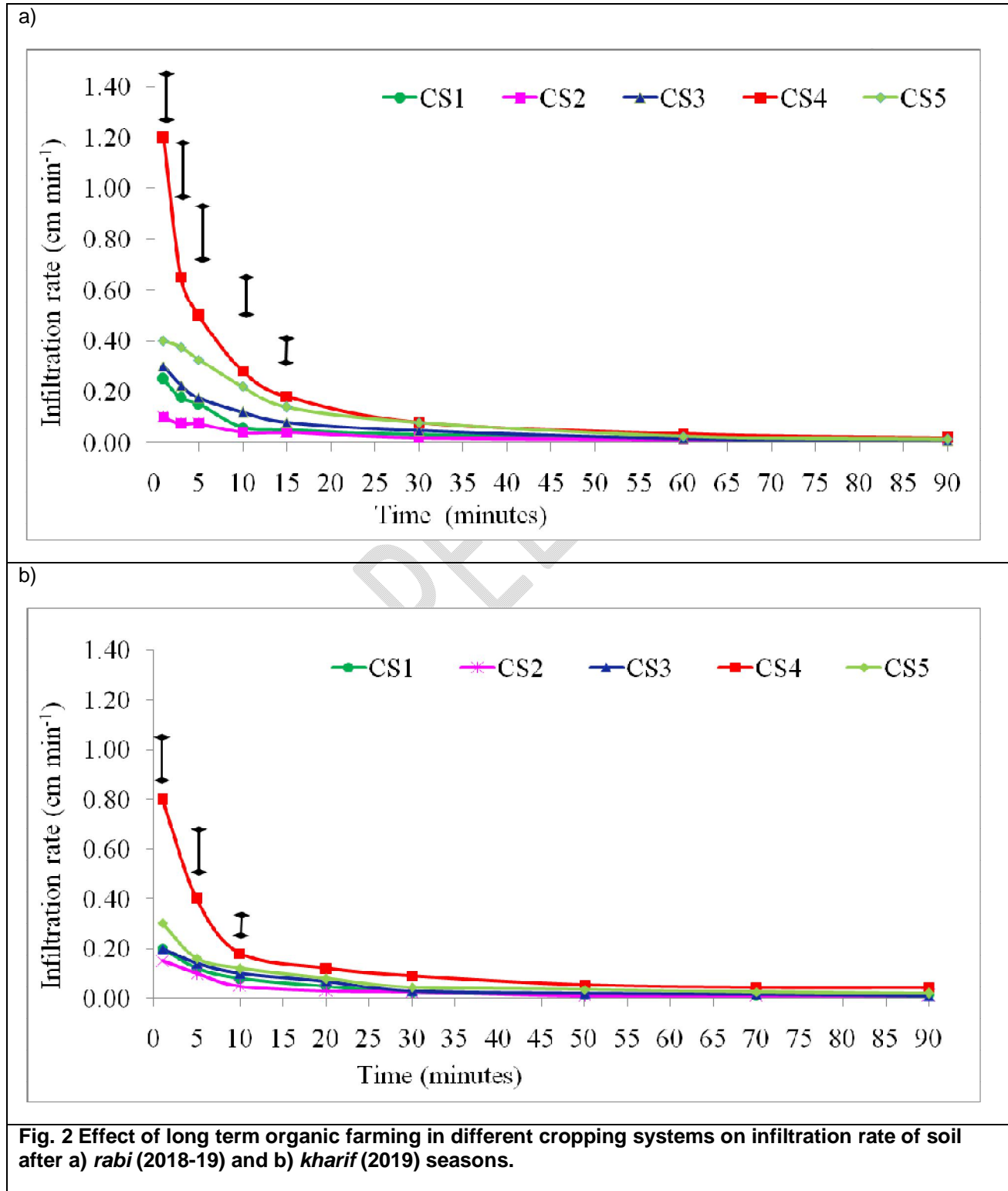
min<sup>-1</sup> in CS<sub>4</sub>, CS<sub>5</sub>, CS<sub>3</sub>, CS<sub>1</sub> and CS<sub>2</sub>, respectively. After 1, 3, 5, 10 and 15 minutes infiltration rate was significantly higher in CS<sub>4</sub> compared to all other cropping systems. Significantly higher infiltration rate in CS<sub>4</sub> may be due to bypass flow of water in decaying root channels of ratoon sugarcane fodder crop and lighter soil texture having more macropores. Increase in infiltration rate with inclusion of perennial crops in rotation has also been reported by Basche and DeLonge (2019). Infiltration rate was also significantly higher in CS<sub>5</sub> compared to CS<sub>2</sub>. The higher infiltration in CS<sub>5</sub> may be due to more proliferation of roots of intercropped

