Minimum Soil Disturbance Planting for Rice-based Rotations in Northwest Bangladesh:

Effects on Plough Pan and Water Balance

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Declaration

I declare that the thesis is my own account of my research work that has not been previously submitted for any degree at any other institution at any level.

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Abstract

Soil degradation in the rice-based cropping system of Bangladesh has prompted research to switch from conventional tillage (CT) to minimum soil disturbance crop establishment, featuring strip planting (SP) and increased crop residue retention. However, the new residue retention levels and crop establishment methods need to be tested for their water use efficiency. Therefore, two field trials were initiated to evaluate the effects of SP and bed planting (BP) with increased crop residue retention on soil physical properties, components of the water balance and water productivity in two rice-based crop rotations. Field trials were conducted during 2015-2017 in two long-term conservation agriculture (CA) experimental fields established since 2010 in two regions of northwest Bangladesh, namely 1) Alipur, the alluvial soil region, and 2) Digram, the High Barind Tract (HBT) region. The trials consisted of three tillage treatments in the main plots - SP, BP and CT. The subplots comprised of two levels of residue retention - high residue (HR) and low residue (LR). High residue and LR treatment involved the retention of respectively 50 % and 20 % by the height of the previous crop, either anchored or loose. Strip planting and BP were done with a Versatile Multi-crop Planter mounted on a two-wheel tractor (2-WT).

Seven years of continuous CA practices have provided evidence that minimum soil disturbance and increased residue retention have altered the soil physical properties in both silty loam soil at Alipur and silty clay loam soil at Digram. The physical changes were reflected in the reduction of soil BD, enhancement of total porosity (TP) and reduction of penetration resistance (PR) in the 0-20 cm soil depth. High residue treatment reduced BD from 1.37 to 1.33 g cm^{-3} at Alipur and 1.27 to 1.24 g cm^{-3} at Digram soil in the 0-10 cm soil depth compared to the LR treatment. High residue retention increased macroporosity by an average of 55 % over LR treatment. Irrespective of residue retention, the average (two soils) decrease in BD was 4.5 % and 2.6 % in 0-10 cm depth for SP and BP treatment, respectively, compared to CT. The highest BD of 1.65 g cm^{-3} was achieved at 10-20 cm soil depth in the

CT plot, which clearly indicates a massive plough pan at this depth. However, BD of the plough pan was reduced by 3.8 % in the SP and 4.6 % in the BP treatment indicating the amelioration of subsoil compaction due to the absence of puddling over seven years. Penetration resistance in the plough pan was also decreased from 2.15 MPa (CT) to 1.93 MPa (SP) at Alipur and 2.55 MPa (CT) to 2.32 MPa (SP) at Digram. In the silty loam soil, saturated hydraulic conductivity (K_{sat}) at 0-10 cm under CT was 1.00 cm hr^{-1} which was increased to 1.39 cm hr^{-1} by SP and to 1.52 cm hr^{-1} by BP. In the silty clay loam soil, K_{sat} at 0-10 cm was increased from 0.32 cm hr^{-1} under CT to 0.66 cm hr^{-1} by SP and to 0.81 cm hr^{-1} by BP. In 10-20 cm soil depth, K_{sat} increased from 0.22 cm hr^{-1} under CT to 0.48 cm hr^{-1} by SP and to 0.43 cm hr^{-1} by BP.

Soil compaction by a 2-WT with a single wheel-pass, two wheel-passes, and four wheel-passes with and without extra loading was also tested in non-CA fields adjacent to the two long-term trials. At 0-5 cm depth, soil BD with a single wheel pass was 1.37 g cm^{-3}, which increased to 1.40 g cm^{-3} after two passes, and further increased to 1.47 g cm^{-3} with four passes. The BD of 0-5 cm depth with no extra loading was 1.37 g cm^{-3} which was increased to 1.39 g cm^{-3} with 100 kg extra loading and further increased to 1.43 g cm^{-3} with 200 kg extra loading. At 5-10 cm depth, compaction by CT involving four passes indicated that a 2-WT, when frequently trafficked at this depth for many years, creates a dense soil layer that is reasonably related to the formation of the plough pan. The least limiting water range (LLWR) range could be a good indicator of soil quality in soil compaction studies since the LLWR concept includes the effects of several growth-limiting factors such as matric potential, aeration and penetration resistance that are integrated into a single parameter. Conventional tillage had a larger LLWR which is also comparable to the LLWR of strip tillage single wheel pass treatment. Conservation agriculture practice facilitates tillage, fertilizer and seeding operation in a single pass. Thus, single wheel pass traffic by a low weight 2-WT may not create measurable compaction in the surface soil and the subsurface soil.

High rice residue retention treatment increased wheat yield by 7-18 % in the whole study period (2015-2017) compared to low residue retention. Strip planting increased wheat yield by 18-25 % compared to CT in the three years. By contrast, BP increased wheat yield by 16 % compared to CT in 2015 but not in 2016 or 2017. Strip planting saved 15-36 % irrigation water for wheat growth compared to CT in three years. In contrast to SP, BP saved only 8-25 % irrigation water than CT. Irrigation water productivity of wheat was higher under SP (2.2 kg m^{-3}) than that under BP (1.7 kg m^{-3}) and CT (1.3 kg m^{-3}). The results suggest that SP performed better than BP in terms of crop productivity and irrigation water productivity.

Total water losses under SP continuous flooding irrigation were 80.0-125.0 cm, while the values were 82.0-123.0 cm for BP and 66.0-86.0 cm for CT. Deep drainage during the rice crop for SP, BP and CT accounted for about 41 %, 44 %, and 39 % of the total loss, respectively. Alternate wetting and drying irrigation reduced the drainage losses by 35 %, 26 % and 48 % for SP, BP and CT, respectively. The yield of rice ranged from 6.1-6.9 t ha^{-1}, 6.1-6.6 t ha^{-1} and 6.5-6.7 t ha^{-1} for SP, BP and CT, respectively. Irrigation water productivity for rice was higher under CT (0.88 kg m^{-3}) compared to SP (0.66 kg m^{-3}) and BP (0.60 kg m^{-3}).

Improved crop yield under SP with residue retention should encourage smallholder farmers to adopt minimum soil disturbance planting in the rice-based rotation. However, altered water balance in the non-puddled minimum soil disturbance plot may require more irrigation for rice while allowing greater infiltration to groundwater. In contrast, for wheat, SP and HR had positive effects on water use and water productivity. Since water lost by deep percolation returns to the groundwater and is potentially available for reuse, non-puddled rice can beneficially increase groundwater recharge when practised in a large command area. Hence, CA practices appear to decrease the requirement for groundwater for irrigation of dry season wheat while increasing the potential for groundwater recharge, but this needs further investigation.

Keywords: Barind area (Bangladesh); bed planting; conservation agriculture; conventional tillage; deep drainage; least limiting water range; minimum soil disturbance; number of wheel passes; soil compaction; strip planting; water balance.

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List of Abbreviations

Air-filled porosity	AFP
Alternate wetting and drying	AWD
Americal Society of Agricultural and Biological Engineers	ASABE
Bangladesh Agricultural Research Institute	BARI
Bangladesh Rice Research Institute	BRRI
Bed planting	BP
Bulk density	BD
Centimetre	cm
Centimetre per day	cm day^{-1}
Centimetre per hour	cm h^{-1}
Centimetre per minute	cm min^{-1}
Changes in soil water content	ΔSMC
Conservation Agriculture	CA
Continuous flooding	CF
Controlled traffic farming	CTF
Conventional tillage	CT
Conventional tillage four wheel pass	CT-4Pass
Conventional tillage one wheel pass	CT-1Pass
Crop evapotranspiration	ET_c
Crown root initiation	CRI
Cubic metre	m^{-3}
Cubic metre per hectare	m^3 ha^{-1}
Cumulative infiltration	I
Days after transplanting	DAT
Deep drainage	DD
Deep drainage (percolation+seepage)	D
Deep percolation	DP
Direct-seeded rice	DSR

Field capacity	FC
Food and Agricultural Organization	FAO
Four wheel tractor	4-WT
Gram per cubic centimetre	$g\ cm^{-3}$
Greater than	$>$
Greater than equal	$\geq$
Harvest	H
High Barind Tract	HBT
High residue	HR
Indo-Gangetic plain	IGP
Initial infiltration	I_i
Irrigation	I
Irrigation Water productivity	WP_I
Kilogram	kg
Kilogram per cubic metre	$kg\ m^{-3}$
Kilogram per hectare	$kg\ ha^{-1}$
KiloNewton	kN
KiloPascal	kPa
Least limiting water range	LLWR
Least significant difference	LSD
Less than	$<$
Low residue	LR
Megagram	Mg
Megapascal	MPa
Millimetre	mm
Minute	min
Nitrogen	N
No-tillage	NT
No traffic, no disturbance	No traffic
Not significant	ns

Number of observations	n
Panicle initiation	PI
Penetration resistance	PR
Percent	%
Percent volumetric	% vol
Permanent raised bed	PRB
Permanent wilting point	PWP
Plant available water	PAW
Plant available water capacity	PAWC
Polyvinyl chloride	PVC
Ponding depth	PD
Probability	P
Puddled transplanted rice	PTR
Rainfall	R
Regression coefficient	R^2
Residual Maximum Likelihood	REML
Residue	Res
Rice Wheat	RW
Saturated hydraulic conductivity	K_{sat}
Seepage	SP
Soil organic carbon	SOC
Soil water content	SWC
Southeast	SE
Steady-state infiltration	I_s
Strip planting	SP
Strip tillage	ST
Strip tillage four wheel pass	ST-4Pass
Strip tillage one wheel pass	ST-1Pass
Strip tillage with 100 kg load four wheel pass	ST100-4Pass
Strip tillage with 100 kg load one wheel pass	ST100-1Pass

Strip tillage with 200 kg load four wheel pass	ST200-4Pass
Strip tillage with 200 kg load one wheel pass	ST200-1Pass
Tillage	Till
Tonnes per hectare	t ha^{-1}
Total porosity	TP
Transplanting	T
Two-wheel tractor	2-WT
United States of America	USA
Versatile Multi-Crop Planter	VMP
Water productivity	WP
Water use efficiency	WUE
Year	yr
Zero tillage	ZT

List of botanical names

Chickpea	*Cicer arientinum L.*
Rice	*Oryza sativa L.*
Wheat	*Triticum aestivum L.*

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The author

Dedicated
to
my departed father

1 General Introduction

1.1 Overview

In Bangladesh, rice is planted in about 75 % of the total arable land, while wheat contributes 7 % of the total cereal food production (Hossain and Teixeira da Silva, 2013). As a result of widespread adoption of high yielding varieties of these cereals along with improved crop management technologies and use of irrigation water and chemical inputs, the Indo-Gangetic plain (IGP) experienced an impressive increase in the system productivity during the Green Revolution, which greatly reduced food deficits in Bangladesh, India, Nepal and Pakistan. However, the key to increasing the productivity of such high yielding varieties was to expand the use of irrigation from shallow tube wells and increase the inputs of fertiliser and pesticides, and intensive tillage, but these gains in productivity ignored the long-term effects on the natural resource base and the environment (Ladha *et al.*, 2007). Recent evidence shows that the yields of both rice and wheat have stagnated and, in some cases, declined (Hobbs and Morris, 1996; Ladha *et al.*, 2003; Ladha *et al.*, 2007) due to degrading the soil and water resources (Timsina and Connor, 2001). For example, the demand for the high yielding varieties for water led to over-extraction of groundwater, and intensive cropping caused mining of soil nutrients (Ladha *et al.*, 2007). Most importantly, the adverse effect of degraded soil physical properties reduces crop yield (Dwivedi *et al.*, 2011). Other reasons for the stagnation of the productivity of RW cropping systems are environmental degradation, increasing water and labour shortage, and socioeconomic changes (Rijsberman, 2006; Erenstein *et al.*, 2007).

Soils for monsoon rice and dry season crops are managed differently. For rice, transplanting seedlings into puddled soil is the typical crop establishment technology in the lowlands of South Asia. Puddling involves the cultivation of the soil after it has been softened by flooding for several days, followed by two or three ploughing and harrowing operations, which create a layer of soft mud. This puddled and flooded soil experiences anaerobic conditions that enhance the availability of some nutrients, which is favourable for rice growth (Sanchez, 1973). By contrast, wheat crops are best grown in well-drained soils having good soil structure. Although puddling has positive effects on rice, it is an energy-intensive process. Moreover, puddling degrades soil physical properties by destroying aggregates (Sharma and De Datta, 1986). Repeated ploughing of wet soils at the same depth of 10-15 cm for many years creates an impermeable layer called a plough pan. While puddling and the maintenance of flooded conditions create favourable conditions for rice, it has an adverse effect on the following wheat crop (Hobbs and Gupta, 2000). Excessive wetness in puddled rice soil can delay the planting of the following non-rice crop that results in yield loss by 35-60 kg day^{-1} ha^{-1} in the IGP (Pathak *et al.*, 2003). The optimum sowing time of wheat in Bangladesh is the second half of November, but the yield of wheat is reduced by 1 to 1.5 percent per day from late sowing (Ortiz-Monasterio R *et al.*, 1994; Hobbs and Mehta, 2003). This reduction of yield is similar to the result reported for India (35-40 kg day^{-1} ha^{-1}) by a delay in planting after November 20 (Randhawa *et al.*, 1981).

In contrast to puddling and conventional ploughing, Conservation Agriculture (CA) is a set of practices in which minimal soil disturbance is used to establish crops. In CA systems, < 25 % of soil is disturbed. There is evidence worldwide that shows positive changes in soil physical properties possible under minimum soil disturbance systems. For instance, reducing soil disturbance intensity from the conventional tillage (CT) to zero tillage (ZT) has been reported by Singh *et al.* (2014) to decrease bulk density (BD) at a depth of 15 cm. The higher BD (1.65-1.74 g cm^{-3}) observed in the 15 to 20 cm layer of three soils (sandy loam, loam and clay loam) under CT indicated the development of plough pan beneath the usually tilled layer in both rice and wheat crops for several decades while the lower BD (1.64-1.68 g cm^{-3}) of the same layer under ZT practice demonstrated that repeated ZT helped to reduce sub-soil compaction.

Another soil management system involves permanent raised bed (PRB) and furrow irrigation together with controlled traffic. The PRB system is believed to be an effective method to improve soil properties (Li *et al.*, 2014). The positive effects of PRB cropping systems on soil properties have been demonstrated globally. For example, Li *et al.* (2014) conducted a study with a wheat-maize cropping system on a Fluvent. They found that the overall soil BD (0–30 cm) in PRB plots was significantly lower (by 12.4 %) than that in CT plots, while the penetration resistance (PR) in the 10 to 20 and 20 to 30 cm soil layers of PRB plots were 18.2 and 26.1 % lower, respectively than that of CT. The percentage of water-stable soil macro-aggregates (>0.25 mm) in the PRB plots was 89.8 % ($P < 0.05$) higher than in the CT plots. In arid and semiarid areas, Verhulst *et al.* (2011) evaluated the effects of tillage and residue management in an irrigated PRB system with a wheat-maize annual double-cropping system and stated that PRB improved aggregate stability compared with CT without beds. Holland *et al.* (2008) and Singh *et al.* (2010) demonstrated that PRB was effective in increasing grain yield because of improved soil properties and reduced waterlogging on Loess soils in the Indian Punjab. The PRB system also significantly improved soil structure in arid northwestern China under a spring wheat-maize rotation system compared with CT and no-till (NT) (He *et al.*, 2008; 2012). In semi-humid and humid areas, Naresh *et al.* (2012) tested the effects of PRBs and tilled raised beds with different residue management under irrigated conditions in western Uttar Pradesh under a maize-wheat system and found higher crop yield and aggregate stability with the PRB system. The positive effects of using PRB systems with furrow irrigation have also been confirmed in Shandong province of China for winter wheat in semi-humid areas with a wheat-maize annual double-cropping system (Wang *et al.*, 2004).

Soil compaction has been a problem in crop production in many soils and environments over the past couple of centuries. Draft animals caused soil compaction during cultivation, but as mechanised power has become more common and machinery weights increased, compaction has become more severe. The extent of compacted soil is estimated worldwide at 68 million hectares of land from vehicular traffic alone (Flowers and Lal, 1998). Soil compaction is estimated to be responsible for the degradation of 33 million ha in Europe (Akker and Canarache, 2001) and about 30 % (about 4 million ha) of the wheat belt in Western Australia (Carder and Grasby, 1986). Similar problems related to soil compaction have been reported in almost every continent ((Hamza and Anderson, 2003), Australia; (Aliev, 2001), Azerbaijan; (Ohtomo and Tan, 2001) Japan; (Bondarev and Kuznetsova, 1999) Russia; (Tardieu, 1994) France; (Suhayda *et al.*, 1997) China; (Mwendera and Saleem, 1997) Ethiopia; (Russell *et al.*, 2001) New Zealand).

Random traffic can severely compact the soil, reduce infiltration, and increase energy consumption for subsequent tillage (Li *et al.*, 2000). By contrast, under minimum soil disturbance, vehicular wheeling is confined to the inter-row space for strip planting (SP) and in the furrows between PRBs. If the traffic is reduced in frequency and the wheeling follows the same path year after year, the untilled beds and inter-row space, which is not wheeled, may be restored by natural amelioration. However, a comprehensive and detailed understanding of the mechanisms involved in natural processes of soil amelioration under controlled traffic is required for the IGP. Controlled traffic farming (CTF) recognises the relationship between controlled traffic and ZT in providing options for more productive and sustainable farming of soil uncompromised by wheel effects (Tullberg *et al.*, 2007). The CTF increases soil water infiltration (Li *et al.*, 2001), improves soil structure, increases soil moisture, reduces run-off, and makes field operations more timely and precise (Li *et al.*, 2000). Other studies have shown that controlled traffic with direct drilling provided marked improvements in the timeliness of farm operations, allowing earlier planting opportunities in all types of seasons (McPhee *et al.*, 1995). Controlled traffic farming, combined with minimum soil disturbance, provides a way to enhance the sustainability of cropping and improve infiltration, increase plant-available water, and reduce soil erosion caused by runoff (Hamza and Anderson, 2005).

The intensity of trafficking (number of passes) plays a vital role in soil compaction because deformations can increase with the number of passes (Bakker and Davis, 1995). It is suggested that the most effective means of protecting soil from structure degradation by the action of agricultural machines is to use units that carry out several operations simultaneously (Aliev, 2001). This will lead to a significant reduction in the number of wheel passes. Under CA, the number of passes is reduced since tillage operation, fertilisation and seed placement are performed in a single pass. In Bangladesh, minimum soil disturbance, one-pass planting is being practised by the Versatile Multi-Crop Planter (VMP) which is made by mounting tillage and seeding tools on a 2-wheel tractor (locally known as the Power Tiller) (Haque and Bell, 2017). The 2-wheel tractor (2-WT) is the main source of farm power in many part of Asia, and over 700,000 units carry out > 90 % of farm tillage in Bangladesh (Mandal, 2014). The use of light tractors with a narrow wheel base usually implies an increased number of wheel passes to cover the field (Botta *et al.*, 2006). Håkansson and Reeder (1994b) stated that with a light vehicle, a higher number of passes could cause subsoil compaction. Furthermore, if a 2-wheel tractor (2-WT) is wheeled randomly, soil compaction is distributed all over the field. Therefore, controlled traffic by a 2-wheel tractor might be a possible solution in avoiding the compacted soil structure and reducing the strength of plough pans.

1.2 Research gaps

Conservation Agriculture methods, including minimum tillage and residue retention, has been shown to improve soil properties in many parts of the world (Gill and Aulakh, 1990; Pedro and Silva, 2001; Shaver *et al.*, 2003; Blanco-Canqui and Lal, 2009). Conservation agriculture allows reduced wheel trafficking since tillage, seed placement, and application of fertilizer could be done in only one pass. In addition, a Versatile Multi-crop planter (VMP) (Haque *et al.*, 2011) mounted on a lightweight 2-WT might not transmit its loading and weight into the subsoil. Collectively, minimum tillage with a 2-WT could help to avoid compaction and restoring the degraded subsoil. The plough pan in the rice-based cropping system plays an important role in soil water retention and infiltration characteristics. A weak plough pan under CA could have low BD and high porosity that could help store more water in the root zone compared to conventional tillage (Figure 1.1). Similarly, better-connected pores in the undisturbed soil under CA would increase both steady-state and cumulative infiltration. Since wheat, a dry land crop, and rice, a wetland plant, grow in two different water regimes, increased infiltration through a weak plough pan could be unfavourable for rice, but wheat could beneficially use the water that infiltrated deep in the soil. Furthermore, wheat roots that penetrate deep in the soil through a weak plough pan could access more water from deep soil. Most such studies have been conducted in the western and central IGP, but little is known of the effects of minimum tillage and residue retention on the water balance in the rice-based cropping systems of the Eastern IGP that includes Bangladesh. Hence, this thesis addresses the following specific research:

- Characterize and quantify the relative strength of plough pan under controlled traffic minimum tillage system and determine the changes in soil physical properties that took place over seven years in the soil.
- How do changes in soil physical properties under CA alter the soil hydrologic properties in the root zone depths?

- What is the spatial variability of soil strength and the least limiting water range (LLWR) from light farm machinery traffic with minimum tillage and or controlled traffic compared to conventional tillage?
- What is the effect of minimum soil disturbance planting and crop residue retention on water balance and water productivity for wheat in a rice-based rotation?
- What is the effect of minimum soil disturbance planting (i.e. absence of puddling) and crop residue retention on water balance and water productivity for rice?

In this thesis, three tillage practices, namely SP, BP and CT; together with two residue management practices, namely high residue (HR) and low residue (LR) on soil physical properties of two different soils was evaluated in two long-term experiments established since 2010 in two regions of Northwest Bangladesh. One soil is silty loam in a Level Barind Tract alluvium area, and the other soil is silty clay loam in the High Barind Tract (HBT) area. Soil compaction by a 2-WT with single pass and four wheel passes was also tested in non-CA fields adjacent to the long-term experiments. Components of water balance and water productivity under rice and wheat were also investigated.

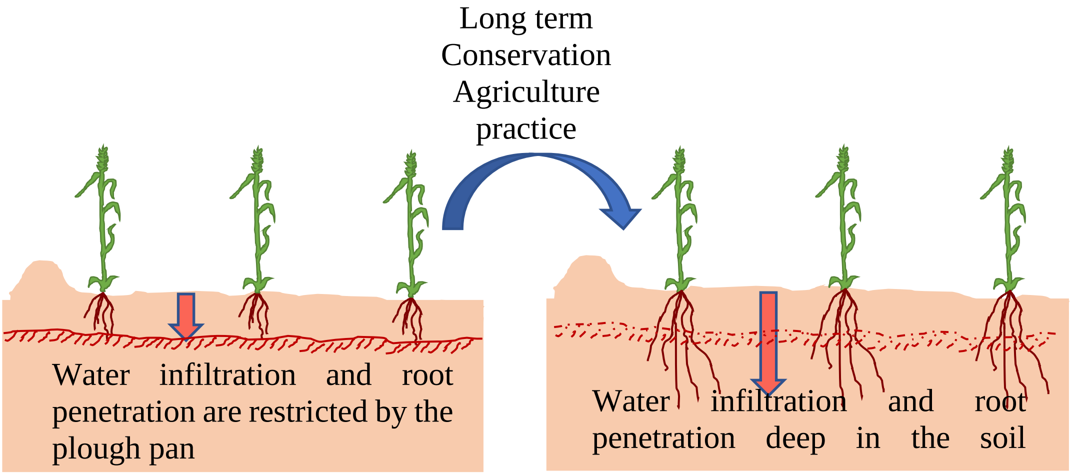


Figure 1.1 Conceptual diagram of water infiltration and root penetration through a weak plough pan after long term Conservation Agriculture practice.