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**Fig.1** Effect of a) cropping systems and b) soil depths on available soil moisture (percent v/v) Vertical bars and dissimilar letters indicate standard errors of means and significant differences at 5% level of significance respectively

summer moong in surface soil. The lowest infiltration rate in CS<sub>2</sub> may be attributed to higher initial moisture content due to more organic carbon compared to CS<sub>4</sub> and CS<sub>5</sub> (Kaur and Singh 2023). Afterwards no significant difference in infiltration rate among different cropping systems was observed. After *Kharif* season the initial infiltration rate was 0.8, 0.3, 0.2, 0.2 and 0.15 cm min<sup>-1</sup> in CS<sub>4</sub>, CS<sub>5</sub>, CS<sub>3</sub>, CS<sub>1</sub> and CS<sub>2</sub>, respectively. After 1, 5 and 10 minutes infiltration rate was significantly higher in CS<sub>4</sub> compared to all other cropping systems. Afterwards no significant difference in infiltration rate among different cropping systems was observed.



### 3.4.2 Cumulative Infiltration rate

The data pertaining to cumulative infiltration in different cropping systems in two seasons is presented in Table 3. After 90 minutes cumulative infiltration in *rabi* season was 8.6, 5.9, 3.6, 2.9 and 1.8 cm in CS<sub>4</sub>, CS<sub>5</sub>, CS<sub>1</sub>, CS<sub>3</sub> and CS<sub>2</sub>, respectively. Cumulative infiltration was significantly different among all cropping systems with significantly highest values in CS<sub>4</sub> and significantly lowest values in CS<sub>2</sub>. The trend in cumulative infiltration was similar after *kharif* season with cumulative infiltration of 7.8, 4.6, 3.3, 2.7 and 2.0 cm in CS<sub>4</sub>, CS<sub>5</sub>, CS<sub>1</sub>, CS<sub>3</sub> and CS<sub>2</sub>, respectively after 90 minutes. Similarly, pooled cumulative infiltration after 90 minutes in CS<sub>4</sub>, CS<sub>5</sub>, CS<sub>1</sub>, CS<sub>3</sub> and CS<sub>2</sub> was 8.2, 5.3, 3.4, 2.8 and 1.9 cm, respectively. The order of significance among different cropping systems was CS<sub>4</sub> > CS<sub>5</sub> > CS<sub>1</sub> > CS<sub>3</sub> > CS<sub>2</sub>.

**Table 3. Effect of different cropping systems on cumulative infiltration (cm) of soil.**

Time (minutes)	Cropping systems					LSD (0.05)
	CS <sub>1</sub>	CS <sub>2</sub>	CS <sub>3</sub>	CS <sub>4</sub>	CS <sub>5</sub>	
5	0.9	0.4	0.7	2.3	1.3	0.68
10	1.4	0.6	1.1	3.4	2.1	0.86
30	2.6	1.3	1.9	6.0	3.9	0.80
60	3.2	1.7	2.5	7.5	4.9	0.47
90	3.4	1.9	2.8	8.2	5.3	0.42

Significantly higher cumulative infiltration in CS<sub>4</sub> may be due to bypass flow of water in decaying root channels of ratoon sugarcane fodder crop and lighter soil texture having more macropores. Similarly Shukla *et al.* (2015) reported higher infiltration in long term organically grown sugarcane compared to inorganic fertilizer application treatments.

### 3.5 Saturated hydraulic conductivity

The pooled data pertaining to saturated hydraulic conductivity (SHC) in different cropping systems at different depths is presented in Table 4. The soil SHC ranged from 2.16-3.90, 0.56-3.18, 0.41-1.58, 10.05-131.01 and 1.45-14.53 mm h<sup>-1</sup> in CS<sub>1</sub>, CS<sub>2</sub>, CS<sub>3</sub>, CS<sub>4</sub> and CS<sub>5</sub> cropping systems, respectively. The order of decrease in saturated hydraulic conductivity with different cropping systems is CS<sub>4</sub> > CS<sub>5</sub> > CS<sub>1</sub> > CS<sub>2</sub> > CS<sub>3</sub>.