1.3 Hypothesis

This study will firstly propose and provide evidence for the following:

1) Continuous use of long-term (7 years) minimum soil disturbance with residue retention can change the soil physical properties such that they can also alter the soil hydrologic properties in the plant root zone depths.
2) A light tractor can cause much damage to soils when used with an increased number of passes.
3) Minimum soil disturbance over time may destroy or weaken the plough pan and, in turn, alter water balance, which may be detrimental for rice but beneficial for wheat.

1.4 Objectives

Mechanised land preparation and planting has many beneficial effects regarding labour saving and timeliness, but in conventional agriculture in the EGP, limited emphasis has been given to avoiding the potentially deleterious consequences of wheel trafficking, even though research demonstrates the value for soil physical properties.

The general objective of this thesis is to investigate the changes in soil physical properties under SP, PRB (referred to as bed planting or BP) and CT and how these changes in soil structure, particularly in the plough pan, have implications for water balance in the rice-based cropping system of Bangladesh. Therefore, field experiments were conducted to characterise and quantify the relative strength and depth of plough pans under minimum soil disturbance planting. Under this study, minimum soil disturbance planting systems were contrasted to CT regarding the soil physical and hydraulic properties. Due to the soil structural changes, minimum soil disturbance such as SP and BP may affect water balance, which could be beneficial for wheat but might have a detrimental effect on rice. Under this study, contrasts between rice and wheat crop regarding water savings will be addressed. The detailed objectives of the thesis are:

1. To determine the changes in soil physical and hydraulic properties under medium to long-term CA (minimum soil disturbance and increased crop residue retention practice) compared to conventional tillage (Chapter 3)
2. To assess the plough pan responses to controlled-traffic strip planting by a two-wheel tractor (Chapter 4)
3. To determine the effect of CA planting on the water balance of wheat (Chapter 5)
4. To determine the effect of CA establishment on the water balance of rice (Chapter 6)

1.5 Structure of this Dissertation

This chapter has provided a brief background to the subject area and introduced the objectives of the remaining six chapters of this dissertation. Chapter 2 serves as a comprehensive review of the concept of tillage and puddling and CA summarising previous findings. The literature review also covers the consequences of puddling in the degradation of soil, most importantly the plough pan, and the restoration of the degraded soil by practising different forms of minimum soil disturbance for crop establishment. Chapter 2 also reviews the nature of water savings by minimum soil disturbance and effects on water productivity.

Chapter 3 deals with changes in soil physical properties such as BD and PR after practising seven years of CA on two different soil types (Objective 1). It also discusses the changes in soil hydrologic properties such as infiltration and hydraulic conductivity as influenced by the altered soil physical properties. Chapter 4 describes the nature of soil compaction by a 2-wheel tractor with increased loading and number of wheel passes in both the surface soil and subsoil (Objective 2). Chapter 4 also includes the effect of compaction on the least limiting water range of soil at different depths and how chickpea emergence is affected by the soil compaction.

Chapter 5 quantifies the water balance components in a wheat crop as affected by minimum soil disturbance and different water management approach (Objective 3). The amount of water savings and the water productivity of wheat under different tillage treatments are also reported in this chapter. The nature of soil water storage capacity at different depths of different tillage treatments is also discussed in this chapter. Chapter 6 deals with the water balance of wetland rice as affected by different tillage treatment and irrigation methods (Objective 4). The infiltration characteristics under different tillage treatments and how the variability in infiltration influence the irrigation water requirement for rice at different growing stages is also discussed in this chapter. Finally, Chapter 7 discusses the key findings of this work and presents a number of recommendations for further research in this area.

2 Review of Literature

This chapter begins with an overview of the constraints of conventional tillage and the opportunities for overcoming these constraints by minimum soil disturbance, with particular reference to the rainfed lowlands of South Asia. It then reviews the benefits of minimum soil disturbance regarding the changes in soil physical properties. The components of the root zone water balance and the importance of evaporation losses are also reviewed.

2.1 Concept of tillage

Tillage is a process of physically manipulating the soil for weed control, creating a fine tilth and friability, levelling, increasing aeration, enhancing macroporosity, and optimising moisture content in the seedbed to facilitate the subsequent sowing, covering of the seed, seed-soil contact and seedling emergence. In the process, the undisturbed soil is cut, accelerated, impacted, inverted, squeezed, burst and thrown, in an effort to break the soil physically and bury weeds, expose live and dead roots of weeds to drying or to physically destroy them by cutting (Baker and Saxton, 2007). Soil tillage may be defined as physical or mechanical manipulation of soil to modify soil conditions for the purpose of crop production by providing a favourable environment for seed germination and root development, suppression of weeds, control of soil erosion, increase of infiltration and the decrease of evaporation of soil moisture (Prihar, 1990). Among various crop production factors, tillage contributes 20 % of crop production costs (Ahmad *et al.*, 1996). However, due to the increasing cost of crop production, farmers have increasingly adopted reduced tillage or no-tillage technologies for land preparation that minimise cost and detrimental effects on soil properties (Lal, 1990).

2.2 Conventional Tillage

Conventional tillage for rice or wheat usually requires multiple passes of a plough to breaking the clods and level the field (Hobbs, 2001). Conventional tillage operations, when done by tractor power, have a high fuel consumption, take many days to complete, compact soil and damage soil structure (Mitchell, 2009). Hence there are many negative aspects of tillage that have to be weighed against the apparent benefits outlined above. Some of the negative aspects of tillage are exacerbated in rice-based crop rotations due to the added process of puddling that is highly destructive to soil structure.

2.3 Puddling

The most common practice for establishing rice in the RW systems of South Asia is puddling. Puddling refers to a tillage system in which soil is repeatedly ploughed and harrowed under submerged conditions to make the soil soft for transplanting and less permeable to water (Hobbs, 2001; Sharma *et al.*, 2003). Soil puddling degrades soil structure and leads to reduced infiltration rates (Kirchhof and So, 1996a). Puddling destroys soil aggregates and thus changes soil physical properties such as BD, soil structure and soil strength. Puddling facilitates the early root growth from transplanted rice seedlings, but in wetland rice, 90 % of roots are confined to the shallow puddled soil layer (El-Henawy, 2013).

The strength of puddled soil increases rapidly during drying, and the unstructured soil becomes massive (Cook *et al.*, 1995). Puddling reduces root growth and distribution of crops grown under dryland conditions after rice (El-Henawy, 2013). The poor physical conditions are the major limiting factors for successful dryland crop cultivation (Kirchhof and So, 1996a). Puddling consumes about 20 to 25 cm of water, which resulted in 17 % of the total water use by transplanted rice (Mahajan *et al.*, 2011).

Figure 2.1 Soil puddling by a two-wheel tractor and levelling for conventional transplanting of rice.

2.4 Plough pan

Wet ploughing and puddling results in the formation of compacted soil layers below the puddled zone called the plough pan. Hobbs and Morris (1996) reported that subsurface compaction in puddled soils adversely affects the yield of the crop following wetland rice due to a reduction in root penetration through the shallow plough pan. The development of a plough pan in the rice field is considered to be an important consequence of conventional tillage practices (Jong Van Lier *et al.*, 2000; Machado, 2003; Silva *et al.*, 2003; Alves and Suzuki, 2004; Reichert *et al.*, 2007). The strength of a plough pan increases very rapidly as the soil dries, limiting the depth of root exploitation for the dryland crops (So and Ringrose-Voase, 1996). The plough pan helps reduce percolation losses and increases water holding capacity for rice crops (De Datta *et al.*, 1978) but creates detrimental effects for the following dryland crops (Aggarwal *et al.*, 1995). Conventional ploughing and puddling over time promote the development of drought-prone crops due to shallow root systems confined to soils above the plough pan. Crops growing on soil with plough pans have poorly developed root systems which restricts access to nutrients deeper in the profile as well as water. Aggressive weeds can have devastating effects on shallow crops with poorly developed root systems and compromise their ability to absorb nutrients. Another consequence of the plough pan is the increased lodging (falling) of tall crops. Crops fall because their root systems are too shallow to support them.

2.5 Conservation Agriculture

In contrast to conventional tillage, Conservation Agriculture (CA) is an approach to managing agroecosystems for improved and sustained productivity and increased profits while preserving and enhancing the resource base and the environment (FAO, 2015). Conservation Agriculture is characterised by three principles: minimum soil disturbance, maintenance of permanent soil cover, and judicious crop rotation (Hobbs, 2007). Conservation Agriculture is practised in all continents and in many cropping systems, including rice-based systems, both rainfed and irrigated around the world. The global total CA cropland area in 2015-16 was 180 M Ha, which is about 12.5 % of the total global cropland. The increase in the global CA cropland area since 2008-09 has continued at an annual rate of about 10 M ha, and since 2013-2014, the increase has been about 14.6 %. By 2015-16, the CA cropland area in Asia had increased by 435 % (from 2.6 M ha to 13.9 M ha) relative to 2008-09 and by 35 % (10.3 M ha to 13.9 M ha) from 2013-14 (Kassam *et al.*, 2019). The regional spread of the CA cropland area is presented in Table 2.1.

Table 2.1 Regional area of annual cropland under Conservation Agriculture (CA) in 2015-16

Region	Cropland area (M ha)	% of global CA	% of arable land
South America	69.9	39.0	63.2
North America	63.2	35.0	28.1
Australia and New Zealand	22.7	12.6	45.5
Asia	13.9	7.4	3.8
Russia and Ukraine	5.7	3.2	3.6
Europe	3.6	2.0	5.0
Africa	1.5	0.8	1.1
Global total	180.5	100	12.5

Adapted from Kassam *et al.* (2019).

2.6 Advantages and disadvantages of Conservation Agriculture

The beneficial effects of CA have been widely studied for several decades and include enhancement of biodiversity in agricultural production systems (Govaerts *et al.*, 2007a), reduced air pollution, time and labour savings (Mahajan *et al.*, 2013; Sidhu *et al.*, 2015), increased soil organic matter content (González-Sánchez *et al.*, 2012); reduced CO_2 emissions (Lal, 2005; Carbonell-Bojollo *et al.*, 2011), greenhouse gas (GHG) mitigation (Alam *et al.*, 2016), reduced soil erosion (Baker *et al.*, 1996; Espejo-Pérez *et al.*, 2013), improved water infiltration (Thierfelder and Wall, 2009), yield increase over time (Jat *et al.*, 2014), and economic benefits for farmers (Uri *et al.*, 1998; García-Torres *et al.*, 2013) by reducing production cost.

Short-term disadvantages include the high initial costs of specialised planting equipment and the completely new dynamics of a conservation farming system, requiring new operational and management skills by farmers.

2.7 Minimum soil disturbance

Minimum soil disturbance means reducing soil disturbance to the minimum necessary for placement of seed and fertiliser. Instead of ploughing the whole field, minimum soil disturbance opens up only a planting lane for seeding. Based on the CA definition of FAO (2015), soil disturbance should be less than 25 %. When using the same lanes year after year, minimum soil disturbance leads to an improved soil structure that facilitates better water infiltration (Erenstein, 2002; Govaerts *et al.*, 2005; Hobbs, 2007).

2.1.1 No-tillage or Zero Tillage

Under zero tillage (ZT), the land is not tilled at all. The minimum soil disturbance is achieved with special equipment like coulters, row cleaners and tine openers. Under ZT, the soil is not inverted and mixed with the crop residues, and this seems to profoundly impact many soil properties, particularly in the upper soil layer (D'Haene *et al.*, 2008). Macro pores, which are the major route for water movement through soil, remain intact under ZT and thus enhance water infiltration. The infiltrated water penetrates deep in the soil profile where it is less likely to evaporate into the atmosphere.

2.1.2 Strip Planting

Strip planting has the potential of creating an ideal seedbed condition (i.e. lower BD and PR) by combining the benefits of conventional tillage with those of zero tillage (Licht and Al-Kaisi, 2005a). Strip planting removes crop residues in a narrow zone of soil and loosens topsoil in a narrow strip (6-7 cm) prior to planting (Vyn and Raimbult, 1993; Temesgen *et al.*, 2007). Strip planting operation leaves the inter-row residue in place while disturbing a narrow zone for seed and fertiliser placement and has attracted the attention of many producers during the last decade. As a result, macro pores which are the major route for water movement through soil, remain unbroken across over > 75 % of the soil surface. Macro pores enhance water infiltration, which helps irrigation or rain water penetrate deep into the soil profile.

Water infiltrated in deep soil is less likely to evaporate and plant roots can uptake more water under SP. These merits of SP might be beneficial for post rice crops in terms of quick drainage of water and reduced waterlogging and reducing irrigation requirement and increasing water use efficiency.

Licht and Al-Kaisi (2005b) conducted a study to evaluate the effect of SP on soil physical properties compared with a chisel plough and no-tillage approaches. The study was conducted on loam (Aquic Hapludoll) and silty clay loam (Typic Haplaquoll) soils in Iowa. Strip planting at both sites resulted in leaving a mound 7–10 cm in high. Penetration resistance was similar (0.1-1.2 MPa) for both SP and NT but commonly greater than chisel plough (0.65-0.75 MPa) in the upper layer (0–20 cm) of the soil profile. At lower depths of the soil profile, SP generally resulted in a decrease in PR (0.75 MPa) compared with a chisel plough and NT (1.0-1.2MPa). The positive aspects of SP are that in the inter-row space, the soil remains untilled, allowing natural swelling and shrinkage process to weaken the plough pan beneath the inter-row space over time. On the other hand, machinery traffic is confined to the inter-row areas, which therefore creates compaction only in the inter-row spaces where wheel pass is performed and leaves the strips uncompacted.

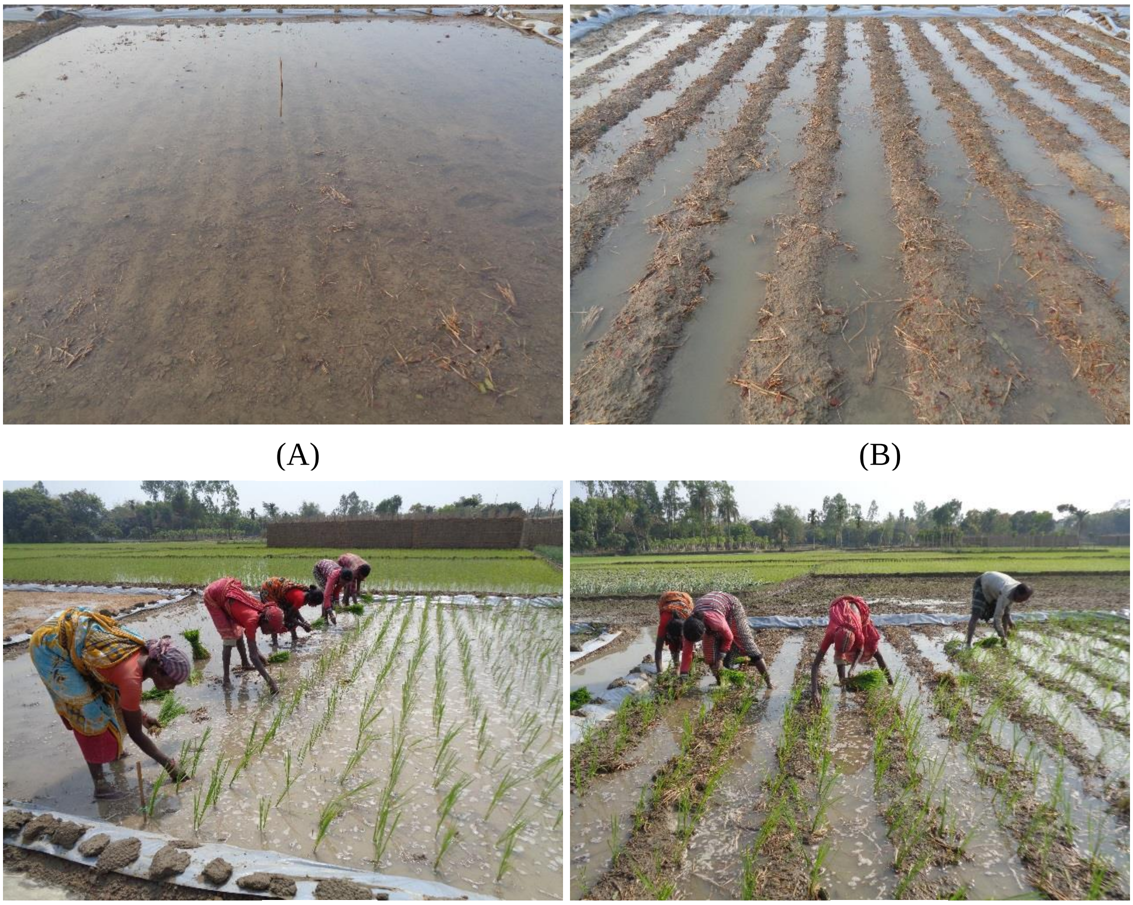
2.1.3 Bed Planting

Permanent bed planting (BP) and furrow irrigation which combines reduced tillage with controlled traffic, have proven themselves to be an effective method to improve soil properties (Li *et al.*, 2014). In this system, raised beds are prepared using a bed-forming machine. Crops are planted in rows on the top of the bed, and irrigation water is applied in the furrows between the beds. Raised beds encourage the concepts of minimum soil disturbance and controlled traffic, thus minimising the compaction on the majority of the paddock and delivering benefits in soil physical properties (Tullberg *et al.*, 2001; Tullberg, 2001; Peries *et al.*, 2004). As the wheels pass through furrows of the BP system, soils in the furrows are compacted, which restricts irrigation water infiltration and makes a favourable condition for rice cultivation. Furthermore, in the beds, the soil is not compacted, which helps plant roots to penetrate deeper into the soil and extract water which is favourable for plant growth.

Figure 2.2 Strip planting and reshaping of permanent beds before water inundation for the establishment of transplanted rice.

2.8 Non-puddled transplanting of Rice

While the most common practice of rice establishment is the transplanting of rice seedlings in the puddled soil, recently suitability of rice transplanting into the minimum soil disturbance non-puddled soil has been tested. The minimum soil disturbance non-puddled transplanted rice yielded a similar grain yield compared to that under full tillage puddled soil (Haque *et al.*, 2016). Under this rice establishment, seedlings are transplanted after minimum soil disturbance operation (such as strip tillage, bed formation or zero tillage) followed by 18 hours of soaking of the field with water to soften the soil (Hossen *et al.*, 2018).



(A) (B)

(C) (D)

Figure 2.3 Overnight inundation under the water of (A) strip planting (B) bed planting plot and non-puddled transplanting of rice (C) in strips under strip planting and (D) on beds.

2.9 Effect of minimum soil disturbance on soil physical and hydrologic properties

Vigorous plant growth needs a favourable soil physical condition for the roots to acquire adequate oxygen, water, and nutrition. Tillage enhances macroporosity and pore continuity which in turn allows water to infiltrate into the soil profile and be stored. Furthermore, when excess water is applied as either rainfall or irrigation, the improved hydraulic conductivity of the soil structure facilitates quick drainage of water and air entry. The excessive pulverisation of soil by conventional tillage can also accelerate losses of water by evaporation from the surface soil. Under the ZT, the land is not tilled at all, and there is less scope of water loss by evaporation. Thus, SP by loosening the topsoil in a narrow strip creates a soil physical condition that is intermediate between the soil physical conditions of CT and ZT. Conservation Agriculture leaves most or part of the crop residues on the soil surface, thus affecting soil chemical, biological, and physical properties. Soil temperature, water content, BD, porosity, PR, and aggregate distribution are some of the physical properties affected by different tillage systems. Therefore, this section reviews how strip planting and bed planting in association with residue retention affect these properties in the RW system, in particular.

2.1.4 Soil bulk density

Minimum soil disturbance greatly influences BD by altering the degree of compaction. The results from many studies, reviewed below, proved an improvement in BD with ZT and surface residue retention. However, the rate of change varied greatly across the studies. Many studies show that the changes took place in the topsoil after only a few years and other studies revealed that the depth of the effects increases with a number of years.

Changes in soil physical properties due to the use of ZT depend on several factors, including soil properties, weather conditions, history of management, and intensity, and type of tillage (Mahboubi *et al.*, 1993). Several authors found greater soil BD under CA than conventional tillage (Hammel, 1989; Ferreras *et al.*, 2000), while others did not find differences (Hill and Cruse, 1985; Chang and Lindwall, 1989) or obtained lower values of BD under soils with a residue layer on the surface (Edwards *et al.*, 1992; Lal *et al.*, 1994). Tillage reduces the BD of the plough layer by increasing porosity (Rasmussen, 1999; Gangwar *et al.*, 2006), although the effect diminishes with time (Suwardji and Eberbach, 1998).

Many studies show higher BD of the topsoil with ZT and surface residue retention compared to CT without residue after a few years, and the BD is further increased when ZT with residue is practised more than ten years (Table-2.2). The increase in BD under ZT is attributed to different processes, such as heavy machinery (Soane *et al.*, 1982; Raper *et al.*, 1998;

Mosaddeghi *et al.*, 2000; He *et al.*, 2009b) or settling of the soil particles (Cassel and Nelson, 1985; Bhattacharyya *et al.*, 2008). On the contrary, there is also evidence of lower BD with ZT and residue retention after 4 to 22 years. Long-term experiments (>20 years) on a silt loam in Central Ohio showed that the BD decreased from 1.46 to 1.31 g cm^{-3} in 0-10 cm depth under NT (Kahlon *et al.*, 2013). Pedro and Silva (2001) reported that after 11 years of soybean-wheat/hairy vetch-maize cultivation, the soil BD of a forest Oxisol is lower under NT than under CT (disc plough followed by two light discs harrowing). Gill and Aulakh (1990) also reported that on a silty soil, the BD of 0-10 cm depth significantly decreased from 1.45 g cm^{-3} under CT to 1.38 g cm^{-3} under NT, and at 10-20 cm BD decreased from 1.48 g cm^{-3} under CT to 1.45 g cm^{-3} under NT, while, the grain yield of wheat increased under NT compared to CT. By contrast, CT generally increases the BD of the subsoil and creates a plough pan at the bottom of the tilled layer (Kahlon *et al.*, 2013). This happens in puddled rice systems in particular (Aggarwal *et al.*, 1995; Jat *et al.*, 2009).