**Table 4 Effect of different cropping systems on saturated hydraulic conductivity of soil (mm h<sup>-1</sup>)**

Soil depth (cm)	Cropping systems					Mean*
	CS <sub>1</sub>	CS <sub>2</sub>	CS <sub>3</sub>	CS <sub>4</sub>	CS <sub>5</sub>	
0-7.5	3.90	3.18	1.58	131.01	14.53	30.8 <sup>a</sup>
7.5-15	2.96	2.43	1.46	88.41	9.70	21.0 <sup>b</sup>
15-22.5	2.30	1.47	0.38	15.76	8.43	5.7 <sup>c</sup>
22.5-30	2.16	0.56	0.41	10.05	1.45	2.9 <sup>d</sup>
Mean*	2.83 <sup>a</sup>	1.91 <sup>ab</sup>	0.96 <sup>b</sup>	61.31 <sup>c</sup>	8.53 <sup>d</sup>	

\*Dissimilar letters are significantly different at 5 percent level of significance

In all soil depths, SHC differed significantly among cropping systems. CS<sub>4</sub> has significantly higher SHC than CS<sub>1</sub>, CS<sub>2</sub>, CS<sub>3</sub> and CS<sub>5</sub>. Higher SHC in CS<sub>4</sub> may be due to more macropores in light textures soils. Similarly, Singh *et al.* (2009) also reported higher saturated hydraulic conductivity in soils having more sand content. CS<sub>3</sub> has significantly lower SHC than all other cropping systems except CS<sub>2</sub>. This may be due to more micropores in cropping system (Basmati) where puddling is done compared to cropping system without puddling. Similarly Singh (2011) reported significantly lower saturated hydraulic conductivity in puddled soils compared to unpuddled soils. Significant differences in SHC was observed in 7.5-15, 15-22.5 and 22.5-30 cm depths. Depth wise differences in SHC were noticed where SHC was significantly lower in 22.5-30 cm depth compared to other soil depths. This may be due to formation of plough pan having higher bulk density in 15-22.5 layer where pore connectivity is less (Singh *et al.*, 2009). CS<sub>3</sub> has significantly lower SHC than all other cropping systems. SHC was at par in CS<sub>1</sub> and CS<sub>2</sub> but these cropping systems have significantly lower SHC than CS<sub>4</sub> and CS<sub>5</sub>. Irrespective of cropping systems SHC of 22.5-30 cm depth was

significantly lower than other soil depths. Generally SHC decreased significantly with depth. In 0-7.5 cm depth saturated hydraulic conductivity was significantly higher than 22.5-30 cm depth. In 0-7.5 cm and 7.5-15 cm depth significant difference in SHC was also observed.