The effect of ZT on soil BD also depends on various initial soil physical conditions. The increase in BD was greater in soils when the initial BD was lower than 1.30 g cm^{-3}(Alvarez and Steinbach, 2009). Tillage causes instantaneous loosening of the topsoil, but it can also cause instantaneous compaction when done at the wrong moisture content (Baver *et al.*, 1972).

Table 2.2 Effect of zero tillage (ZT) or no-tillage (NT) and residue retention on soil bulk density as compared to conventional tillage (CT)

Reference	Experimental location	Soil	Crop	Year	Tillage treatments	Residue management	Changes in bulk density
Jemai *et al.* (2013)	Mateur, Tunisia	Loam to Clay Loam	Durum wheat, etc.	2001-2007	NT, CT	Wheat Residue permanent mulching	Lower in NT (1.18 g cm^{-3}) than CT (1.25 g cm^{-3}) at 0-30 cm.
He *et al.* (2011)	Hebei Province, North China	Silt Loam	Wheat-maize	1998-2009	NT, CT	Maize Residue Retained	The mean BD in NT was 0.03 g cm^{-3} and 0.07 g cm^{-3} lower than CT in 0-10 cm and 10-20 cm, respectively.
He *et al.* (2009b)	Loess Plateau, China	Clay Loam	Wheat	1992 to 2007	NT, CT	With Residue, 15-25 cm high Stubble Left as mulch	Initially, the change in BD was negligible. However, after 16 years, soil BD in the 20-30 cm soil layer was significantly less in NT (1.43 g cm^{-3}) than that in CT (1.54 g cm^{-3}).
Gill and Aulakh (1990)	Mbala, Zambia	Silty and Clay	Wheat	1981-82 to 1982-83	ZT, Harrowing, Ploughing, Chiselling. At-planting, Residue removed	Residue removed	BD of 0-5 depth was significantly lower (1.28 g cm^{-3}) under ZT than CT (1.34 g cm^{-3})
Alam *et al.* (2014)	Gazipur, Bangladesh	Clay Loam	Wheat-mungbean-rice	2008-1012	ZT, Minimum Tillage, CT, Deep Tillage	--	BD decreased by 0.14 g cm^{-3} in ZT compared to the initial value (1.60 g cm^{-3}).
Jat *et al.* (2009)	Uttar Pradesh, India	Sandy Loam	Rice-Wheat	2005-2007	ZT, Raised Bed, CT	Residue Removed, 7.5 cm stubble retained	BD was higher in ZT at 0-5 cm and 5-10 cm depth whereas lower at 10-15 cm and 15-20 cm depth

Reference	**Experimental Location**	**Soil**	**Crop**	**Year**	**Tillage Treatments**	**Residue Management**	**Changes in Bulk Density**
Dwivedi *et al.* (2012)	Modipuram, India	Sandy Loam	Rice-wheat	2000-2001 to 2002-2003	Pre-puddling by discing + harrowing then multiple puddling operations	--	ZT decreased BD at 0-15 cm. Higher BD was reported at 28-33 cm depth with increasing puddling intensity.
Islam *et al.* (2012)	Rajshahi, Bangladesh	Silty Loam	Rice-maize	2009-2011	SP, BP, Single-pass wet tillage, CT, ZT	Previous crop residue retained	At 0-15 cm depth, BD was significantly the lowest under BP (1.20 g cm^{-3}) than that under CT. The second lowest BD was under SP.
Ram *et al.* (2010)	Ludhiana, India	Loamy Sand	Maize-wheat	2003 to 2004	CT, NT, Permanent and Fresh Raised Bed	Wheat Straw Mulch	NT with straw and BP with Straw reduced the BD slightly compared to without straw treatments.
Kahlon (2014)	Ludhiana, India	Sandy Loam and Loamy Sand	Rice-wheat	--	NT, Roto-tiller, Happy seeder =NT with residue	With and without residue	No significant differences among different tillage practices
Pelegrin *et al.* (1990)	Seville, Spain	Sandy clay loam	Cereal-sunflower	1984-1987	NT, Disc Ploughing, Mouldboard ploughing, Cultivator Application, Disc Harrowing	--	BD was higher (1.64 g cm^{-3}) in NT than other tillage treatment at 0-20 cm depth.

Reference	**Experimental Location**	**Soil**	**Crop**	**Year**	**Tillage Treatments**	**Residue Management**	**Changes in Bulk Density**
Dikgwatlhe *et al*. (2014)	Hebei Province, North China	Silt Loam	Wheat-maize	2001-2014	Mould Board Plough, Rotary Tillage, NT	Maize Residue Removed, Residue incorporated	Soil BD was significantly higher under NT compared to the other three tillage systems in all depths and years
Dam *et al*. (2005)	Quebec, Canada	Loamy Sand	Corn	1992 to 2002	NT, Reduced Tillage, Conservation Tillage	With and Without residue tillage	At 0-10 cm depth, NT and no residue was found to have a greater BD (1.36 g cm^{-3}) than the CT (1.21 g cm^{-3}).
Gangwar *et al*. (2006)	Modipuram, India	Sandy Loam	Rice-wheat	1998-1999 to 2000-2001	ZT, reduced/strip tillage, CT	Rice Straw Removed, Burnt, Incorporated	Soil BD decreased with an increase in the level of tillage—lowest (1.60 g cm^{-3}) under CT and highest (1.68 g cm^{-3}) under ZT.
Bhattacharyya *et al*. (2006a)	Uttaranchal, India	Sandy-clay-loam	Soybean-wheat, Soybean-lentil, Soybean-field pea	1999-2003	ZT, Minimum Tillage, CT	--	Significantly higher in ZT (1.35 g cm^{-3}) than CT (1.34 g cm^{-3}) at 0-7.5 cm. Similar, ZT (1.40 g cm^{-3}) and CT (1.40 g cm^{-3}) at 22.5-30 cm depth
Gathala *et al*. (2011b)	Uttar Pradesh, India	Sandy Loam	Rice-wheat	2003 to 2009	ZT, Raised Bed, CT	--	Higher (1.55 g cm^{-3}) in ZT than CT (1.48 g cm^{-3}) at 0-5 cm. However, lower (1.71 g cm^{-3}) in ZT than CT (1.76 g cm^{-3}) at 16-20 cm.

Changes in soil BD can occur with or without residue retention following the adoption of ZT (Stone and Schlegel, 2010; Kuotsu *et al.*, 2014). Over an extended period, retention of previous crop residue in ZT generally reduces soil BD (Ghuman and Sur, 2001; Blanco-Canqui and Lal, 2009). After 16-years of application, with residue retention, ZT reduced soil BD of 20-30 cm soil layer compared to CT (He *et al.*, 2009b). The effect of residue retention on BD also depends upon the nature and amount of residue, climate and soil type (Blevins and Frye, 1993; Jemai *et al.*, 2013). Over a 12-year period, the addition of each extra tonne of crop residue per hectare reduced soil BD by 0.01 g cm^{-3} and increased effective porosity by 0.3 % in the surface 2.5 cm soil depth in wheat-fallow, wheat-corn-fallow and continuous cropping (Shaver *et al.*, 2003). Irrespective of tillage methods, Kahlon *et al.* (2013) observed a decrease in BD of the topsoil (0-10 cm) with increasing mulch rate from 0 to 16 t ha^{-1}. Application of mulch of fodder radish decreased the soil BD and increased transmission pores in the 0-10 cm soil layer (Głąb and Kulig, 2008). The method of residue addition also significantly influences the soil BD. Soil BD was lower when crop residue was incorporated compared to when it was retained on the soil surface as mulch (Acharya *et al.*, 1998). Bhattacharyya *et al.* (2006a) observed that soil BD was significantly lower in a CT system compared to ZT due to the incorporation of crop residues in the surface soil of CT in the Indian Himalayas. After 11-years of a wheat-maize system, He *et al.* (2011) reported an effect of residue retention on BD at 0-20 cm, whereas Dikgwatlhe *et al.* (2014) observed the effect of NT with residue retention on BD in the 0-50 cm depth.

2.1.5 Khepar *et al.* (2000)Soil water storage

Many studies throughout the world have indicated that one of the benefits of ZT is water conservation through the maintenance of surface residue. Conservation Agriculture leads to positive changes in soil physical properties, such as aggregation (Dalal, 1989; Dalal and Bridge, 1996), aggregate stability (McQuaid and Olson, 1998) and soil water content (Pelegrin *et al.*, 1990; Mahboubi *et al.*, 1993; Norwood, 1994; Lampurlanés *et al.*, 2001). An increase in soil water storage under CA has been attributed to a mulching effect of stubble and crop residue on the soil surface that reduces water loss by evaporation (Jones *et al.*, 1968; Blevins *et al.*, 1984; Munawar *et al.*, 1990; Phillips and Phillips, 2012). Reduction or slowing down of water loss by evaporation under CA is also attributed to the lower soil temperature in CA compared to CT (Alam *et al.*, 2018b). Retaining stubble and crop residue also improves water infiltration (Triplett *et al.*, 1968; Shipitalo *et al.*, 2000) and increase soil water storage since water that infiltrated deeper in the soil profile is less likely to evaporate quickly.

Conservation Agriculture practices such a ZT and residue retention are important tools for conserving water (Reeves, 1994) and its transmission (Azooz *et al.*, 1996). Jemai *et al.* (2013) reported the highest soil water storage at 0-30 cm under NT with residue compared to CT in a clay loam soil after 3 and 7 years in a wheat-oat/sulla/faba bean/fenugreek rotation. In northeast China, Liu *et al.* (2013a) reported higher soil water content (SWC) under NT than in CT at 0-30 cm soil depth. In North Cameroon, Naudin *et al.* (2010) found improved SWC and corn yield under NT or reduced tillage (RT) compared to CT. However, there are a few reports on the effects of ZT with surface rice straw retention on water holding capacity in the RW system. Pagliai *et al.* (2004) reported that soil water storage was lower under CT that reduced wheat root growth cultivated after rice. In an RW cropping system with CA, increased water holding capacity was reported in the surface soil after ten years of rice straw incorporation (Bellakki *et al.*, 1998). In two different soils of Ludhiana, India, Kahlon (2014) found maximum soil water storage under NT with residue followed by NT without residue and Roto-tiller. No-tillage with residue is especially effective in enhancing soil water storage (Ma *et al.*, 2008; Kumar *et al.*, 2014). Bhattacharyya *et al.* (2006a) reported that in sandy clay loam, the soil under ZT retained significantly more water than soil under minimum soil disturbance and CT at 0-7.5 and 7.5-15 cm soil depth. They also suggested that higher soil water storage has been attributed to the significant rearrangement of pores near the soil surface. In a sandy clay loam soil in Seville, Spain, Pelegrin *et al.* (1990) observed that NT treatment showed higher soil water storage in the surface layer (0-20 cm) at the mid-season of rainfed wheat. However, Alam *et al.* (2014) reported that the available water content was lower in the ZT plots compared to the deep tillage plots. He *et al.* (2011) reported that in north China over an 11-year experiment, NT increased soil water storage by 19.3 % at 0-30 cm soil depth compared to conventional ploughed soil. The results of an increase in soil water storage under CA also suggest that there is a close relationship between reduced soil BD and increased soil water storage. Another experiment by He *et al.* (2009b) revealed that in the 0-20 cm soil layer, NT treatment increased mean SWC by 6.3 % compared with CT treatment. In the deeper soil layer (20-30 cm), soil water in NT was 10.9 % greater ($P < 0.05$) than that of CT. They also suggested that the improvement at this depth which is below the plough layer, could have been attributed to the lower soil BD and higher mesoporosity of NT treatment (Yang and Wander, 1998). Soil water storage is one of the most responsive soil physical parameters to crop residue removal, and rapid evaporation takes place in an unprotected soil when the crop residue is removed (Blanco-Canqui and Lal, 2009). By contrast, crop residues improve soil water storage by increasing soil organic matter concentration, which increases water retention capacity of the soil (Blanco-Canqui and Lal, 2009)

2.1.6 Hydraulic conductivity and infiltration rate

The effect of tillage on infiltration rate is variable, as tillage disrupts macropore continuity which sometimes results in reduced infiltration rate and hydraulic conductivity (Godwin, 1990; Logsdon *et al.*, 1990; McGarry *et al.*, 2000), while in other short and medium-term studies tillage increased infiltration rate (Pelegrin *et al.*, 1988; Ferreras *et al.*, 2000; Bhattacharyya *et al.*, 2006b; Bhattacharyya *et al.*, 2008). The effect also varies with time after tillage. Several studies reported higher saturated hydraulic conductivity (K_{sat}) under CT than ZT at the start of the growing season due to increased porosity (Radcliffe *et al.*, 1988; Hill, 1990; Suwardji and Eberbach, 1998), but K_{sat} in the tilled soil decreased to values similar to those in the ZT soil as the season progressed (Suwardji and Eberbach, 1998). Lower K_{sat} of the topsoil in ZT systems has been attributed to higher BD (reduced pore size) when compared with CT (Rasmussen, 1999; Tebrügge and Düring, 1999; Singh *et al.*, 2002a). Conversely, a higher K_{sat} and infiltration rate with ZT than CT has been associated with the development of earthworm channels and termite galleries (Tebrügge and Düring, 1999; McGarry *et al.*, 2000). In an RW cropping system, laboratory-determined values of K_{sat} in the 5-10 cm soil depth were higher with ZT than with tillage after four years of treatment implementation (Bhattacharyya *et al.*, 2006b; Bhattacharyya *et al.*, 2008). The higher K_{sat} with ZT was attributed to better aggregate stability, better pore continuity and larger pore size than in the tilled soil (Bhattacharyya *et al.*, 2006a).

Crop residues increase soil hydraulic conductivity and infiltration rate by modifying soil structure and aggregate stability. The magnitude of the effects on these properties depends on the quality and amount of residues, the time since residue retention commenced, the tillage system, and the climate (Blanco-Canqui and Lal, 2007b). Increases in hydraulic conductivity have been reported for both surface retention in ZT systems and partial incorporation conservation tillage systems (Murphy *et al.*, 1993). Increases in hydraulic conductivity of up to 8-fold in ZT residue-retained treatments have been reported over ZT with stubble burning after 15 years (Valzano *et al.*, 1997). Residue mulch or partial incorporation has also been shown to increase the infiltration rate by reducing surface sealing and decreasing runoff velocity (Box *et al.*, 1995; Pikul and Aase, 1995). Baumhardt and Lascano (1996) reported that mean cumulative rainfall infiltration was least for bare soil and increased curvilinearly with increasing residue rate up to 2.4 t ha^{-1} due to increasing raindrop interception.

In the RW systems of the IGP, many studies have shown increased infiltration and hydraulic conductivity with the incorporation of both wheat and rice residues after 2-10 years (Bhagat and Verma, 1991; Walia, 1995; Bellakki *et al.*, 1998; Das *et al.*, 2001) however, information on the effect of surface residue retention on infiltration rate are scarce. In a short-term RW system study, Kahlon (2014) did not observe any effect of residue retention on infiltration rate with ZT. However, Kahlon *et al.* (2013) reported an increase in hydraulic conductivity and infiltration rate with increasing mulch rate from 0 to 16 t ha^{-1} under ZT after 22 years in a 'no crop' study. Similarly, Barzegar *et al.* (2002) observed that infiltration rate and water retention increased linearly with an increase in a mixture of farmyard manure, wheat straw and composted bagasse from 0 to 15 t ha^{-1}.

2.10 Effect of minimum soil disturbance on water saving and water productivity

A brief review of water saving by different tillage methods is presented in Table 2.3.

Wang *et al.* (2004) conducted an experiment assessing the performance of wheat under the furrow irrigated raised bed compared to flat planting with flood irrigation. Higher values of water use efficiency were reported for the furrow irrigated raised beds (1.96–1.99 kg grain m^{-3}) than for the flat-planted wheat with flood irrigation (1.51–1.67 kg grain m^{-3}). Cultivation of wheat on furrow irrigated raised beds resulted in 17 % lesser consumption of irrigation water as compared to that in flat beds with flood irrigation.

Fahong *et al.* (2004) carried out an experiment for assessing the performance of wheat under the furrow irrigated raised bed and flat planting with flood irrigation. Higher values of water use efficiency were reported for the furrow irrigated raised beds, i.e. 1.96–1.99 kg grain $m^{-3,}$ while for the flat planted wheat with flood irrigation, the values of water use efficiency were considerably lower, i.e. 1.51–1.67 kg grain m^{-3}. Cultivation of wheat on furrow irrigated raised beds resulted in lesser consumption of irrigation water by 17 % as compared to that in flat beds with flood irrigation.

Fahong *et al.* (2005) reported that the cultivation of wheat on raised beds resulted in an improved water use efficiency to the extent of 40 to 90 %. The possible explanation for such high values of water use efficiency includes more wastage of water due to unnecessarily excessive irrigation in flat planting and a favourable and conductive micro-climate, which resulted in better crop stand and lesser disease infestation in a crop planted on raised beds. They also noted that thicker and shorter basal internodes contributed to improved lodging resistance in wheat on raised beds.

Ahmad and Mahmood (2005) reported that in comparison to the flat method of planting, wheat cultivated on raised beds resulted in 15 % reduced lodging, 13 % more yield, 51 % saving of irrigation water, 46 % higher water productivity (2.35 kg m^{-3} in bed and 1.28 kg m^{-3} on flat) and 35 % greater net economic benefit.

Zhongming and Fahong (2005) tested different soil water conservation strategies for their possible effects on yield and soil moisture storage in wheat crops. Among these treatments, shallow tillage showed increased moisture storage by 12 %, deep tillage by 30 %, 75 % inorganic fertilizer + farm manure by 35 %, while raised bed treatments increased soil water by 45 % over the conventional wheat cultivation technique followed by the farmers in the region. Raised bed sowing registered an increase in wheat yield by 34 %, shallow tillage by a margin of 13.9 %, while deep tillage by a margin of 27 % over the wheat yield obtained from the conventional practice followed by the farmers in the region (Hadda and Arora, 2006). Zhang *et al.* (2011) found that the raised beds showed a 6 % higher yield compared to that flat planting of the wheat. As compared to the flat sowing with flood irrigation, the cultivation of wheat on wide and narrow beds led to saving of irrigation water by 35 % and 9.6 %, respectively (Ghani Akbar *et al.*, 2007). The width, the gap between the centre of two furrows, of wide and narrow beds were 130 cm and 65 cm, respectively.

Table 2.3 Effect of minimum soil disturbance on water productivity

Reference	**Site**	**Soil**	**Crop**	**Year**	**Treatments**	**Water mngt**	**Water Saving**
Sandhu *et al*. (2012)	Ludhiana Punjab, India.	Loamy Sand	Rice	Summer 2009 and 2010	CT (transplanting in the puddled flat plot), transplanting on the fresh bed. Irrigation 1day/2day/3day after standing water disappeared and tensiometer guided irrigation (150±20cm).	Irrigated	Transplanting rice on slopes of fresh beds saved 15 % irrigation water without sacrificing yield. The reduction in the amount of irrigation water applied in beds may be attributed to the less depth of irrigation water application to beds (5 cm) as compared to puddled plots (7.5 cm)
Cabangon *et al.* (2005)	IRRI research station, Los Banos, Laguna, Philippines	Clay	Wet season rice and dry season rice	2002 dry and Wet season	Conventional puddled flat, and beds of 65 cm centre-to-centre spacing and 130 cm spacing furrows 35 cm wide. Water regimes: -10 kPa, -20 kPa and well-watered	Irrigated and partially Rainfed	Beds reduced irrigation water input by as much as 20.0–50.0 cm (30-40 %) compared with puddled flats during the dry season.
Choudhury *et al.* (2007)	New Delhi, India	Sandy loam and loam	Rice in summer and Wheat in winter-spring	2001 to 2003	Six treatments: Transplanted, wet seeded and dry seeded on raised beds, dry seeded on flat beds, dry seeded on flat lands—two water management: flooded and non-flooded.	Irrigated	Total water input (irrigation+rain) in rice on raised beds was 38–42 % less than in flooded transplanted rice and 32–37 % less than in flooded wet seeded rice.

Reference	**Site**	**Soil**	**Crop**	**Year**	**Treatments**	**Water mngt**	**Water Saving**
Humphreys *et al.* (2008)	Two sites-Ludhiana and Phillaur, Punjab, India in small plots and large blocks.	Sandy loam and loam, respectively.	Rice-wheat system	2002 to 2006	Tillage-Flat, Fresh bed and permanent bed. Water management-continuous flooding and irrigated 2 days after water disappeared.	Irrigated	In large blocks, over one-third (~80.0 cm), irrigation water was saved by transplanted rice on a permanent bed applying water 2 days after standing water disappeared compared to puddled transplanted rice on flat with continuous flooding. However, the results suggested that the reduction in irrigation amount in rice on beds is due to switching to intermittent irrigation rather than changing to beds.
Humphreys *et al.* (2005)	Indo-Gangetic Plain	Loamy sands to silty clay loams.	Rice-wheat	2000 to 2003	Direct-seeded and transplanted rice on beds, puddled flooded transplanted rice.	Irrigated	12-60 % irrigation water was reduced in transplanted or dry-seeded rice on raised beds compared with flooded transplanted rice from an analysis of several farmer and researcher trials.
Hobbs and Gupta (2003)	Indo-Gangetic Plain	Loamy sands to silty clay loams.	Rice-wheat	2000 to 2003	Zero tillage (ZT)	Irrigated	Reduced or zero-tillage systems ensured 25 % saving in water

Reference	**Site**	**Soil**	**Crop**	**Year**	**Treatments**	**Water mngt**	**Water Saving**
Gupta and Gill (2003)	Indo-Gangetic Plain	Loamy sands to silty clay loams.	Rice-wheat	2000 to 2003	ZT	Irrigated	About 20-30 % water savings with zero-tillage just after rice harvest. Residual moisture was available for wheat germination.
Hassan *et al*. (2005)	Mardan in Northwest Frontier Province of Pakistan	Sandy clay loam	Maize-wheat	2000 to 2004	Basin and puddled transplanted rice (PTR)	Irrigated	For the maize crop, there were increases of 32 % and 65 % in water saving and water productivity, respectively, under permanent raised beds compared to basins. Similarly, permanent raised beds demonstrated 36 % and 50 % higher water saving and water productivity, respectively, for the wheat crop.
Singh *et al.* (2010)	Modipuram, western Uttar Pradesh, India.	Sandy Loam	Pigeonpea–wheat cropping system	2001-02 to 2003-04	Permanent raised bed (PRB) and conventional flat bed (CT). In PRB, a tractor mounted bed planter was used for forming beds.	Irrigated	PRB saved irrigation water by 9.5–13.4 ha cm and improved the irrigation application efficiency by 9.5–13.4 % and the irrigation use efficiency by 19–28 kg ha cm^{-1} over flat beds.
Temesgen *et al.* (2007)	Melkawoba and Wulinchity Ethiopia	Sandy Loam	Eragrostis tef and maize	2003 to 2005	CT (Maresha plough), strip tillage (ST) using the maresha plough and ST with subsoiling	Rainfed	Surface runoff in ST with subsoiling was 58 % and in ST was 38 % less than that in CT. Transpiration in ST with subsoil was 24 % and in ST was 13 % more than that in CT.