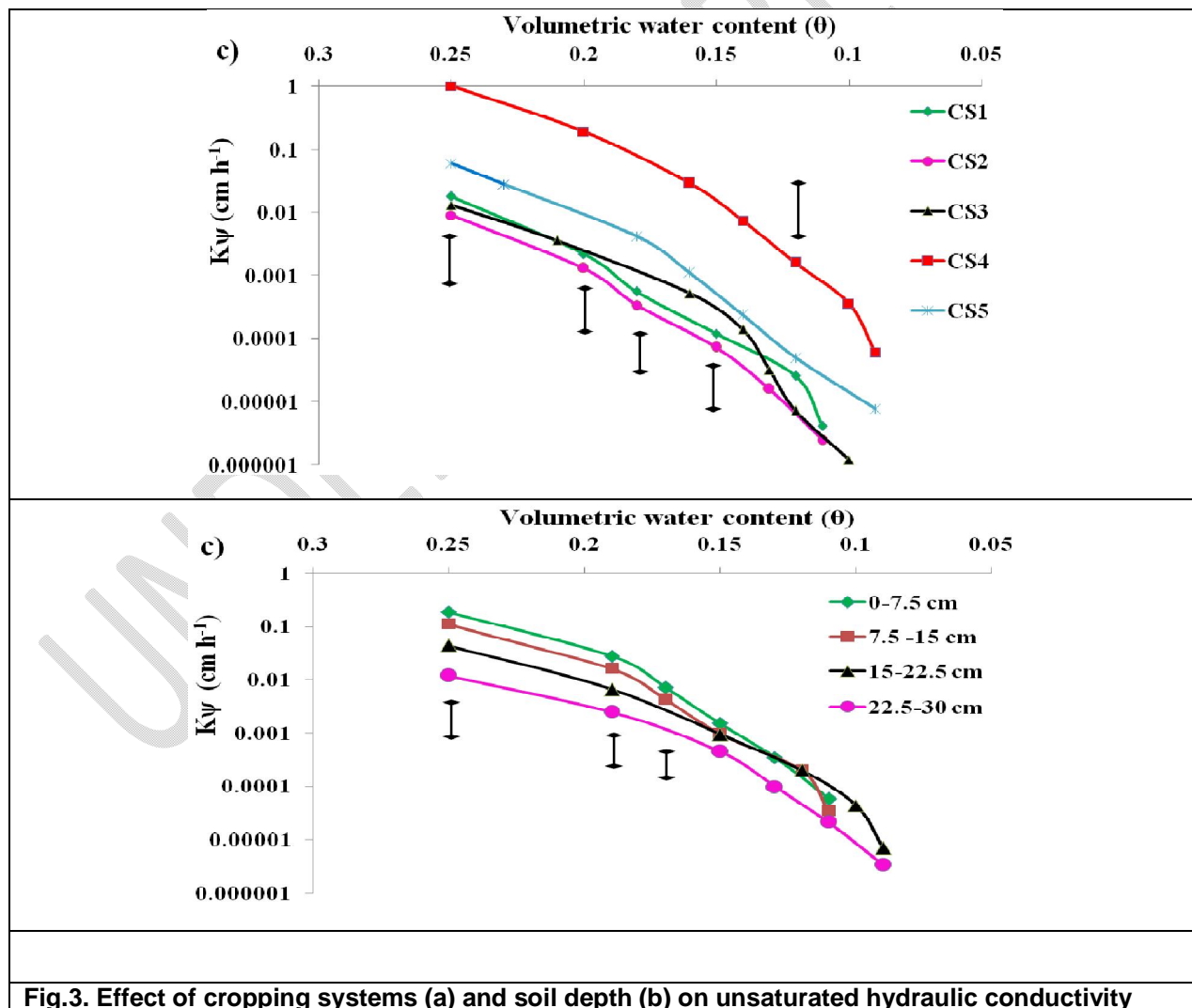
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### 3.6 Unsaturated hydraulic conductivity

The data pertaining to unsaturated hydraulic conductivity ( $K_{\psi}$ ) in different cropping systems and different depths are presented in Fig 3.

In different cropping systems unsaturated hydraulic conductivity ( $K_{\psi}$ ) generally decreased with decrease in soil moisture content.  $K_{\psi}$  was significantly higher in CS<sub>4</sub> compared to all other cropping systems at different moisture contents.  $K_{\psi}$  at 26 percent volumetric soil moisture content was 1.2, 0.06, 0.018, 0.09 and 0.043 cm h<sup>-1</sup> in CS<sub>4</sub>, CS<sub>5</sub>, CS<sub>1</sub>, CS<sub>2</sub> and CS<sub>3</sub>, respectively and the corresponding values at 11 percent volumetric moisture content were  $3.6 \times 10^{-4}$ ,  $5 \times 10^{-5}$ ,  $4.2 \times 10^{-6}$ ,  $2.5 \times 10^{-6}$  and  $1.2 \times 10^{-6}$  cm h<sup>-1</sup>. Significantly higher  $K_{\psi}$  values in CS<sub>4</sub> may be due to higher saturated hydraulic conductivity due to more macro pores in the soil related to coarser texture and low organic carbon. Similar results have been reported by Seema *et al.* (2019). Significant differences in  $K_{\psi}$  among cropping systems at higher moisture than lower moisture content may be due to more difference in macropores and soil aggregation (Kaur and Singh 2023).