2.11 Review of water balance studies for rice

During field experiments carried out on a clay loam soil on the research farm of Punjab Agricultural University, Ludhiana, India, during 2008 and 2009, Sudhir-Yadav *et al.* (2011) found deep drainage was significantly higher in direct-seeded rice (DSR) (117.9 cm) than in the puddled transplanted rice (PTR) (89.9 cm). The higher deep drainage in DSR was reported due to the higher infiltration rate in the non-puddled soil (ponded infiltration rate 0.4 and 2.0 cm day^{-1} in daily irrigated puddled and non-puddled soil, respectively, in 2009). The amount of seepage was significantly higher in PTR (29.2 cm) than in DSR (5.5 cm) each year because the PTR was continuously flooded for the first 15 days after transplanting.

On a loam soil of Punjab, India, Humphreys *et al.* (2008) reported, with the same irrigation scheduling (irrigation application after 2 days of floodwater disappearance) 16-21 % higher irrigation amount in transplanted rice on bed (TRB) than puddled transplanted rice (PTR). The water in the furrows of the permanent beds disappeared within 2-3 hours compared with 12-18 hours for the floodwater to disappear from PTR. They estimated the deep drainage from infiltration rather than using the water balance approach. On the loam soil, the infiltration rate in the continuous flooded PTR was smaller (0.5 cm day^{-1}) compared to that in the furrows of daily irrigated DSR on permanent beds (0.7 cm day^{-1}). On the sandy loam soil, ponded infiltration rate in furrows of daily irrigated DSR on permanent beds (1.3 cm day^{-1}) was triple than that in continuous flooded PTR (0.4 cm day^{-1}), suggesting that puddling reduced infiltration rate by about two-thirds. For wheat, deep drainage was 9.0 cm higher on beds than conventional tillage on the sandy loam soil but 4.0 cm less on the beds than the conventional tillage on the loam.

In a study conducted in loam and clay loam soil at the research farm of the Indian Agricultural Research Institute, New Delhi, India, Choudhury *et al.* (2007) reported irrigation amount for rice was significantly higher in PTR (131.3-136.0 cm) compared to that in DSR either on the flat or raised bed (56.7-81.3 cm). Percolation loss in continuous flooded PTR (67.9-82.8 cm) was statistically higher than that in DSR on flat irrigated at field capacity (46.6-49.3 cm) and that in DSR on raised bed irrigated at field capacity (43.3-49.7 cm). Evapotranspiration followed the trend as PTR>DSR on flat>DSR on raised bed, with the value of 78.1-89.9 cm, 56.0-55.6 cm, and 47.5-47.7 cm, respectively. Percolation loss in raised bed irrigated at field capacity was significantly higher than that in raised bed irrigated at 20 kPa.

Field experiments were conducted by Khepar *et al.* (2000) to validate the water balance model for rice under intermittent irrigation, i.e. application of irrigation water 2 days after the ponded water had infiltrated into the soil. The studies were conducted at the experimental field (clay loam soil) of Punjab Agricultural University, Ludhiana, India, in 1998 with conventional tillage practices. The total application of water was 12.7 cm (irrigation 7.2 cm + rainfall 5.5 cm), excluding water applied for land preparation. The measured value of deep percolation, crop evapotranspiration, and runoff loss was 9.4, 5.1 and 0.6 cm, respectively.

Govindarajan *et al.* (2008) estimated water balance components using soil-water-atmospheric-plant (SWAP) model at field laboratory, Centre for Water Resources, Anna University, India, for rice crop under irrigation regimes such as flooded (FL) up to 2 cm standing water depth, alternate wetting and drying (AWD) irrigation, and saturated soil culture (SSC). Total applied water (irrigation + rainfall) was 133 cm, 120 cm and 108 cm, respectively, for FL, AWD, and SSC. Drainage was highest (94 cm) under FL, intermediate (81 cm) under AWD, and lowest (66 cm) under SSC irrigation. Evaporation under AWD (37.91 cm) irrigation practice was lower than that under FL (38.67 cm) and SSC irrigation (39.08 cm).

Luo *et al.* (2009) compared the irrigation requirements and water balance components for aerobic rice to simulate a model from field data of Huibei Irrigation Experiment station, Kaifeng. Total water (irrigation and rainfall) for the irrigation treatment T_1 (irrigation application when the soil water potential falls lower -10 kPa) was higher (155.3 cm) than the irrigation treatment T_2 (78.8 cm) (irrigation application when the soil water potential falls lower -30 kPa). Percolation under T_1 and T_2 were 123.1 cm and 58.4 cm, respectively. The crop evapotranspirations for both treatments were the same (31.6 cm).

Jyotiprava Dash *et al.* (2015) estimated water balance components within the 120 cm soil profile simulated by HYDRUS-1D for rice crop grown in a clay loam soil in Indian Agricultural Research Institute, New Delhi, India. Percolation was 55.5 % of the total water input (153.0 cm).

Jehangir *et al.* (2007) analysed water balance components for conventional rice-wheat rotation at farmer’s field in Ghour Dour Distributary, Panjab, Pakistan. Evapotranspiration and percolation for rice was 53.2 cm, and 120.2 cm, respectively, of the water input (145.8 cm). Evapotranspiration for wheat was 39.6 cm relative to water input (35.6 cm), percolation was negative (-4.0 cm). For both crops, soil water storage was depleted.

Wopereis *et al.* (1994) conducted field experiments to validate simulation algorithm for water flow in aquatic habitats (SAWAH) model in International Rice Research Institute (IRRI), Los Baños, Phillippines. The field was not immediately surrounded by other flooded rice fields; the nearest was at about 5 m distance. The results demonstrated, seepage and percolation under the flooded rice field through the plough pan of clay type was 3.6 cm day^{-1} which was reduced by 10 fold by installing plastic sheets in the bunds. The difference in seepage and percolation rate before and after installing plastic sheets proved large water loss through seepage. The only percolation before and after installing the plastic sheets was 0.41 and 0.43 cm day^{-1}.

2.12 Review of water balance studies for wheat

Wheat sown with a seed drill in rows spaced 20 cm apart in the formerly PTR and DSR on flat received significantly higher irrigation (26.4-28.5 cm) compared to wheat sown with the seed drill on raised bed (22.8-25.6 cm) (Choudhury *et al.*, 2007). Evapotranspiration was significantly higher in wheat on flat (30.7-35.1 cm) compared to wheat on raised bed (27.4-32.0 cm). Percolation loss was significantly higher in wheat on flat (5.5 cm) than wheat on raised bed (4.9 cm) in the year 2002-2003 with 9.5 cm rainfall. But, there was a similar percolation loss in two wheat treatments (5.7-5.9 cm) with comparatively less rainfall (2.5 cm) in the year 2001-2002.

Eitzinger *et al.* (2003), in a semi-arid agricultural area in central Europe using the CERES-Wheat model, found simulated soil evaporation was 17.7 cm, and transpiration from winter wheat was 17.9 cm out of growing season rainfall of 37.1 cm.

Sun *et al.* (2006) have performed experiments on the water balance of winter wheat at Luancheng experimental station, China, from 1999 to 2002 with five irrigation scheduling. The straw and plant residue of the previous maize crop or any other mulch was removed. Irrigation scheduling involved controlled soil moisture level (no irrigation, θ/θ_{FC}= 1 and 0.8, where θ=soil water content and θ_{FC}= soil water content at field capacity) during different growth stages of wheat. Results showed a linear correlation with the increase in irrigation amount, ET_c increased. The amount of ET_c was highest (45.5 cm) with the highest irrigation amount (38.0 cm) with irrigation scheduling to reach soil water level θ/θ_{FC}= 1 at all five growth stages (winter Dormancy, recovering, stem-elongation, heading and grain-filling). In contrast, ET_c was 9 % reduced (39.1 cm) with reduced irrigation (26.7 cm) that involved irrigation scheduling θ/θ_{FC}= 1 at winter dormancy, no irrigation at recovering, θ/θ_{FC}= 0.8 at stem-elongation, heading, and grain-filling stages. The irrigation treatment with the highest irrigation amount had 41 % higher deep drainage (3.4 cm) compared to the deep drainage (2.0 cm) under the irrigation treatment with no irrigation at recovering.

Experimenting with NT (straw retained) vs CT (straw removed, ploughed twice followed by harrowing) over 5 years (2000-2005) in a silty loam soil of eastern Chinese Loess Plateau, Jin *et al.* (2007) found ET_c of rainfed wheat (rainfall during growing period 78.1 cm) was higher under NT (40.9 cm) than that under CT (39.5 cm). They also reported that during the fallow period with an average rainfall of 53.2 cm, runoff under CT was higher (1.1 cm) than that under NT (1.0 cm).

Zhang *et al.* (2007a) have performed CoupModel, a one-dimensional model simulating fluxes of water, from 2001-2002 to 2003-2004 in a silty loam soil of Shaanxi province in south Loess Plateau, China, to study the effect of mulching on the components of annual water balance (winter wheat growing season plus fallow period). They compared the water balance components for three soil management regimes. The management treatments were conventionally managed winter wheat –summer fallow, mulching (conventionally managed but unploughed treatment in which air-dried, unchopped wheat straw at a rate of 0.8 kg m^{-2} was placed over the soil surface), and conventional management and a fallow crop (bean). They reported that simulated soil evaporation from 200 cm soil profile under mulched treatment was lower (38.2 cm) than that under conventional management (46.7 cm) against the measured annual rainfall of 73.3 cm in 2003-2004. The drainage was higher (23.9 cm) in the mulched treatment than that in the conventional management (13.4 cm). In another simulation study using 45 years' weather data and the same model with the same soil management treatments and soil type in Luochuan, China, Zhang *et al.* (2007b) reported lower soil evaporation (5.8 cm) in mulched treatment than conventional management (7.0 cm). Drainage was higher in mulched treatment (0.9 cm) than that in conventional management (0.3 cm).

2.13 Water balance models for irrigated rice

Though water balance in the rice field has been studied extensively, most studies have been limited to ponded water conditions in the rice field. The problem of estimating water balance components, the deep drainage in particular, under both ponded water condition and ponded water disappearance condition has drawn the attention of many researchers when intermittent irrigation practice such as AWD irrigation has been introduced in the rice field. The water balance model that can be used to estimate various water balance components on a daily basis under both ponded and water disappearance condition was developed by and Panigrahi *et al.* (2001). Under the ponded water condition, the model used the water flow equation for one-dimensional steady-state, saturated flow in the vertical direction through an isotopic, homogenous and layered soil. Under AWD irrigation, the water is allowed to disappear from the surface, and the field is allowed to remain dry for several days prior to the next irrigation event. After the disappearance of water, the subsoil becomes unsaturated. For this situation, well established empirical soil water retention function proposed by Brooks and Corey (1964)was used by incorporating unsaturated hydraulic conductivity concepts to predict deep percolation.

Agrawal *et al.* (2004) developed a field water balance model for rain-fed rice with intermittent ponding and provision of supplemental irrigation from an on-farm reservoir in Eastern India. The model estimated various water-balance parameters such as actual crop evapotranspiration, percolation, seepage supplemental irrigation, surface runoff and ponding depth in the field on a daily basis under ponded and unsaturated conditions, but similar to Khepar *et al.* (2000) the saturation and depletion phases of the rice field were considered as a single-phase (i.e., unsaturated condition).

Bhadra *et al.* (2013) performed the water balance calculations considering three different phases, such as ponding phase, saturation phase and depletion phase. For the ponding phase, deep percolation was estimated using the steady-state flow equation proposed by Khepar *et al.* (2000). For the saturated phase, deep percolation was calculated by the method developed by Khepar *et al.* (2000) with a difference in the estimation of unsaturated hydraulic conductivity. For example, they used the Brooks and Corey (1964) parametric model to describe the soil water retention function. But, researchers demonstrated that the most commonly used Van Genuchten (1980) model for the retention curve together with Mualem (1976) expression for unsaturated hydraulic conductivity performed better than the Brooks and Corey model (Van Genuchten and Nielsen, 1985). Hence, instead of Brooks and Corey model, Bhadra *et al.* (2013) used Van Genuchten-Mualem model for estimation of deep percolation.

2.14 Effect of compaction on soil physical properties

Soil compaction can be defined as the formation of dense layers of well-packed soil, not only at the bottom of the cultivated layer but also deeper (Reintam *et al.*, 2009). Since soil is a three-phase system, it can undergo changes immediately after the external stresses exceed the internal soil strength, defined by the precompression stress. According to Koolen and Kuipers (2012), soil compaction in agriculture is usually accompanied by deformation in addition to compression lateral movement. Soil compaction can be divided into two different problems:

1. Topsoil compaction: the formation of densified layers within the range of depth corresponding to the cultivated horizon (plough layer). Topsoil may appear during a conventional preparation cycle, but the topsoil compaction problem can be solved by annual tillage.
2. Subsoil compaction: appears at depths below the plough layer depth limit. This means that the densification effects can be annually cumulative and that the amelioration of such effects can be achieved only by applying special tillage techniques such as subsoiling or deep ploughing. Such techniques are always expensive and usually are accompanied by important technical problems such as insufficient available tractor power.

Soil compaction by vehicle wheel pass can result in a reduction in pore space between the soil particles and increasing soil BD and PR (Håkansson *et al.*, 1988; Arvidsson, 1997; Lipiec and Hatano, 2003; Håkansson, 2005). For most soils, compaction reduces the volume of large pores and consequently affects water retention properties, soil water flow, hydrologic response and hydraulic conductivity (Klute and Dirksen, 1986; Onstad and Voorhees, 1987). Arvidsson and Håkansson (1996) found that soil compaction increased the strength and size of aggregates within a seedbed and that greater clods were an underlying feature of compacted soils. Kooistra and Tovey (1994) showed that microporosity was increased by compaction.

A comprehensive summary of the effect of compaction by vehicles of different wheel loads on BD and PR has been given in Table 2.4.

2.15 Effect of repeated wheel passes on soil compaction

Jorajuria *et al.* (1997) examined the effect of tractor size and number of passes on soil compaction at a constant ground contact pressure on soil properties. They concluded that the heavier tractor always resulted in greater increases in BD in the 30-60 cm depth range, but a lighter tractor with a large number of passes was capable of producing just as much compaction as the heavier tractor with fewer passes. This is also reflected by Hamlett *et al.* (1990), who found that repeated traffic increased BD by 27 % and PR by 100 % compared with the condition of post ploughing. Botta *et al.* (2006) reported that high frequency (10 and 12 tractor passes in the same tracks equipped with 18.4-34 cross-ply tyre) of a light tractor (3.1 Mg) on typical Argiuol soil in the northeastern Pampa region of Argentina produced significant increases in PR and BD. Horn *et al.* (2003) examined the effect of repeated passes on a Stagnic Luvisol and reported that repeated compaction with up to 5.5 Mg tractor continued to increase BD in the 35-39 cm depth layer in the range 0 – 10 passes and increased the degree of compaction saturation in this layer from 61 to 89 %.

Table 2.4 The effect of different wheel loads applied to different soils in different parts of the world on bulk density and penetration resistance.

References	Soil texture	Wheel load, kN	Increase in BD, % change from before wheeling	Depth of measurement, m	Increase in PR, % change from before wheeling	Depth of measurement, m
Abu-Hamdeh (2003)	loam	78.5	22	0-0.48	39	0-0.48
Blackwell *et al.* (1986)	Lawford clay	29.4	-	-	13	0.3
Botta *et al.* (2004)	-[A]	13.5	13.5	0.015	-	-
Braunack and McGarry (2006)	Clay loam	19.6	15	0.2	48	0.4
Canarache *et al.* (1984)	-	12.0	25	0-0.2	28	-
Chamen and Audsley (1993)	Sand and clay	24.5	5	-	75	-
Chamen and Cavalli (1994)	Clay	31.9	17	0-0.175	23	0-0.45
Chan *et al.* (2006)	Clay	28.4	22	0.075	-	-
Hansen (1996)	Sandy loams	28.9	27	0.2	100	0.225
Jorajuria and Draghi (1997)	Clay	7.8	48	0-0.3	56	0.3
Pagliai *et al.* (2003)	Clay	7.4	7.9	0-0.1	12.5	0-0.4
Pangnakorn *et al.* (2003)	-	7.4	11.7	0-0.1	50	0-0.4
Radford and Yule (2003)	Clay	49.1	-	-	13	0.18-0.36
Schäfer-Landefeld *et al.* (2004)	-	98.1	7.5	0.15-0.2	-	-
Stenitzer and Murer (2003)	Loamy silt	32.4	27	0-0.3	88	0-0.3
Stewart and Vyn (1994)	Loam	58.9	6.9	0-0.3	87	0-0.3
Yavuzcan (2000)	Clay loam	10.8	15	0-0.5	52	0-0.1
Zhang *et al.* (2007b)	Fine silt	5.3	23	0-0.2	95	0.15-0.2

[A] -, not determined

Table 2.4 also presents an overview of the range of wheel axle loads used in studies worldwide. The range of wheel load was 5.3 kN to 98.1 kN. However, the wheel load of a commonly used 2-WT in Bangladesh is about 2.6 kN.

2.16 Subsoil compaction by vehicle weight

Smith and Dickson (1990) reviewed previous work which showed that ground contact pressure influences topsoil compaction, while subsoil compaction (below 40 cm) is directly influenced by the weight of the vehicle independent of pressure on the soil at the surface. This is reflected by Botta *et al.* (2008), who studied the effects of different wheel loads and ground pressures within NT and CT regimes on a silty clay loam soil. Håkansson *et al.* (1988) concluded that the risk of subsoil compaction due to vehicle traffic was mainly determined by the wheel load even when the ground contact pressure was extremely low. Håkansson (2005) summarises most of the work relevant to soil compaction by wheel traffic. Ground contact pressure and axle load are the dominating influences in terms of potential for compaction in the surface or in the subsurface. Ground pressure determines the initial level of stress at the surface, but the axle load decides the rate at which the pressure-induces stress decreases with an increase in depth (Chamen *et al.*, 2003). The relationship illustrated in Figure 2.4 shows that even if the pressure at the surface is kept the same, an increase in axle load tends to increase the depth to which the stresses reach.

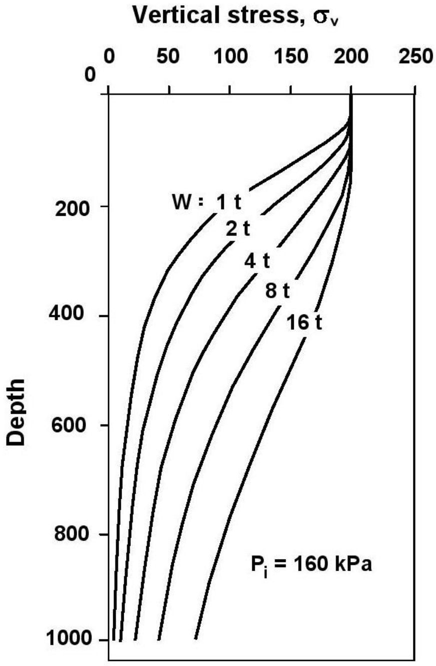


Figure 2.4 The effect of increasing axle load while maintaining the same ground pressure (vertical stress). Increasing axle load reduces the rate at which vertical stress decreases with depth in the soil. (W=Wheel load=axle load in Mg, P_i=inflation pressure=ground pressure in kPa) . Adopted from Chamen *et al.* (2003).

1.17 Conclusions

This chapter reviewed different aspects of conventional tillage, puddling, non-puddled tillage, and minimum tillage, i.e. CA. From different studies, it was found that minimum tillage practices resulted in positive changes in soil physical properties. The beneficial effects of CA have been reported for several decades around the world. Nonetheless, it should be noted that different minimum tillage practices are applicable for different regions to fit with the corresponding climate and agricultural ecosystem of different regions.

Minimum tillage practices have changed soil physical properties in different ways for different soils and regions. Some practices increased the BD, some decreased it, while some studies resulted in no changes in soil BD. However, most of the studies focused on the surface soil. Minimum tillage practices, including non-puddled soils, have a positive effect on the soil BD of the plough pan. In Chapter 3, changes in soil BD of the plough pan after several years of practising SP have been examined and compared to the BD of the plough pan under conventional tillage practices as well as the natural soil at the corresponding depth.

A review of the water saving under minimum tillage practices concluded that variable volumes of water were saved under different minimum tillage practices. Water savings under rice ranged from 15-60 %, while water savings for wheat was up to 50 %. Reviews of water balance components suggest that under non-puddled rice, deep percolation and seepage was higher than that under puddled conventional rice, which also resulted in higher irrigation application in non-puddled rice. The studies reviewed did not examine the water balance of rice under SP and BP. In Chapter 6 of this thesis, water balance components were measured under transplanted rice crops. After reviewing the water balance models, the most suitable model for the current project was chosen since rice was irrigated considering the saturated and unsaturated condition under alternate wetting and drying irrigation practices. Evapotranspiration of wheat under minimum tillage practices was reported to be less than that under conventional tillage, mostly due to the mulching effect of crop residue retention on the soil surface. Some studies also suggest that drainage under wheat was also higher under minimum soil disturbance compared to that under CT practices. In Chapter 5, an in-depth analysis of the water balance components of wheat was presented.

The review suggests that the use of wheel traffic in agriculture can result in soil compaction in the surface soil and in the subsurface soil. The consequences of the compaction were the increase in soil BD and PR. The increase in soil BD mostly ranged between 10 to 20 %. The compaction can increase the PR up to 100 %. However, the wheel loads were in the range of 0.5-8.0 Mg, which were much higher than the wheel loads of commonly used tractors in Bangladesh. The wheel load of a 2-WT in Bangladesh is about 0.27 Mg. Thus, there is a scope to investigate the compaction by 2-WT. In Chapter 4, the soil physical properties and the hydrologic properties in the surface soil and in the plough pan as responses to the compaction by a 2-WT with or without extra loading and increased number of passes were examined and compared to the undisturbed soil.

3 Effects of medium to long-term minimum soil disturbance and residue retention on soil physical properties in two rice-based rotations in northwest Bangladesh.

3.1 Introduction

Minimum soil disturbance with residue retention has been shown to improve soil properties in many parts of the world. For example, in Brazil, Pedro and Silva (2001) reported that the soil BD tended to be lower under NT than under CT. In a study conducted at the Katito Wheat Scheme, Mbala, Zambia, Gill and Aulakh (1990) reported that soil BD decreased under NT compared to CT. Crop residue retention also decreases BD, as reported by Blanco-Canqui and Lal (2009). For each one tonne of crop residue added per hectare over a 12-year period, soil BD reduced by 0.01 g cm$^{-3,}$ and total porosity (TP) increased by 0.3 % in the near-surface soil in wheat-fallow, wheat-corn-fallow and continuous cropping systems (Shaver *et al.*, 2003).

Puddling results in the formation of a plough pan at a shallow depth (Gathala *et al.*, 2011a). By contrast, minimum soil disturbance and residue retention reduce PR of the soil within the plough layer, as reported by Carman (1997) and (Franzen *et al.*, 1994).