With respect to different soil depths, in the surface layer  $K_{\psi}$  was more compared to lower layers.  $K_{\psi}$  in 0-7.5 cm was significantly higher compared to 22.5-30 cm depth. It may be due to decrease in soil organic carbon with soil depth (Kaur and Singh 2023). In all depths  $K_{\psi}$  also decreased with decrease in soil moisture content. Pooled  $K_{\psi}$  at 26 percent volumetric soil moisture content was 0.19, 0.11, 0.045 and 0.012 cm h<sup>-1</sup> in 0-7.5, 7.5-15, 15-22.5 and 22.5-30 cm depths, respectively and the corresponding values at 10 percent volumetric moisture content were  $5.9 \times 10^{-5}$ ,  $3.4 \times 10^{-5}$ ,  $4.4 \times 10^{-5}$  and  $2.1 \times 10^{-5}$  cm h<sup>-1</sup>. At lower soil moisture content differences in  $K_{\psi}$  among different soil depths were non significant because of less variability in micropores (Seema *et al.*, 2019).



**Fig.3. Effect of cropping systems (a) and soil depth (b) on unsaturated hydraulic conductivity**

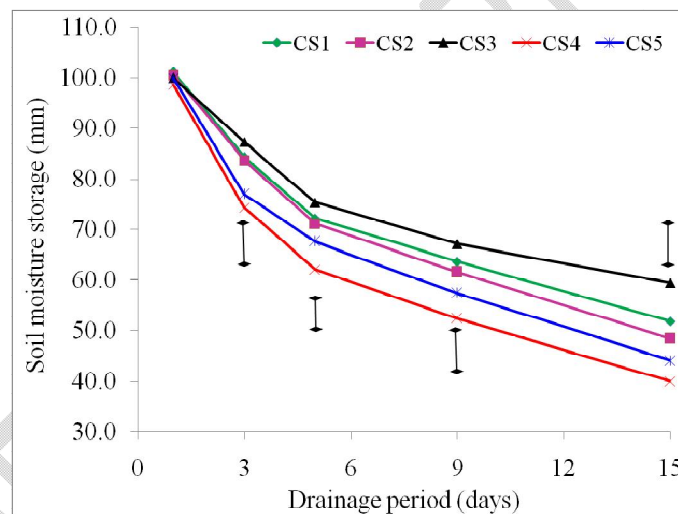
( $\text{cm h}^{-1}$ ) of soil. Vertical bars indicate significant differences at 5% level of significance

**3.7 Deep Drainage:** The curvilinear relationships were obtained between total soil water storage and drainage time under different cropping systems (Fig. 4a). These relationships indicated maximum drainage occurred under  $\text{CS}_4$  and minimum under  $\text{CS}_3$ . However, on evaluating drainage rate as affected by function of time under cropping systems followed the trend:  $\text{CS}_4 > \text{CS}_5 > \text{CS}_2 > \text{CS}_1 > \text{CS}_3$  (Fig. 4b) and Table 5.

**Table 5 Empirical constants of drainage curves ( $W = At^B$ ) for different cropping systems in 0-30 cm profile**

Cropping systems	A	B	R <sup>2</sup>
$\text{CS}_1$	105.1	-0.24	0.972
$\text{CS}_2$	105.8	-0.26	0.960
$\text{CS}_3$	102.4	-0.19	0.978
$\text{CS}_4$	102.9	-0.32	0.981
$\text{CS}_5$	103.6	-0.29	0.973

a)



b)

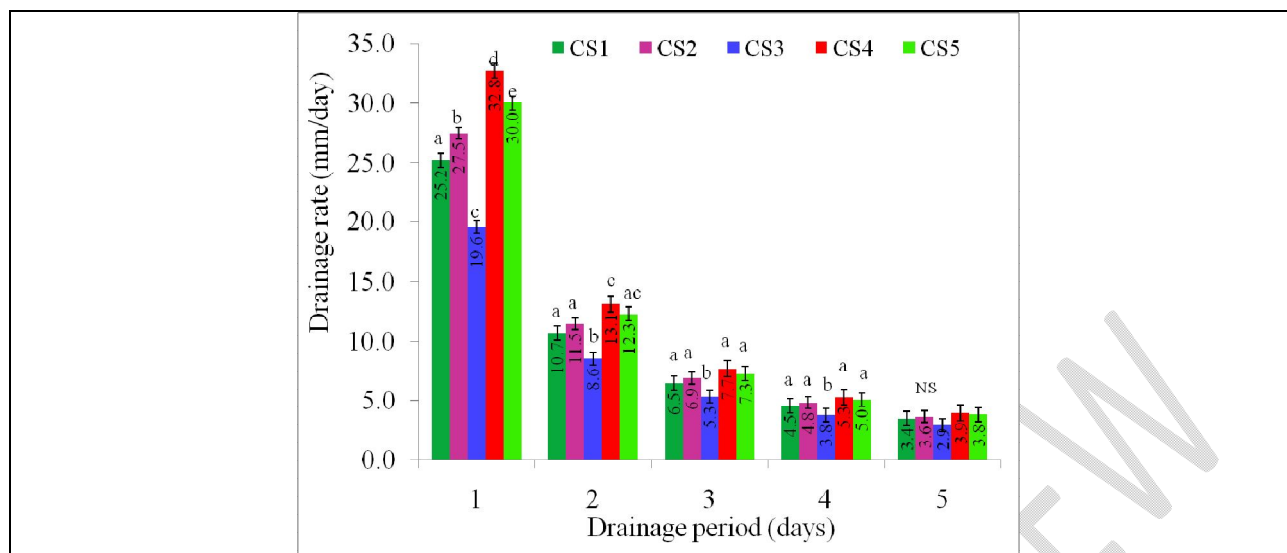


Fig.4. Periodic profile (0-30 cm) a) moisture storage (mm) and b) drainage rate (mm/day) in different cropping systems. Vertical bars indicate significant differences at 5% level of significance

There was steep decline as indicated by a negative and steeper slope under a cropping system. It was maximum under a CS<sub>4</sub> (-0.32) followed by CS<sub>5</sub> (-0.29) followed by CS<sub>2</sub> (-0.26) followed by CS<sub>1</sub> (-0.24) and CS<sub>3</sub> (-0.19). Stone *et al.* (2011) also reported similar observations for estimating drainage of different soils and field conditions. However, the value of intercept obtained was least under the CS<sub>3</sub> (Basmati-wheat) and maximum under CS<sub>2</sub> (sugarcane +vegetables). After 1 day drainage period the drainage rate was 32.8, 30.0, 27.5, 25.2 and 19.6 mm/day in CS<sub>4</sub>, CS<sub>5</sub>, CS<sub>2</sub>, CS<sub>1</sub> and CS<sub>3</sub>, respectively. At this drainage period, drainage rates were significantly different among all cropping systems with highest in CS<sub>4</sub> and lowest in CS<sub>3</sub> (Fig 4b). Generally the drainage rate was of the order CS<sub>4</sub>>CS<sub>5</sub>>CS<sub>2</sub>>CS<sub>1</sub>>CS<sub>3</sub>. After 2, 3 and 4 days drainage period drainage rate was significantly lower in CS<sub>3</sub> compared to all other cropping systems. After 5 days drainage period no any significant difference in drainage rate among cropping systems was observed. The significantly higher drainage rate in CS<sub>4</sub> may be due to more infiltration rate and lighter texture of the soil. The lowest drainage rate in CS<sub>3</sub> may be due to formation of hardpan during puddling in basmati which lowered the saturated hydraulic conductivity and infiltration rate of water into the soil profile.

#### 4. CONCLUSION

Conclusively, maximum water retentivity was observed in sugarcane+bottle gourd-broccoli and highest soil moisture retention at lower suctions and plant available water in poplar+ turmeric cropping systems. Infiltration rate, commulative infiltration, drainage rate, saturated and unsaturated hydraulic conductivity were highest in sugarcane fodder cropping system. However, puddling in basmati-wheat cropping system significantly reduced drainage rate, saturated and unsaturated hydraulic conductivity of the soil. The improvement in soil hydraulic properties in different cropping systems followed the trend of poplar + turmeric ≥ sugarcane + bottle gourd – broccoli > maize + summer moong – wheat > basmati – wheat > sugarcane fodder. Thus, agroforestry and vegetable based cropping system is promising for improvement in soil hydraulic properties in the state of Punjab compared to the prevalent rice (basmati) – wheat cropping system where water availability to crops. The sugarcane fodder based cropping resulted in more water movement through infiltration and drainage due to perennial root decay forming root channels resulting less available water to crops. Favourable changes in soil hydraulic properties were more in surface soil layers compared to sub surface soil layer of 15-22.5 cm.

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