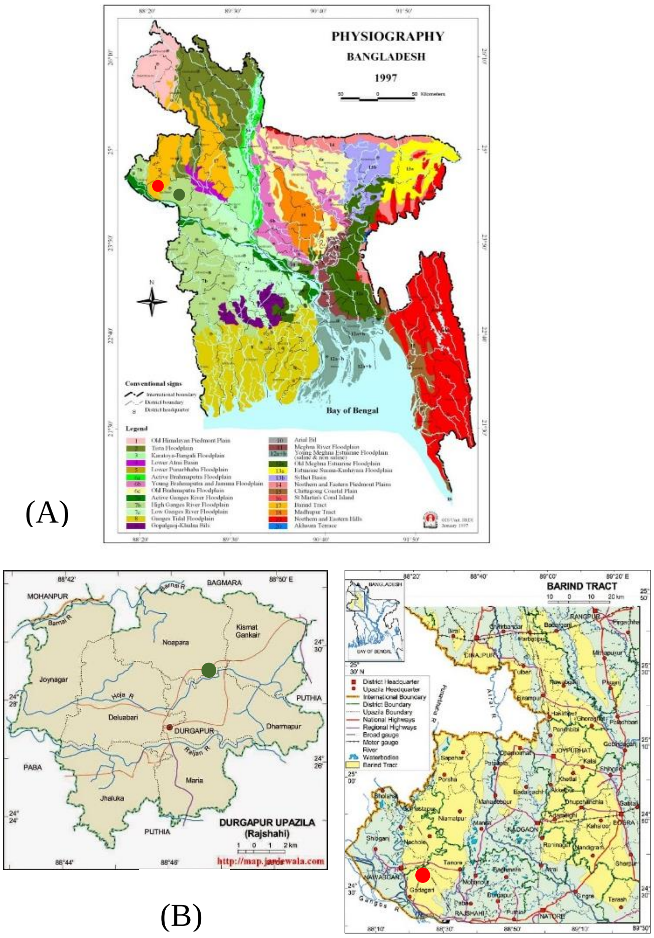
Minimum soil disturbance and residue retention systems are also effective means of improving soil water regimes (Reeves, 1994). Switching from CT to minimum soil disturbance usually increases available water capacity and infiltration rate (McGarry *et al.*, 2000). Minimum soil disturbance with residue retention facilitates increased soil organic matter (Beare *et al.*, 1994), promoted better aggregation (Lal *et al.*, 1994) and improved pore size distribution (Bhattacharyya *et al.*, 2006a), which in turn beneficially affects soil water retention and infiltration characteristics. Studies have shown that intensive tillage disrupts pore continuity and decreases water infiltration (Shukla *et al.*, 2003). By contrast, ZT studies showed no disruption of pore continuity and increased infiltration (Bhattacharyya *et al.*, 2008).

Since the establishment in 2010 of the research site described in this chapter, Islam (2016) and Alam *et al.* (2018b) have conducted research in different years, each with different objectives related to tillage and residue retention. The common parameters taken during each study were BD, PR and crop yield. Islam (2016) reported minimum soil disturbance with residue retention reduced soil BD and PR compared to CT after 7 crops that started from 2010 (three crops per year). Under the current study, it was hypothesized that continuous use of long-term (7 years) minimum soil disturbance with residue retention could change the soil physical properties such that they can also alter the soil hydrologic properties in the plant root zone . The main objectives of this chapter are, therefore, 1) to determine the effect of 7 years continuous use of minimum soil disturbance with increased residue retention on the soil physical properties such as BD and PR, and 2) to understand their effect on soil hydrologic properties such as soil water retention, saturated hydraulic conductivity (K_{sat}), and infiltration for two rice-based cropping systems in the northwest of Bangladesh.

3.2 Materials and methods

3.2.1 Experimental sites

Effects of minimum soil disturbance and residue retention on the water balance and water productivity of wheat and rice were investigated for three seasons each during 2.5 years (2015 to 2017) in the two replicated experimental fields, which were established in 2010 in the Rajshahi district of northwest of Bangladesh. The results of water balance and water productivity of wheat and rice are presented in Chapter 5 and Chapter 6, respectively. The current chapter deals with the changes in soil physical properties under different tillage types and residue retention levels. Bulk density and PR soil samples were collected, and K_{sat} and infiltration measurements were done in 2017. Locations and soil characteristics of the two sites are presented in Figure 3.1 and Table 3.1, respectively. Initial soil properties and the two different crop rotations since 2010 at the two locations are presented in Table 3.2 and Table 3.3.



(A)

(B)

(C)

Figure 3.1 (A) Bangladesh physiographic map showing two long-term experimental sites (B) Alipur Experimental site in Durgapur Upazilla (C) Digram experimental site in Godagari upazilla. The green circle indicates the location of Alipur site, and the red circle indicates Digram site.

Table 3.1 Experimental site characteristics of two different locations in northwest Bangladesh

Characteristics	Site 1	Site 2
Location	Alipur, Durgapur, Rajshahi	Digram, Godagari, Rajshahi
Latitude, Longitude	24^o 28′ N, 88^o 46′	24^o 31′ N, 88^o 22′
Elevation above sea level	20 metres	40 metres
Agro-ecological zone (BARC, 2012)	Level Barind Tract	High Barind Tract
Physiography	Calcareous Brown Flood-plain	Grey Terrace soils
USDA* soil classification (USDA, 1975)	Aeric Eutrochrept	Aeric Albaquepts

*USDA-United States Department of Agriculture

Table 3.2 Initial soil properties of two long-term experimental sites in Rajshahi since the beginning of the present study that started in 2015

Soil properties (0-30 cm)	Alipur	Digram
Textural class	Silty loam	Silty clay loam
Sand, %	25	19
Silt, %	54	48
Clay, %	21	32
Bulk density, g cm $^{-3}$	1.50	1.43
Field capacity, % vol	38	36
Permanent wilting point, % vol	17	14

Table 3.3 Cropping sequence of two long-term experimental sites in Rajshahi since establishment in 2010

Crop cycle	Year	Season*	Alipur	Digram
1	2010	Rabi	Lentil	Wheat
2	2011	Kharif-1	Mungbean	Mung bean
3	2011	Kharif-2	Monsoon Rice	Monsoon Rice
4	2011	Rabi	Lentil	Wheat
5	2012	Kharif-1	Mungbean	Mung bean
6	2012	Kharif-2	Monsoon Rice	Monsoon Rice
7	2012	Rabi	Lentil	Wheat
8	2013	Kharif-1	Jute	Sesbania
9	2013	Kharif-2	Monsoon Rice	Monsoon Rice
10	2013	Rabi	Mustard	Chickpea
11	2014	Rabi to Kharif-1	Irrigated Boro Rice	Jute
12	2014	Kharif-2	Monsoon Rice	Monsoon Rice
13	2014	Rabi	Mustard	Wheat
14	2015	Rabi to Kharif-1	Irrigated Boro Rice	Jute
15	2015	Kharif-2	Monsoon Rice	Monsoon Rice
16	2015	Rabi	Mustard	Wheat
17	2016	Rabi to Kharif-1	Irrigated Boro Rice	Mungbean
18	2016	Kharif-2	Monsoon Rice	Monsoon Rice
19	2016	Rabi	Lentil	Wheat
20	2017	Rabi to Kharif-1	Irrigated Boro Rice	-

*Rabi: Mid-November to Mid-March, Kharif-1: Mid-March to Mid-July, Kharif-2: Mid July to Mid-November

3.2.2 Climate and weather

Climatic conditions of both experimental sites are characterized by hot and humid summers and cool winters with an average annual rainfall of 125 cm at the Rajshahi weather station, which is representative of both experimental sites. Eighty percent of the rainfall occurred in the months from April to August. During the observation years from 2014 to 2017, the monthly mean minimum temperature was lowest (11 °C) in January and the monthly mean maximum temperature highest (36 °C) in April (Figure 3.2). Daily temperature and rainfall data were collected at the weather station at Shyampur, Rajshahi, Bangladesh. The weather station is approximately 10 km from Alipur and 25 km from Digram.

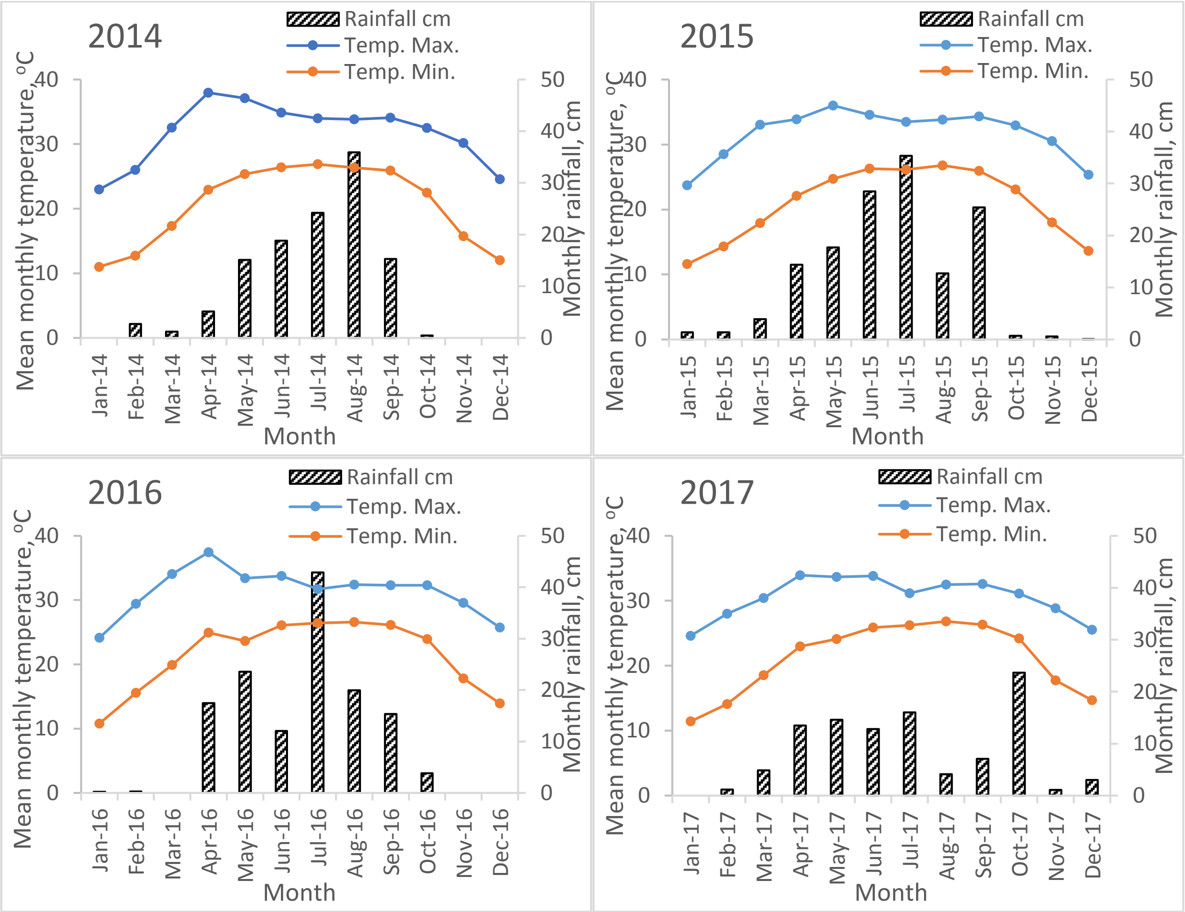


Figure 3.2 Mean monthly rainfall (cm) and minimum and maximum temperatures (°C) in Rajshahi Bangladesh for 2014 to 2017. Rajshahi Station. Latitude: 24.35°N, Longitude: 88.56°E, Elevation: 20 m.

3.2.3 Experimental design, and tillage and residue management treatments

The design was a two-factor experiment with four replicates. There were three tillage treatments (strip planting ‘SP’, bed planting ‘BP’ and conventional tillage ‘CT’) and two residue retention treatments (low residue ‘LR’, and high residue ‘HR’). Thus, there was a total of 6 treatment combinations (Table 3.4). The main plots (7.5 m × 14 m) consisted of tillage treatments, with residue retention treatments in the subplots (7.5 m × 7 m), in a split-plot design. The treatment combinations and the experimental design were the same for both Alipur and Digram sites. Based on the average height of the standing crops across all subplots, the high and low amounts of residues were retained either anchored and standing or loose in the field. For the high residue and low residue treatments, respectively, 50 % and 20 % of the height of the cereal crops after the harvesting were retained. Residues were cut in quadrats, dried and weighed, and converted to a tonne per hectare to determine the amount of anchored and standing residues retained in the plots. Loose residues were weighed and converted to tonnes per hectare before placing in the fields. The tillage and residue retention treatments are described briefly below, with further detail in Table 3.4, Table 3.5, and Table 3.6.

Rice tillage at Alipur

SP- non-puddled rice was hand transplanted following strip tillage (Haque *et al.*, 2016)

BP- non-puddled rice was hand transplanted following reshaping permanent bed

CT- rice seedlings were transplanted in the puddled soil

Residue retention at Alipur

LR- retaining 20 % by the height of the loose mustard crop residue

HR- retaining 50 % by the height of the loose mustard crop residue

Wheat tillage at Digram

SP- a Versatile Multi crop Planter (VMP, Haque *et al.* (2011)) was used for planting wheat

BP- the VMP was used to reshape the permanent beds and plant wheat on the top of the beds

CT- intensive tillage was used for wheat

Residue retention at Digram

LR- retaining 20 % by the height of the anchored and standing rice crop residue

HR- retaining 50 % by the height of the anchored and standing rice crop residue

Table 3.4 Tillage treatments details at Alipur and Digram

Tillage	Treatment details
SP- Strip planting	5 cm wide and 7 cm deep strip was formed using VMP (Figure 3.3) 20 cm row to row distance 5-7 cm deep seed placement
BP- Bed Planting	Dimensions of a reshaped Bed: (Figure 3.3) Bed dimensions- width of the base 55 cm width of the top 35 cm Furrow dimensions- width of the base 15 cm width of the top 30 cm Bed height- 12 cm The slope of the bedsides- 50°

CT- Conventional Tillage	Wheat: Three times intensive tillage by 2-WT to a depth of 5 to 10 cm, incorporating residues, followed by a land levelling was done. Seeds were broadcast before the final tillage. Rice: Land was inundated for 1 day under the water, then 3 wet tillage was done to puddle the land to a depth of 5-10 cm, incorporating residues, followed by a land levelling. Hand transplanting was done for rice.

Table 3.5 Dry weight of residues retained of different crops under different tillage treatments in the Boro rice dominant cropping sequence at Alipur in 2014 to 2017.

Crop Cycle	**Crop residue**	**Residue type**	**Residue dry weight (t ha^{-1})**					
			High Residue			**Low Residue**		
			SP	**BP**	**CT**	**SP**	**BP**	**CT**
13	Mustard	Loose	1.45	1.48	1.24	0.53	0.55	0.48
14	Boro Rice	Anchored	2.65	2.86	2.70	1.38	1.50	1.41
15	Monsoon Rice	Anchored	2.81	2.50	2.36	1.40	1.19	1.27
16	Mustard	Loose	1.35	1.36	1.18	0.62	0.52	0.45
17	Boro Rice	Anchored	2.71	2.66	2.59	1.45	1.52	1.35
18	Monsoon Rice	Anchored	2.91	2.63	2.31	1.46	1.39	1.30
19	Lentil	Loose	1.20	0.90	1.14	0.40	0.30	0.38
20	Boro Rice	Anchored	2.74	2.60	2.55	1.54	1.61	1.40

Table 3.6 Dry weight of residues retained of different crops under different tillage treatments in the wheat dominant cropping sequence at Digram in 2014 to 2017.

Crop Cycle	Crop residue	Residue type	Residue dry weight (t ha^{-1})					
			High Residue			Low Residue		
			SP	BP	CT	SP	BP	CT
13	Wheat	Anchored	1.64	1.36	1.63	1.02	0.91	0.92
14	Jute	Anchored	2.35	2.33	2.33	1.96	1.81	1.87
15	Monsoon Rice	Anchored	2.15	2.23	2.12	1.37	1.10	1.15
16	Wheat	Anchored	1.34	1.21	1.45	0.90	0.95	1.02
17	Mungbean	Loose	1.49	1.38	1.24	0.50	0.46	0.41
18	Monsoon Rice	Anchored	2.14	2.01	1.92	1.11	0.98	0.85
19	Wheat	Anchored	1.54	1.23	1.35	1.04	0.96	1.04

3.2.4 Soil sample collection and bulk density

The bulk density of three soil layers from different tillage and residue treatments was determined in 2017 after the monsoon rice harvest in Alipur and after wheat harvest in Digram. Intact soil cores were extracted from three trenches dug in each plot. The stainless-steel core dimensions were 5 cm high and 7.5 cm in diameter. One core was removed at 0 cm, 10 cm and 20 cm depth from the side of the trenches. For BP treatment, soil cores were collected from both the permanent bed and the furrows; for SP treatment, soil cores were collected from the strip and the interrow spaces, and for conventional treatment, cores were collected from between plants. Details of the depths of soil sample collection are presented in Figure 3.3 and Table 3.7. Depths of soil collection were determined according to a datum point fixed on the top of the ground surface of the CT treatment. According to the datum point, a plough pan was found at a depth of 10 cm for all tillage treatments and positions (bed or furrow) for both Alipur and Digram sites. In the case of newly reformed beds, the top of the bed was at an elevation of

+7 cm above the datum, and that of a seasoned bed (after one crop cycle) was at +5 cm elevation. The bottom of the furrow of a reformed bed was at a depth of -5 cm, i.e. 5 cm below the datum where wheel compaction was likely to take place (Figure 3.3). Core soil samples were wrapped immediately after removal from the trenches and then stored in a plastic crate. Bulk density was determined after oven drying the core soil samples at 105° C for 72 hours (Blake and Hartge, 1986). Gravimetric soil water content was also determined in the soil core samples.

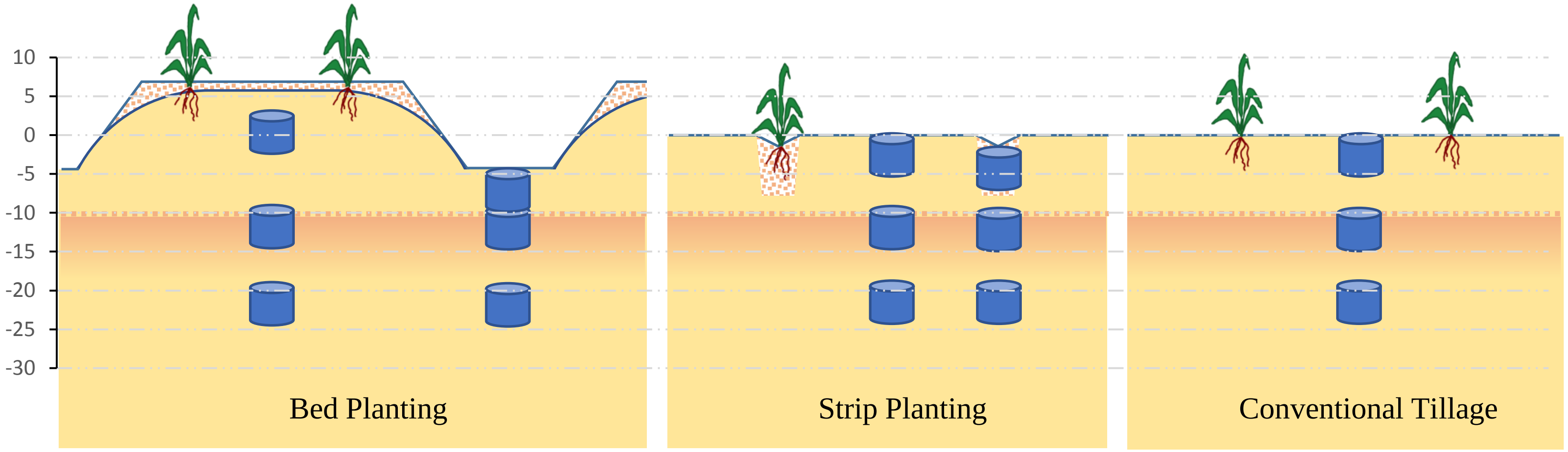


Figure 3.3 Cross-sections of soil profile under different tillage treatments illustrating depths of core soil sample collection from different positions. There was a plough pan at a depth of 10 cm below the datum for both Alipur and Digram long term experiments. The blue cylinders indicate 5 cm high and 7.5 cm diameter steel cores. Pattern fill indicates a reshaped bed, and the solid fill indicates a seasoned bed after one crop cycle, especially rice.

Table 3.7 Depths of soil samples collected from different positions of different tillage treatments

Soil Layer	**Depth of soil layer* of different tillage treatment and position**				
	Bed planting		**Strip planting**		**Conventional tillage**
	Bed	Furrow	Inter-row	Strip	
1	+2.5	-5	0	-2.5	0
2	-10	-10	-10	-10	-10
3	-20	-20	-20	-20	-20

*Depth of soil layer was determined from a datum reference point fixed on the top of the ground surface of the conventional tillage treatment. Number with +ve sign indicates elevation above and –ve sign indicates depth below the datum (0 cm).

3.2.5 Soil porosity and pore size distribution

Soil porosity was calculated from the soil water retention curve constructed for each treatment following the procedure of He *et al.* (2011). The pore sizes were classified as: macropores of equivalent radius >60 μm, mesopores from 0.2 to 60 μm in diameter and micropores <0.2 μm. Macroporosity was taken as the volumetric water content difference between 0 kPa and –5 kPa matric potential. Mesoporosity was taken as the volumetric water content difference between –5 kPa and –1500 kPa matric potential. Microporosity was determined by the volumetric water content at –1500 kPa matric potential.

3.2.6 Soil water content and soil penetration resistance

Soil water content was measured four weeks after the monsoon rice harvest in November 2016 at Alipur and after wheat harvest in March 2017 at Digram. Soil water content and PR were measured in the same trenches after BD soil samples were collected. In the trenches, volumetric SWC was measured by the MP406 probe (ICT international, Australia), which was calibrated for both sites in 2015 and 2017. Calibration was done after mustard harvest at Alipur and Monsoon rice harvest at Digram in 2015. Another measurement for probe calibration was done in 2017 during the PR measurements in trenches at both sites. During calibration for Alipur soil in 2015, volumetric SWC were measured with the probe at 0-10 cm, 10-20 cm, 20-30 cm, 30-40 cm and 40-50 cm depth from a random spot of a subplot. Intact soil cores were also collected from the same depths and spot to determine the gravimetric SWC. After oven drying of the soil cores (105° C for 24 hrs) gravimetric SWC and the BD were determined (Cresswell and Hamilton, 2002). Gravimetric SWC was converted to volumetric SWC using the BD of each plot (Cresswell and Hamilton, 2002). The same method was used to calibrate the probe for Digram soil. For each site, the pairs of data (n=192) comprising calculated volumetric SWC (θ_v) and volumetric SWC from the MP406 (θ_{probe}) were used to construct a calibration curve (Vance, 2013). Figure 3.4 presents the combined data for probe calibration done in 2015 and 2017, showing a wide range of water content for different seasons. The combined calibration equations for both years and site are:

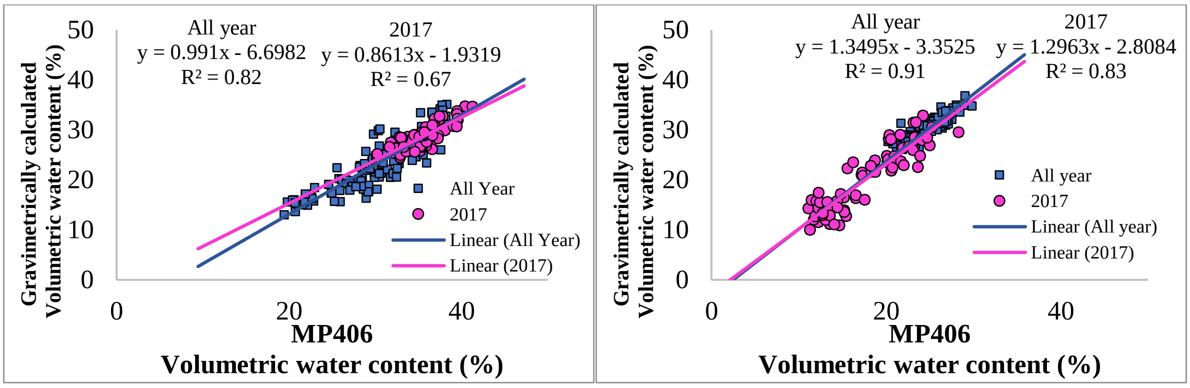
Alipur: $\theta_v = 0.991\,\theta_{probe} - 6.6982$, $r^2 = 0.82$,

Digram: $\theta_v = 1.3495\,\theta_{probe} - 3.3525$, $r^2 = 0.91$

Where θ_v = volumetric SWC calculated from gravimetric SWC, %

θ_{probe} = volumetric SWC measured with the probe, %

The calibration was then used to convert the probe reading (θ_{probe}) to actual volumetric SWC (θ_v) (Vance, 2013).



(a) (b)

Figure 3.4 Relationship between volumetric water content (θ_v) (%) (calculated from the gravimetric SWC) and MP406 volumetric water content (θ_{probe}) (%) for the data collected at 10 cm increments down the soil profile collected in 2015 and 2017 (a) Alipur soil, (b) Digram soil. The soil profile depth was 50 cm. Symbols are data points, and the line represent the regression equation shown above in the text. Blue symbols are data for combined measurements taken in 2015 and 2017, while Pink symbols are for the data measured in 2017.

3.2.7 Soil penetration resistance measurements in the trenches

Soil PR was measured in 2017, four weeks after monsoon rice harvest at Alipur and after wheat harvest at Digram. Penetration resistance and SWC were measured at the same time and from the same trenches. Penetration resistance measurement was taken in the field from 0-10 cm, 10-20 cm and 20-30 cm depths on both the bed and the furrow of the BP treatment, on the strip and interrows of the SP treatment and at random spots of the CT plots (the actual depth of soil sampling is presented in Figure 3.3). Three trenches per plot were opened perpendicular to the direction of the wheel tracks, one at the end and one in the middle part of the plot, all at a 1-m distance from the plot boundary. The penetration was done by hand, pushing the penetrometer horizontally into the vertical plane of the soil surface. The penetrometer used is a force gauge (Dillon, model: GL250, origin: USA) of 250 N capacity with a precision of 0.1 N, equipped with a 61.48 mm^2 base area, 30^0 stainless circular cones with a 1.5 cm long 0.85 cm diameter shaft. The penetrometer was inserted into the wall of each trench and soil layer to 0.5 cm deep at a constant speed of 2.0 cm s^{-1}. The dimension of the cone and the speed were in conformity to ASABE standard S313.3 (ASABE Standards, 2010). Penetration resistance in MPa was determined by dividing the applied force required to push the cone penetrometer into the soil by the area of the base of the cone. Five readings were taken at each soil layer of a trench, and their mean was determined.

3.2.8 Measurements of saturated hydraulic conductivity (K_{sat})

Saturated hydraulic conductivity in the field was measured with a constant head digital infiltrometer (Meter group, USA) (Figure 3.5). The infiltration rate resolution of the instrument was 0.0038 cm h^{-1}. The instruments were operated for 2.5 to 3 hours depending on the compactness of the soil profile. The hydraulic head during the K_{sat} measurement was 10 cm. One K_{sat} measurements were taken for one replication of each treatment. Thus, four measurements were taken for each treatment. For SP treatments, measurements were taken for three depths of the interrow space. For BP treatments, three measurements were taken for three depths in the bed, and two measurements were taken from the furrow bottom. For CT, three measurements were taken at random positions for three depths.

Figure 3.5 Field measurement of saturated hydraulic conductivity with a constant head digital infiltrometer (Meter group, USA). Picture showing measurements in the furrows.

3.2.9 Soil water retention curve

Soil water retention curves were determined with different sets of soil cores as described in the soil sampling section. For determination of the water retention curve, core samples were saturated for 24 hrs and then weighed. Then water content of the soil cores was determined at -5, -10, -30, -50, -100, -200, -392, -1500 kPa tension using a pressure plate apparatus (Soilmoisture Equipment Corp., USA) (Dane and Hopmans, 2002). At equilibrium, the soil cores were weighed at each matric potential. Then, the cores were oven-dried at 105^0 C for 24 hrs to determine the volumetric water content (Grossman and Reinsch, 2002). Gravimetric water content was converted to volumetric water content using the BD of the corresponding soil samples. Volumetric water content at matric potential -10 kPa and -1500 kPa was considered as the volumetric water content at field capacity (θ_{FC}) and permanent wilting point (θ_{PWP}), respectively. Soil water retention curves were established for each treatment and soil type using the RETC computer program (Van Genuchten *et al.*, 1991). The equation from Van Genuchten (1980) was used to model the water retention curve:

$$\theta_v = \theta_r + \frac{(\theta_s - \theta_r)}{\{1 + (\alpha\psi)^n\}^m}$$

Where θ_v is the volumetric water content (%), θ_r is the residual water content (%), θ_s is the saturated water content (%), ψ is the water potential (cm), and α, n and m are constants that affect the slope of the retention curve: α approximates the inverse of the air-entry potential of the water retention curve, and n and m are parameters that control the slope of the curve (Reutenauer and Ambroise, 1992). As in (Van Genuchten, 1980), the Mualem model was used and m restricted to be:

$$m = 1 - \frac{1}{n}$$

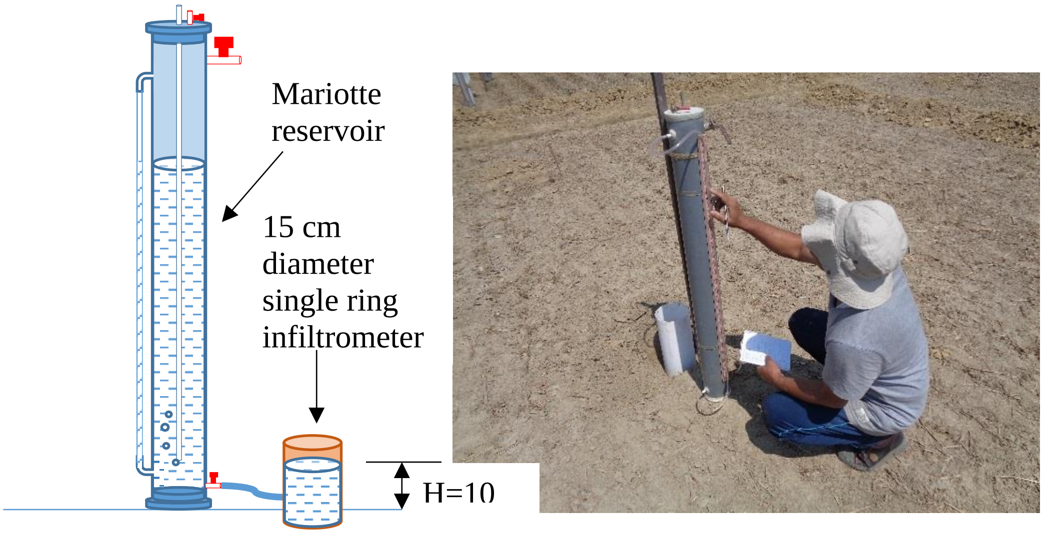
3.2.10 Infiltration measurements in the field

A constant head single ring infiltrometer was used to measure the infiltration rate in the field as described by (Reynolds *et al.*, 2002). Most ring infiltrometers are 10-50 cm in diameter, although much smaller ring diameters have been used for special purpose applications (Leeds-Harrison & Youngs, 1997; E. G. Youngs, Spoor, & Goodall, 1996). For the current study, since the width of the interrow space under the SP was 20 cm, a ring of 15 cm in diameter was used (Figure 3.6). The ring infiltrometer was inserted into the unsaturated soil to a depth of 5 cm. The depth of water ponding was 10 cm which was maintained by connecting a Mariotte reservoir to the infiltrometer. Both the ring and the Mariotte reservoir was manufactured in the BRRI workshop. The height of the Mariotte reservoir was adjusted to set the depth of ponding. The rate of fall of the water level in the Mariotte reservoir was monitored at 10-minute intervals to determine the infiltration rate into the soil. After some preliminary tests, 4 hours duration of the measurement was chosen since this duration was found to be adequate to detect the apparent steady-state condition. Steady-state was reached after an average of 3 hours. The criterion used for attaining steady-state infiltration was that the 10 min infiltration volume during a 60 min record remained effectively constant. This method was used by Mertens *et al.* (2002), except they used the 5 min infiltration volume during a 30 min record.

Horton’s infiltration model was used to fit the data and to present the infiltration characteristics graphically.

$$f_{cap} = (f_o - f_c)e^{-bt} + f_c$$

Where f_{cap} is the maximum infiltration capacity of the soil (cm min^{-1}), f_o is the initial infiltration capacity of the soil (cm min^{-1}), f_c is the final infiltration capacity of the soil (cm min^{-1}), b is the Horton’s constant, and t is the elapsed time (min).



(a) (b)

Figure 3.6 (a) Schematic diagram of a constant head single ring infiltrometer with a Mariotte reservoir used for measuring infiltration rate in the field, (b) Field measurement of infiltration. H= ponding depth in the infiltrometer.

3.2.11 Soil physical parameters of natural soils

A set of soil physical parameters, namely BD, SWC and PR, and K_{sat}, were measured and determined from undisturbed representative natural sites from the same depth as the long-term experimental plots. Natural sites were at Alipur and Digram of Rajshahi, Baliakandi of Rajbari, Bangladesh Agricultural University farm and Gouripur of Mymensingh. Soil physical parameters were compared with those of long-term CA experimental plots. Detail of the natural sites is given in the table below.

Table 3.8 Description of undisturbed natural sites at five locations in three districts where short to medium long-term CA experiments were underway.

Locations	Soil types	Description of the sites
Alipur, Rajshahi	Silty loam	The natural site has been undisturbed for more than 20 years. The site was near a pond, abandoned due to its irregular shape and not suitable for cultivation. Long term CA PhD experimental site was about 50 m away.
Digram, Rajshahi	Silty clay loam	The natural site was irregular in shape, has not been cultivated for more than 20 years. Long term CA PhD experimental site was 75 m away.
Bangladesh Agricultural University farm (BAU), Mymensingh	Sandy clay loam (50 % sand, 23 % silt, 27 % clay) (Zahan *et al.*, 2018)	The natural site was near a mosque, abandoned and not cultivated for more than 30 years. The natural site was about 250 m away from the BAU farm PhD experimental plot where CA has been practised for 3 years.
Gouripur, Mymensingh	Loam	The natural site was near an orchard, abandoned and not cultivated for more than 20 years due to shade and irregular shape. 120 m away from the natural site, CA in a PhD experimental plot has been practised for 3 years.
Baliakandi, Rajbari	Sandy loam (Salahin *et al.*, 2017)	The irregular shaped natural site was near a graveyard, has been owned by four absentee farmers for more than 25 years, abandoned and not cultivated. Three years CA PhD plot was about 100 m away from the natural site

3.2.12 Statistical methods

The data were analysed by analysis of variance (ANOVA) with split-plot design using GenStat version 18.0 (VSN international Ltd. United Kingdom). The difference between treatments was evaluated for their significance using the least significant difference (LSD) at the 5 % level of significance. Soil parameters were also analysed with depth as a repeated measure. The tests of normality of the parameters were also done with Genstat software, and all were normally distributed. The statistical analysis of BD, PR and K_{sat} according to the position for SP (strip and inter-row space) and BP (bed and furrow) were done using one way ANOVA (Gomez *et al.*, 1984) with the position as the main effect plots, and depths within positions as repeated measures.

3.3 Results

3.3.1 Alipur

Bulk density

After seven years, the effect of tillage on BD of soils varied significantly with depth ($P<0.05$). The minimum BD of 1.33 to 1.38 g cm^{-3} was observed in the 0-10 cm soil depth with no variation between SP and BP or between BP and CT. However, SP had 0.05 g cm^{-3} lower BD than CT. The maximum values of BD ranging from 1.60 to 1.65 g cm^{-3} were observed in the 10-20 cm soil depth in the order of SP=BP<CT. The ANOVA test indicated that residue retention treatment had a significant effect on BD at 0-10 cm depth only. Averaged across the tillage treatment, HR treatment decreased BD by 0.04 g cm^{-3} over the LR treatment. While taking the averages across the residue management, SP had significantly lower BD (1.33 g cm^{-3}) than CT (1.38 g cm^{-3}), with no significant difference between SP and BP. In the 10-20 cm soil depth, SP and BP decreased BD by 0.05 and 0.06 g cm^{-3}, respectively, over CT. In the 20-30 cm soil depth, neither tillage nor residue treatment affected soil BD.

Table 3.9 Soil BD (g cm^{-3}) in the 0-30 cm depth as affected by three tillage and two residue retention treatments after 7 years of minimum soil practices treatments in the Alipur long term experiment.

Tillage	**0-10 cm ***			**10-20 cm**			**20-30 cm**		
	LR	**HR**	**Mean**	**LR**	**HR**	**Mean**	**LR**	**HR**	**Mean**
SP	1.35	1.31	1.33	1.60	1.60	1.60	1.51	1.51	1.51
BP	1.37	1.33	1.35	1.59	1.59	1.59	1.53	1.55	1.54
CT	1.40	1.36	1.38	1.65	1.65	1.65	1.51	1.52	1.52
Mean	1.37	1.33		1.62	1.61		1.52	1.53	
$LSD_{0.05}$									
Tillage	0.034			0.025			ns		
Residue	0.025			ns			ns		
Depth	0.014								
Tillage × Depth	0.028								

SP= strip planting, BP=bed planting, CT=conventional tillage, LR=low residue, HR=high residue, $LSD_{0.05}$= least significant difference.
*For BP, the actual depth of the 1st soil sample was from +5 to -5 cm depth (Figure 3.3).

Soil water content at the time of penetration resistance measurements

Volumetric SWC determined at the time of PR measurement was significantly affected by tillage and depth (Figure 3.7). Irrespective of tillage treatment, mean SWC was highest (31 %) in the 0-10 cm soil depth and lowest (27 %) in the 10-20 cm depth, while SWC was intermediate (28 %) in the 20-30 cm soil depth. In the 0-10 cm depth, SP stored 3.38 % more water than CT. There was no significant difference in SWC between BP and CT. However, in the 20-30 cm depth, BP significantly increased SWC by 2.50 % over CT. In the 0-10 cm soil depth averaged across the residue retention treatment, SP (33 %) contained higher SWC compared to the BP (30 %) and CT (30 %). Averaged across the tillage treatment, the HR treatment contained significantly higher

SWC (32 %) compared to that of LR (30 %). A similar trend in terms of tillage treatment effects on SWC was also observed in the 10-20 cm soil depth, where SWC under SP (29 %) was significantly higher than that under BP (27 %) and CT (26 %). In the 10-20 cm soil depth, HR treatment showed significantly higher SWC (28 %) compared to LR treatment (27 %). In the 20-30 cm soil depth, both SP and BP had SWC values of 29 %, which was higher than that under CT (26 %).

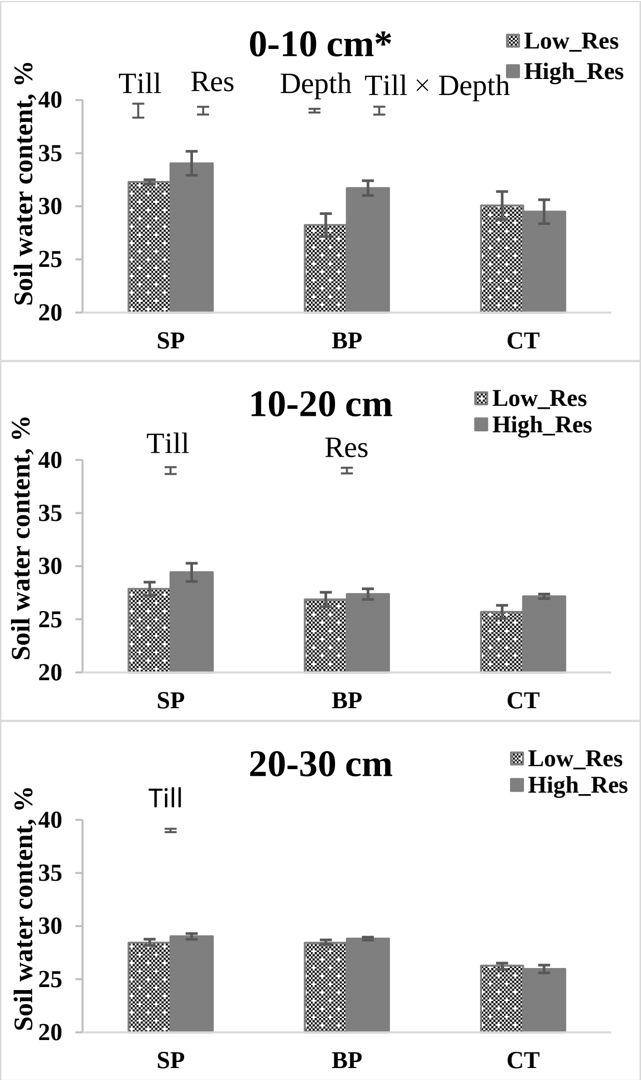


Figure 3.7 Soil volumetric water content taken four weeks after the monsoon rice harvest in November 2016 during penetration resistance measurement for three tillage treatments viz. strip planting (SP), bed planting (BP) and conventional tillage (CT), and residue management viz. low residue and high residue for the Alipur long-term experiment. The floating bar presents LSD at P<0.05. *For BP, the actual depth of the 1st soil sample was from +5 to -5 cm depth (Figure 3.3).

Penetration resistance

Penetration resistance varied significantly due to tillage and residue retention interactions ($P<0.05$) (Figure 3.8). In the 0-10 cm depth, SP and BP had 60 % higher PR compared to CT, while in the 10-20 cm depth, where the plough pan appeared, PR under SP and BP were 11 % lower than that under CT. In the 20-30 cm depth, similar to 10-20 cm, the variation in the tillage treatments followed the order of SP=BP<CT. Penetration resistance was significantly affected by the main effect of tillage treatment and the main effect of residue retention at the 0-10 cm and 10-20 cm depth. In the 0-10 cm depth, regardless of tillage treatments, HR reduced PR by 23 % compared to LR retention. While in the 10-20 cm depth, HR retention reduced PR by 10 % over LR retention.

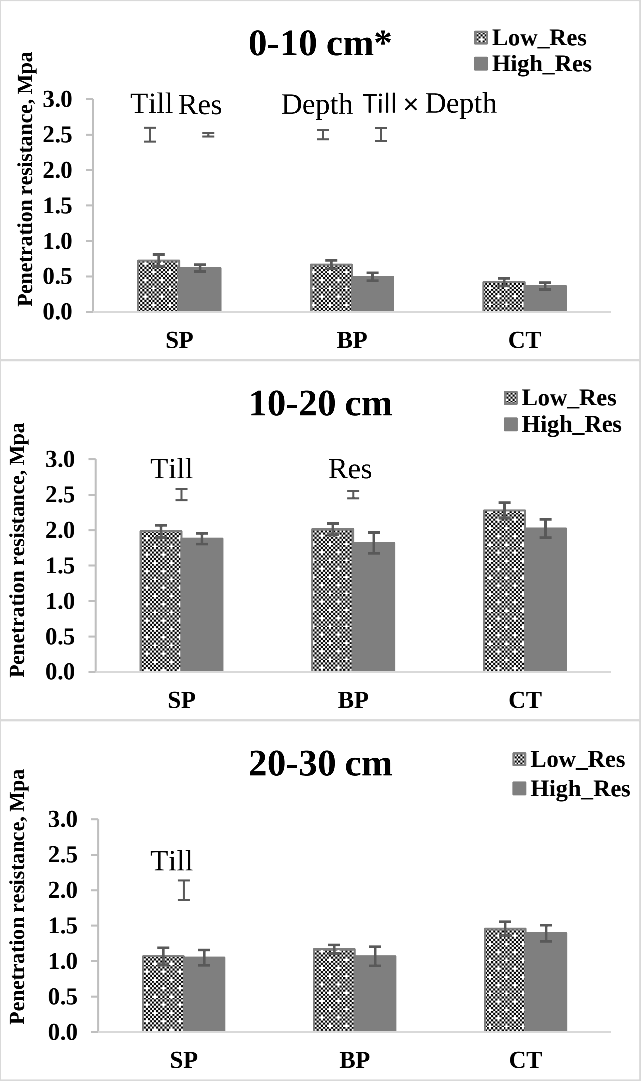


Figure 3.8 Soil penetration resistance measured four weeks after the monsoon rice harvest in November 2016 for three tillage treatments viz. viz. strip planting (measurement was taken from inter-row; SP), bed planting (measurement taken from bed; BP) and conventional tillage (CT), and residue management viz. low residue and high residue for Alipur long-term experiment. The floating bar presents LSD at P<0.05. *For BP, the actual depth of the 1st soil sample was taken from +5 to -5 cm depth (Figure 3.3).

Saturated Hydraulic Conductivity

The effect of tillage treatments on K_{sat} significantly ($P<0.05$) varied with respect to depth (Table 3.10). Averaged across the tillage treatments, the highest K_{sat} values (1.30 cm h^{-1}) were found at the surface soil, and the lowest values (0.38 cm h^{-1}) were at the plough pan, which is the most restricting layer for vertical water flow. Generally, greater K_{sat} was observed for the soil under SP and BP than that under CT. Strip planting and BP tillage system resulted in 45 % higher ($P<0.05$) K_{sat} at the 0-10 cm depth than that under CT plot with no significant difference between SP and BP. At the 10-20 cm depth, i.e. at the plough pan, the K_{sat} of BP was twice as much as SP and CT plots, with no significant difference between SP and CT. However, at the 20-30 cm depth, tillage treatment had no significant effect on K_{sat}.

Table 3.10 Saturated hydraulic conductivity taken after lentil harvest in February 2017 for three soil depths under three tillage treatments and two residue retention treatments for Alipur long-term experiment.

Tillage	Saturated Hydraulic Conductivity, cm h^{-1}		
	0-10 cm *	10-20 cm	20-30 cm
SP	1.39	0.27	0.62
BP	1.52	0.58	0.58
CT	1.00	0.28	0.56
$LSD_{0.05}$ Tillage		0.20	
$LSD_{0.05}$ Depth		0.15	
$LSD_{0.05}$ Tillage × Depth		0.27	

SP= strip planting, BP=bed Planting, CT=conventional tillage.
*For BP, the actual depth of the 1st soil sample was from +5 to -5 cm depth (Figure 3.3).

Water retention and plant available water capacity (PAWC)

The results show that the main effect of tillage treatment at 0-10 cm depth was significant on water content between 0-50 kPa matric potential but not at higher matric potential (Figure 3.9). At -10 kPa matric potential (field capacity), the water content of SP (39 %) was significantly higher than that under BP (37 %) and CT (36 %). At this matric potential, the water content of BP was significantly higher than that of CT. The main effect of residue retention treatment at 0-10 cm depth was significant on water content between 0 and -30 kPa matric potential (Figure 3.10).

Water content at -10 kPa under HR treatment was 39 %, while under LR treatment, water content was 38 %. At 10-20 cm depth, water content under tillage treatment was significantly affected at 0-5 kPa and between 100-1500 kPa matric potential. At matric potential -1500 kPa (permanent wilting point), SP and BP had significantly higher water content (18 % and 19 %, respectively) than the water content of CT (16 %). There was no significant effect of residue retention treatment on water content across the whole measured tension range in the 10-20 cm soil depth.

In the 0-10 cm soil depth, PAWC under SP (21 % or 2.1 cm) was significantly higher than that under BP (20 % or 2.0 cm) and CT (19 % or 1.9 cm). High residue treatment had higher PAWC (21 % or 2.1 cm) compared to LR treatment (19 % or 1.9 cm). However, in the 10-20 cm soil depth PAWC under three tillage treatments were not significantly different, with an average value of 17 % or 1.7 cm.

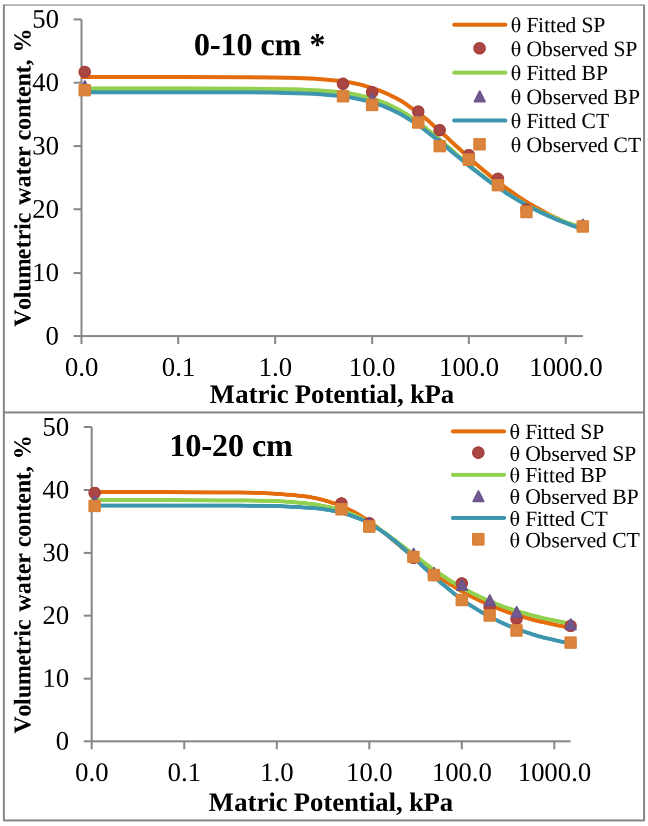


Figure 3.9 Tillage effects on water retention curve in two depths of Alipur soil. Values are means across residue levels (n=8). SP= Strip planting, BP=Bed Planting, CT=Conventional Tillage. *For BP, the actual depth of the 1st soil sample was taken from +5 to -5 cm depth (Figure 3.3).

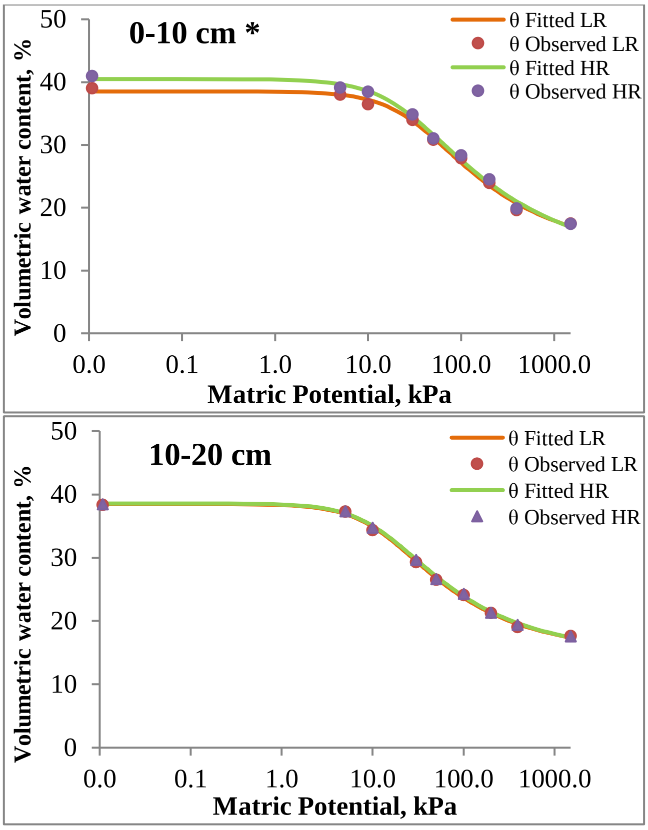


Figure 3.10 Residue effects on water retention curve in two depths of Alipur soil. Values are means across tillage treatments (n=12). HR=High Residue, LR=Low Residue. *For BP, the actual depth of the 1st soil sample was from +5 to -5 cm depth (Figure 3.3).

Soil porosity and pore size distribution

In the 0-10 cm depth, TP under SP was 7 % higher than the CT plot ($P < 0.01$) which was associated with 150 % more macroporosity ($P < 0.01$) and 15 % mesoporosity compared to CT plots (Figure 3.11). Similarly, BP resulted in a significant increase in TP with mean values of 44 % more macroporosity compared to CT plots. In the 10-20 cm depth, SP had significantly ($P <0.01$) greater (220 %) macroporosity and greater (17 %) microporosity, but significantly ($P<0.01$) less (8 %) mesoporosity compared to CT treatment, which resulted in 6 % more TP. Bed planting in the 10-20 cm depth (plough pan) significantly increased macroporosity by 120 %, microporosity by 19 %, but significantly reduced mesoporosity by 13 % ($P <0.01$), which resulted in 2 % greater TP.

In 0-10 cm depth, the mean TP was 41 % under HR and 39 % under LR management treatment (P < 0.05) (Figure 3.12). The increase in TP was largely due to 80 % and 6 % higher macroporosity and mesoporosity in the HR treatment than LR, respectively.

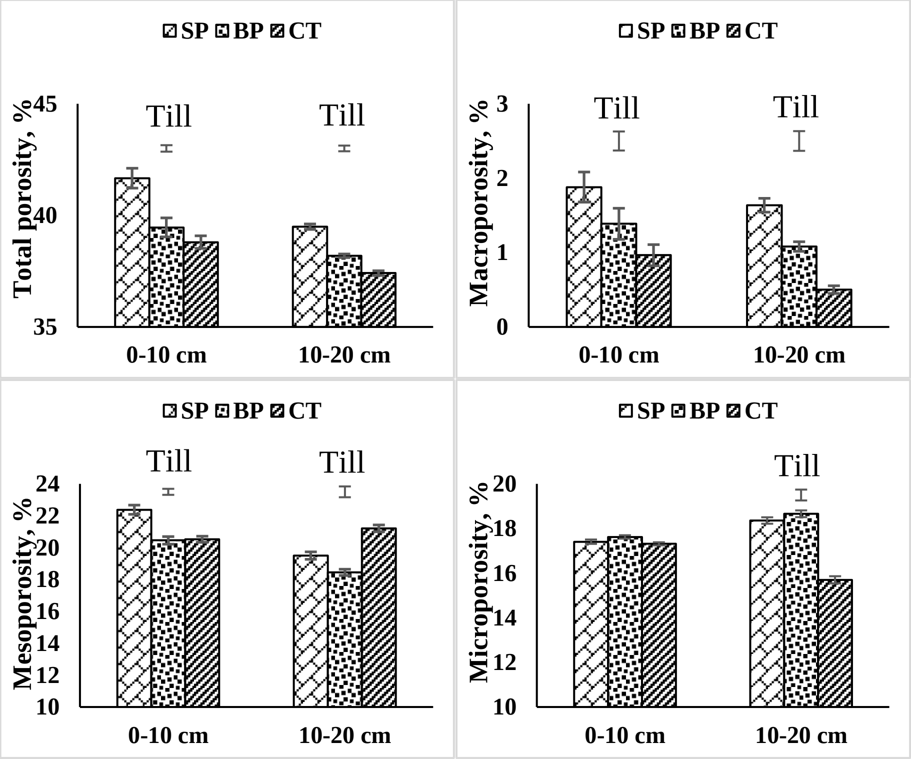


Figure 3.11 Mean soil porosity under three tillage treatments in 0-20 cm soil depth for Alipur long term experiment. SP= Strip planting, BP=Bed Planting, CT=Conventional Tillage. The floating bar presents LSD P<0.05.

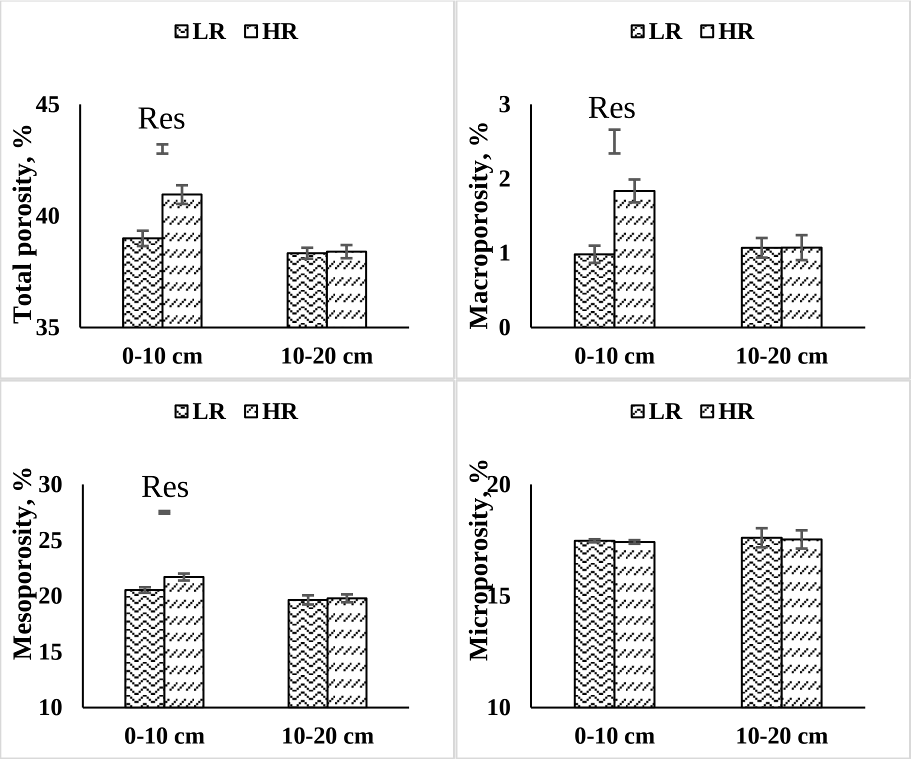


Figure 3.12 Mean soil porosity under two residue managements in 0-20 cm soil depth for Alipur long term experiment. LR= Low residue, HR= High Residue. The floating bar presents LSD at P<0.05.

Soil physical properties according to the sampling position

Sampling position had a significant ($P<0.05$) effect on the soil physical properties such as soil BD, PR and K_{sat} (Table 3.11). Sampling positions for the SP treatment were the strip and the inter-row space, while sampling positions for the BP treatment were the bed and the furrow (Figure 3.3). Bulk density in the strip was significantly lower than that in the inter-row space determined in the 0-10 cm depth. However, in the 10-20 cm and 20-30 cm depth, there was no effect on sampling position. Similarly, in the 0-10 cm depth, PR in the strip was significantly lower compared to the PR measured in the inter-row space. In the 10-20 cm and 20-30 cm depth, PR values were not affected by sampling position. Soil BD and PR in the 1st soil depth (-5 to -10 cm depth in Figure 3.3) of the furrow was significantly higher compared to the soil BD and PR determined in the 1st soil depth of the bed (+5 to -5 in Figure 3.3). Bulk density and PR of the plough pan in the 10-20 cm depth beneath the furrow were significantly higher than the BD and

PR of the plough pan beneath the bed. There were no significant differences in BD and PR values in the 20-30 cm depth under the bed or the furrow. In the 0-10 cm depth, K_{sat} in the bed was twice as much higher than that in the furrow bottom. In the plough pan of the furrow, the K_{sat} value was 57 % lower than the K_{sat} value of the plough pan beneath the bed.

Table 3.11 Soil physical properties according to the sampling position for SP and BP treatments at three depths of Alipur soil.

Tillage	Sampling position	Soil physical properties		
		0-10 cm *	10-20 cm	20-30 cm
		BD, g cm^{-3}		
SP	Interrow	1.33	1.60	1.51
	strip	1.30	1.61	1.53
$LSD_{0.05}$	Position Depth	0.02 0.02	ns	Ns
BP	Bed	1.35	1.59	1.54
	Furrow	1.46	1.63	1.56
$LSD_{0.05}$	Position Depth	0.036 0.023	0.017	Ns
CT	Random	1.38	1.65	1.52
		PR, MPa		
SP	Interrow	0.67	1.93	1.06
	strip	0.41	1.86	1.12
$LSD_{0.05}$	Position Depth	0.07 0.087	ns	Ns
BP	Bed	0.58	1.92	1.12
	Furrow	1.31	2.14	1.24
$LSD_{0.05}$	Position Depth	0.165 0.151	0.104	Ns
CT	Random	0.39	2.15	1.43
		K_{sat}, cm h^{-1}		
SP	Interrow	1.39	0.27	
BP	Bed	1.52	0.58	
	Furrow	0.86	0.24	
$LSD_{0.05}$	Position Depth	0.242 0.278	0.253	
CT	Random	1.00	0.28	

SP= strip planting, BP= bed planting, CT=conventional tillage BD= bulk density, PR=penetration resistance, K_{sat}= saturated hydraulic conductivity. *For BP, the actual depth of the 1st soil sample was from +5 to -5 cm depth (Figure 3.3).

Infiltration characteristics

Effect of tillage on the infiltration characteristics, such as initial infiltration after 10 minutes (I_i), steady-state infiltration (I_s) and 240 minutes cumulative infiltration capacity (I_c), are presented in Table 3.12. Higher I_i, I_s and I_c were measured in SP and BP treatments compared to CT treatments. Initial infiltration rate under SP and BP were 47 % and 60 % higher than those under CT treatment. Between the tillage treatments, the I_i under CT started approaching a steady-state sooner (approximately 40 min after the start of the run) than the SP (about 70 min) and BP (about 80 min after the start of the run) (Figure 3.13). In SP, I_s was twice as high as CT, while BP had three times higher I_s. Cumulative infiltration after 240 minutes increased significantly with SP and BP treatments by 50 % and 86 %, respectively, over the CT treatments. There was no significant effect of residue retention on infiltration characteristics.

Table 3.12 Effect of tillage on soil infiltration characteristics taken after lentil harvest in February 2017 at Alipur, Rajshahi.

Tillage	Infiltration characteristics		
	i_i (cm min^{-1})	i_s (cm min^{-1})	I (cm)
SP	0.22	0.051	16.9
BP	0.24	0.063	21.0
CT	0.15	0.021	11.3
$LSD_{0.05}$			
Tillage	0.05	0.028	4.5

i_i = initial infiltration after 10 min, i_s = Steady-state infiltration, mean of last 60 minutes infiltration rate, I= Cumulative infiltration after 240 minutes. All data are mean of four replicates. SP=Strip Planting, BP=Bed Planting, CT=Conventional Tillage.

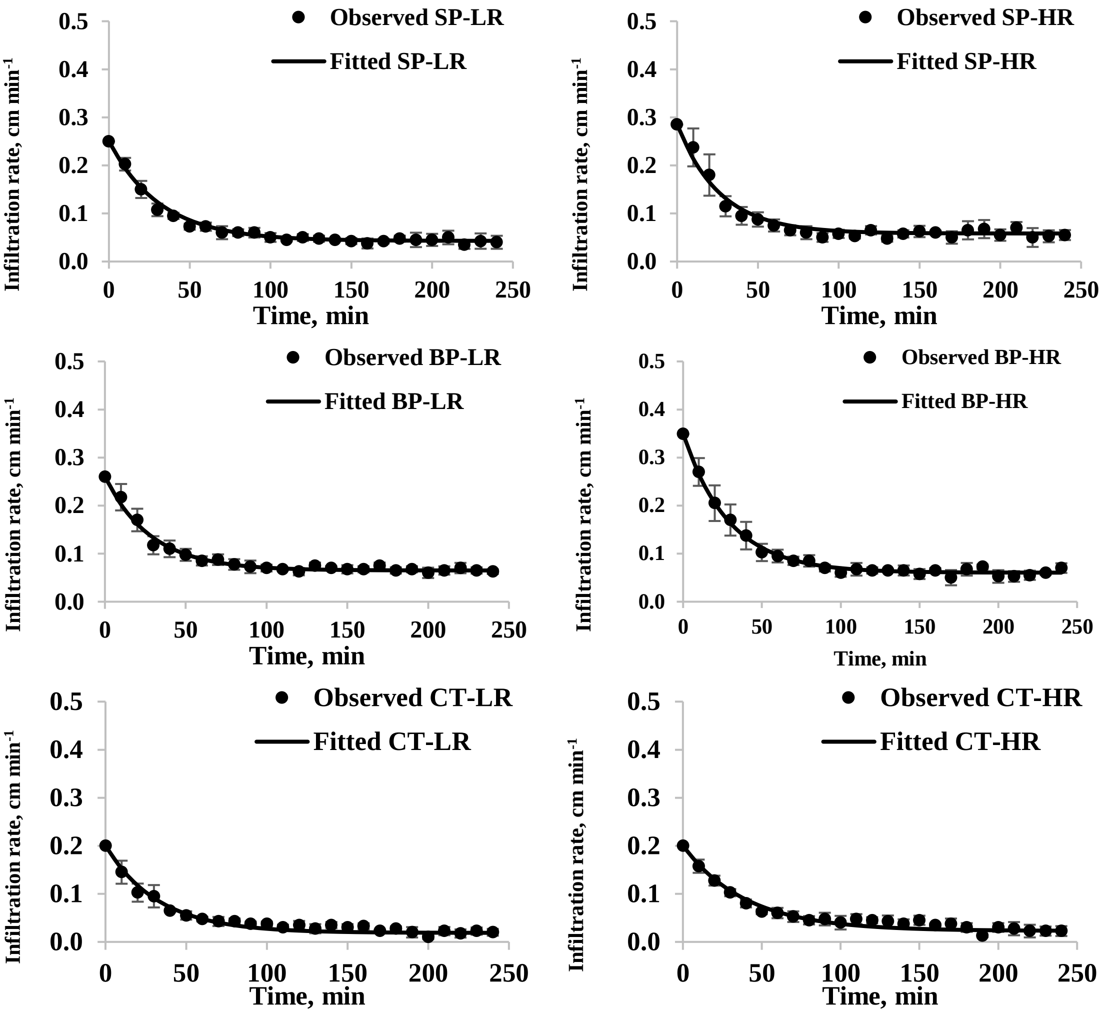


Figure 3.13 Infiltration curves for different tillage and residue retention treatments. SP-LR-Strip planting low residue, SP-HR-Strip planting high residue, BP-LR-Bed planting low residue, BP-HR-Bed planting high residue, CTLR- Conventional tillage low residue, and CT-HR-conventional tillage high residue. The infiltration data were fitted to Horton's model.

3.3.2 Digram

Bulk density

After seven years, the effect of tillage on BD of soils varied significantly with depth ($P<0.05$). The minimum BD of 1.22 to 1.29 g cm^{-3} was observed in the 0-10 cm soil depth with variation among the tillage treatments in the order; SP<BP<CT, while the maximum value of BD, ranging from 1.56 to 1.65 g cm^{-3}, was observed in the 10-20 cm soil depth in the order; SP=BP<CT. In the 0-10 cm depth, SP had 0.07 g cm^{-3} lower BD than CT and 0.03 g cm^{-3} lower BD than BP. In the 10-20 cm depth, SP and BP both had an average 0.09 g cm^{-3} lower BD value compared to CT. The ANOVA test indicated that residue retention treatment had a significant effect on BD in 0-10 cm depth only. Averaged across the tillage treatment, HR treatment decreased BD by 0.03 g cm^{-3} over the LR treatment.

Table 3.13 Soil dry bulk density (g cm^{-3}) in the 0-30 cm depth as affected by three tillage and two residue management treatments after 7 continuous years of disturbance treatments in the Digram long term experiment.

Tillage	0-10 cm *			10-20 cm			20-30 cm		
	LR	HR	Mean	LR	HR	Mean	LR	HR	Mean
SP	1.24	1.21	1.22	1.58	1.56	1.57	1.44	1.46	1.45
BP	1.26	1.24	1.25	1.56	1.55	1.56	1.45	1.49	1.47
CT	1.32	1.27	1.29	1.65	1.65	1.65	1.46	1.43	1.45
Mean	1.27	1.24		1.59	1.59		1.45	1.46	
$LSD_{0.05}$									
Tillage		0.024			0.02			ns	
Residue		0.023			ns			ns	
Depth		0.013							
Tillage × Depth		0.021							

SP= Strip planting, BP=Bed Planting, CT=Conventional Tillage, LR=Low Residue, HR=High Residue.

*For BP, the actual depth of the 1st soil sample was from +5 to -5 cm depth (Figure 3.3).

Soil water content at the time of penetration resistance measurements

Volumetric SWC determined at the time of PR measurement was significantly affected by tillage only in the 0-10 cm and 20-30 cm soil depth, while SWC was significantly affected by tillage and residue in the 10-20 cm soil depth (Figure 3.7). Irrespective of tillage treatment, mean SWC was highest (27 %) in the 20-30 cm soil depth and lowest (13 %) in the 0-10 cm depth, while SWC was intermediate (21 %) in the 10-20 cm soil depth. In the 0-10 cm soil depth averaged across the residue retention treatments, SP showed higher SWC (15 %) compared to the BP (12 %) and CT (13 %), with no significant difference between BP and CT. In the 10-20 cm soil depth, SWC under SP (23 %) and BP (23 %) was significantly higher than that under CT (16 %) irrespective of residue retention. Averaged across the SWC values under the tillage treatments, HR treatment had significantly higher SWC (21 %) in the 10-20 cm depth compared to LR treatment (20 %). In the 20-30 cm soil depth, SP and BP had SWC values of 30 % and 28 %, respectively, which were significantly higher than that under CT (24 %).

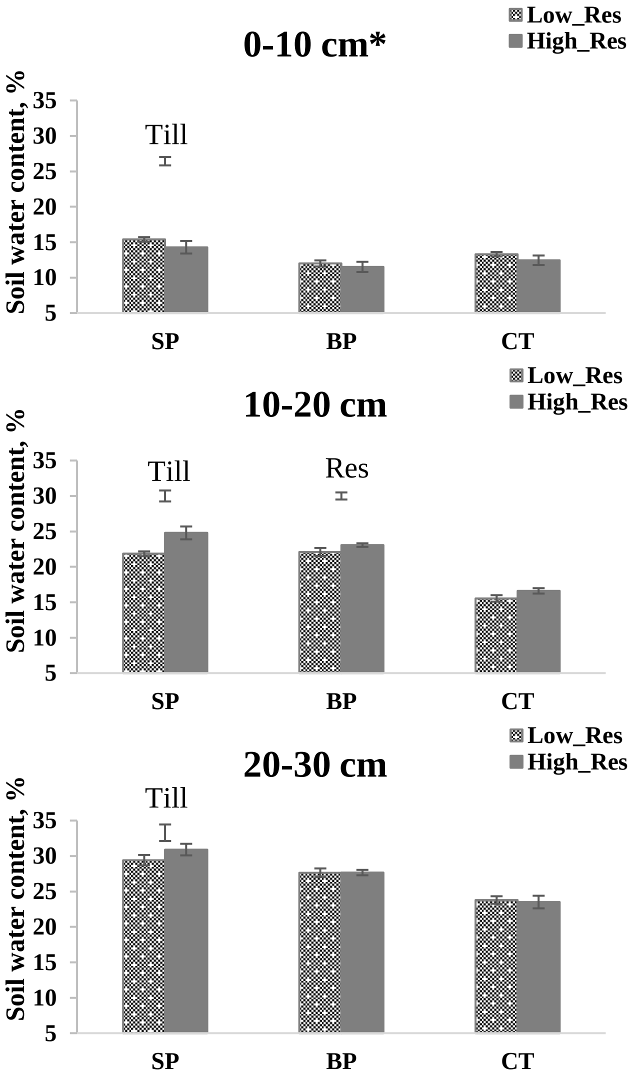


Figure 3.14 Soil volumetric water content taken after wheat harvest in March 2017 during penetration resistance measurement for three tillage treatments viz. strip planting (SP), bed planting (BP) and conventional tillage (CT), and residue management viz. low residue and high residue for Digram long term experiment. The floating bar presents LSD at P<0.05. *For BP, the actual depth of the 1st soil sample was from +5 to -5 cm depth (Figure 3.3).

Penetration resistance

The residue retention treatment significantly affected the soil PR at the first 0-10 cm and the 10-20 cm depth (Figure 3.15). Averaged across the tillage treatments, PR of the 0-10 cm depth with low residue retention was 0.55 MPa, which was reduced to 0.46 MPa with retention of high residue. While in the 10-20 cm, high residue retention reduced PR from 2.2 to 2.0 MPa compared to low residue retention. Tillage treatment had a significant ($P<0.05$) effect on PR with a trend of

CT>SP=BP. Averaged across the residue retention levels, SP and BP (mean 1.88 MPa) reduced soil PR of the plough pan by 26 % compared to CT (2.55 MPa). At the 20-30 cm depth, this reduction in PR by BP and SP was 24 % compared to CT. In this depth, PR of BP, SP and CT was 1.04, 0.97 and 1.33 MPa, respectively. Averaged across the tillage treatments, the 10-20 cm depth, i.e. the plough pan, showed the maximum values for PR, which was four times higher than that of the 0-10 cm depth and twice as much as that of 20-30 cm depth.

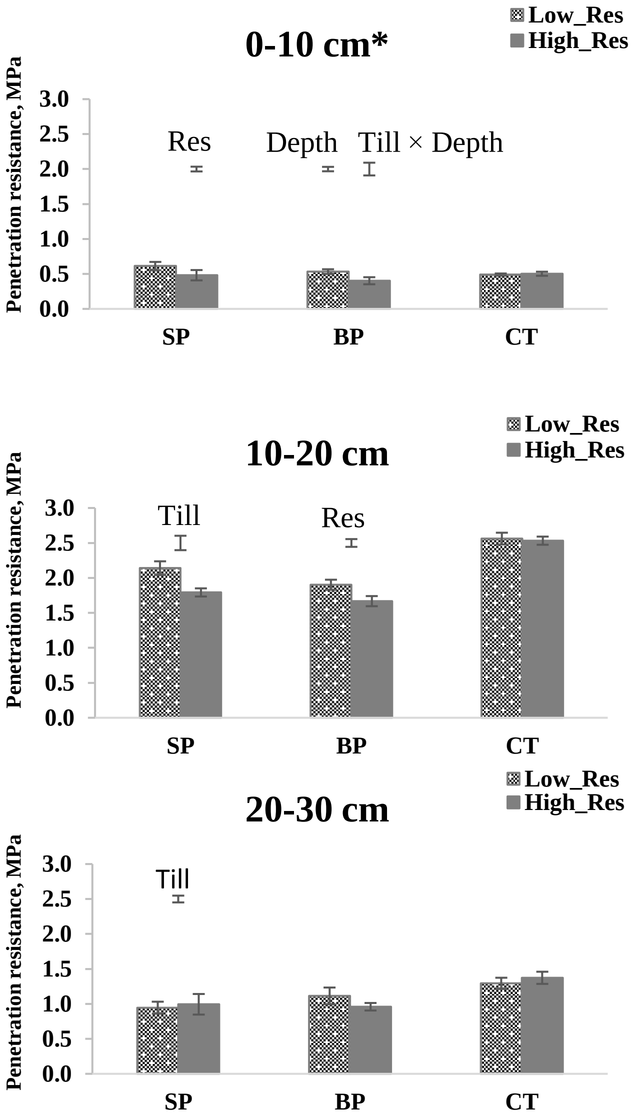


Figure 3.15 Soil penetration resistance measured after Wheat harvest in March 2017 for three tillage treatments viz. strip planting (measurement was taken from inter-row; SP), bed planting (measurement taken from bed; BP) and conventional tillage CT, and residue management viz. low residue and high residue for Digram long term experiment. The floating bar presents LSD $P<0.05$. *For BP, the actual depth of the 1st soil sample was from +5 to -5 cm depth (Figure 3.3).

Saturated hydraulic conductivity (K_{sat})

The effect of tillage on K_{sat} varied significantly due to depth (Table 3.14). The value of K_{sat} was lowest in the 10-20 cm depth for all tillage treatments, while for SP and BP, the highest K_{sat} value was recorded in the 0-10 cm soil depth. In the 0-10 cm soil depth, the effect of tillage treatment on K_{sat} varied in the order; BP>SP>CT. Bed planting had a 22 % higher K_{sat} value than SP and more than twice as high as the K_{sat} value of CT. Similarly, in the 0-10 cm depth, SP had a K_{sat} about twice as much as CT. In the 10-20 cm depth, the K_{sat} value of SP and BP were twice the K_{sat} value of CT. In the 20-30 cm soil depth, there was no significant effect of tillage treatment on K_{sat}.

Table 3.14 Saturated hydraulic conductivity taken after wheat harvest in March 2017 for three soil depths under three tillage treatments and two residue levels for Digram long term experiment.

Tillage	Saturated Hydraulic Conductivity, cm h^{-1}		
	0-10 cm*	10-20 cm	20-30 cm
SP	0.66	0.48	0.62
BP	0.81	0.43	0.69
CT	0.32	0.22	0.64
$LSD_{0.05}$ Tillage		0.14	
$LSD_{0.05}$ Depth		0.09	
$LSD_{0.05}$ Tillage × Depth		0.18	

SP= Strip planting, BP=Bed Planting, CT=Conventional Tillage.
*For BP, the actual depth of the 1st soil sample was from +5 to -5 cm depth (Figure 3.3).

Water retention and plant available water capacity (PAWC)

The results show that the main effect of tillage treatment at 0-10 cm depth was significant on water content at saturation and onwards up to 200 kPa (Figure 3.16). At -10 kPa matric potential (field capacity), the water content of SP (36 %) and BP (35 %) was significantly higher than that under CT (34 %). At this matric potential, the water content of SP and BP were not significantly different. At -200 kPa matric potential, the water content under SP (21 %) and CT (21 %) was significantly higher than that under BP (19 %). At -10 kPa HR (35.2 %) had higher water content than LR (34.8 %) treatment.

At 10-20 cm depth, water content under tillage treatments was significantly affected at all matric potentials. At -10 kPa matric potential, water content under tillage treatments was in the order of BP (36 %)>SP (35 %)=CT (35 %). At matric potential -1500 kPa (permanent wilting point), BP and SP had significantly lower water content (18 % and 20 %, respectively) than the water content under CT (21 %). There was no significant effect of residue retention treatment on water content across the whole measured tension range in the 10-20 cm soil depth.

In the 0-10 cm soil depth, PAWC under SP (25 % or 2.5 cm) was significantly ($P<0.01$) higher than that under BP (24 % or 2.4 cm), which in turn was greater than CT (22 % or 2.2 cm). In the 10-20 cm soil depth PAWC under SP (16.6 % or 1.7 cm) and BP (16.2 % or 1.6 cm) were significantly ($p<0.05$) higher than that under CT (14.0 % or 1.4 cm). In the 0-10 cm soil depth, HR (23.8 % or 2.4 cm) had significantly ($P<0.01$) higher PAWC than LR (23.2 % or 2.3 cm).

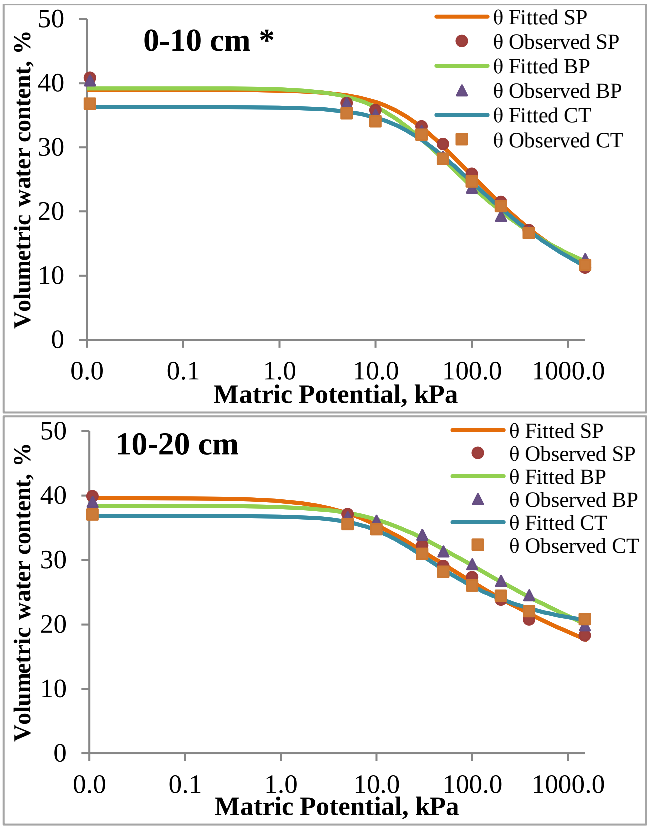


Figure 3.16 Tillage effects on water retention curve in two depths of Digram soil. Values are means across residue levels (n=8). SP= Strip planting, BP=Bed Planting, CT=Conventional Tillage. *For BP, the actual depth of the 1st soil sample was from +5 to -5 cm depth (Figure 3.3).

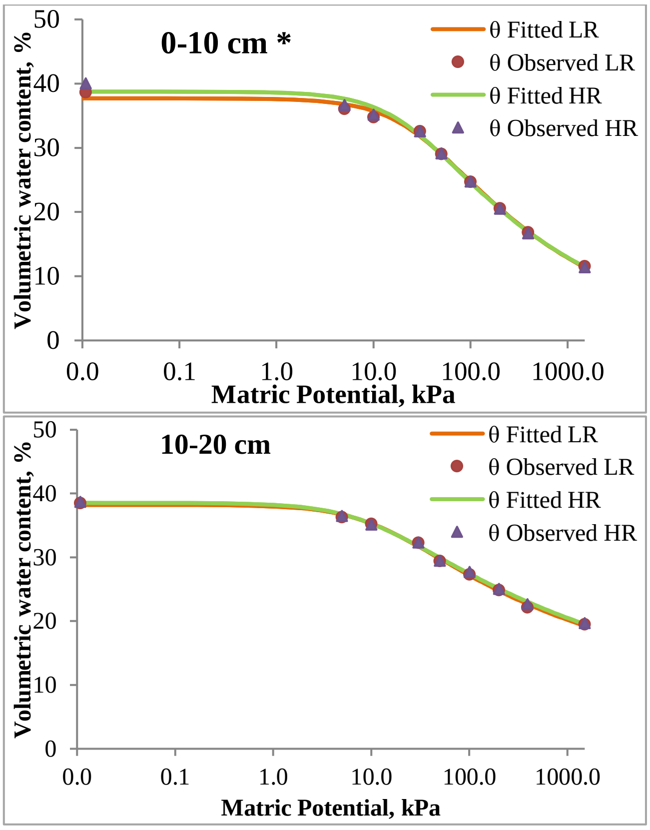


Figure 3.17 Residue effects on water retention curve in two depths of Digram soil. Values are means across tillage treatments (n=12). HR=High Residue, LR= Low Residue. *For BP, the actual depth of the 1st soil sample was from +5 to -5 cm depth (Figure 3.3).

Soil porosity and pore size distribution

In the 0-10 cm depth, TP under SP was 10 % higher than the CT plot ($P < 0.01$) which was associated with 165 % more macroporosity ($P < 0.01$) and 8 % more mesoporosity compared to CT plots (Figure 3.18). Similarly, BP resulted in a significant increase in TP with mean values of 138 % more macroporosity and 7 % more mesoporosity, compared to CT plots. In the 10-20 cm depth, SP had significantly ($P < 0.01$) greater (89 %) macroporosity, and greater (38 %) mesoporosity, but significantly ($P<0.01$) less (12 %) microporosity compared to CT treatment. Bed planting in the 10-20 cm depth (plough pan) significantly increased macroporosity by 63 %, mesoporosity by 9 % but significantly reduced microporosity by 5 % ($P <0.01$). In 0-10 cm depth, the mean TP was 40.1 % under HR and 38.7 % under LR management treatment (P < 0.05) (Figure 3.19). The increase in TP was largely due to 30 % and 3 % higher macroporosity and mesoporosity in the HR treatment than LR, respectively.

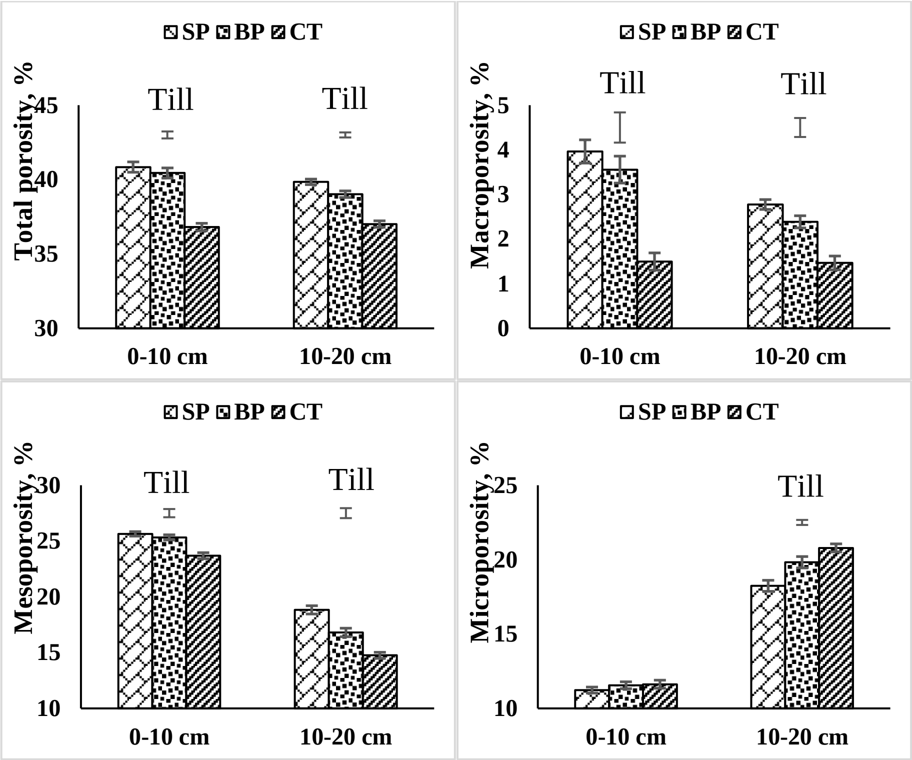


Figure 3.18 Mean soil porosity under three tillage treatments in 0-20 cm soil depth for Digram long term experiment. SP= Strip planting, BP=Bed Planting, CT=Conventional Tillage. The floating bar presents LSD at P<0.05.

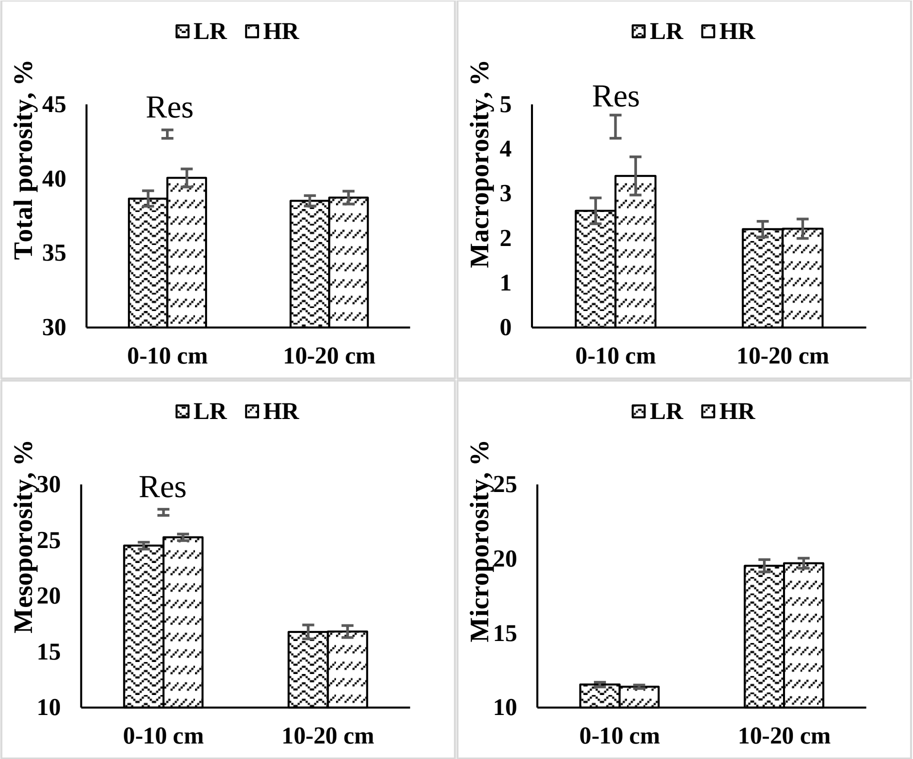


Figure 3.19 Mean soil porosity under two residue managements in 0-20 cm soil depth for Digram long term experiment. LR= Low residue, HR= High Residue. The floating bar presents LSD at P<0.05.

Soil physical properties according to the sampling position

The BD in the strip was significantly similar to the BD in the interrow space determined in the three soil depths (Table-3.15). However, PR in the 0-10 cm depth of the strip was significantly lower compared to the PR measured in the interrow space. In the 10-20 cm and 20-30 cm depth, PR values were not affected by the sampling position. Soil BD in the 1st soil layer of the furrow (-5 to -10 cm depth in Figure 3.3) was increased by 0.12 g cm^{-3} over the BD in the 1st soil depth (+5 to -5 cm in Figure 3.3) of the bed. Penetration resistance in the 1st soil depth of the furrow was twice as high as the PR in the 1st soil depth of the bed. Bulk density and PR of the plough pan (-10 to -20 cm depth in Figure 3.3) beneath the furrow was significantly higher than those of the plough pan beneath the bed. There were no significant differences in BD and PR values in the 20-30 cm depth under either of the sampling positions. In the 0-10 cm layer, K_{sat} in the bed was twice high as in the furrow. While, in the plough pan under the furrow, the K_{sat} value was 35 % lower than the K_{sat} value of the plough pan beneath the bed.

Table 3.15 Soil physical properties according to the sampling position for Strip planting and bed planting treatments at three depths in Digram soil.

Tillage	Sampling position	Soil physical properties		
		0-10 cm *	10-20 cm	20-30 cm
BD, g cm^{-3}				
SP	Interrow	1.22	1.57	1.45
	strip	1.21	1.56	1.46
LSD$_{0.05}$	Position Depth	ns 0.038	Ns	ns
BP	Bed	1.24	1.56	1.47
	Furrow	1.36	1.60	1.45
LSD$_{0.05}$	Position Depth	0.032 0.015	0.025	ns
CT	Random	1.29	1.65	1.45
PR, MPa				
SP	Interrow	0.55	1.97	0.97
	strip	0.42	1.88	0.95
LSD$_{0.05}$	Position Depth	0.06 0.127	Ns	ns
BP	Bed	0.47	1.79	1.04
	Furrow	1.11	2.32	1.13
LSD$_{0.05}$	Position Depth	0.118 0.143	0.31	Ns
CT		0.50	2.55	1.33
K_{sat}, cm h^{-1}				
BP	Bed	0.81	0.43	-
	Furrow	0.42	0.28	-
LSD$_{0.05}$	Position Depth	0.164 0.155	0.106	-
CT		0.32	0.22	-

SP= Strip planting, BP= Bed planting, CT=Conventional Tillage, BD= bulk density, PR=penetration resistance, K_{sat}= saturated hydraulic conductivity. *For BP, the actual depth of the 1st soil sample was from +5 to -5 cm depth (Figure 3.3).

Infiltration characteristics

Higher $I_{s,}$ and I_c was measured in SP and BP treatments compared to CT treatments (Table 3.16). However, I_i was not affected by tillage treatments. After 10 minutes, there was a steeper reduction in infiltration rates in the SP treatment than the CT treatment. Between the tillage treatments, the infiltration rate under SP started approaching a steady-state sooner, approximately 30 min after the start of the run, while under CT, the infiltration rate started approaching the steady-state approximately 60 minutes after the start of the measurement (Figure 3.20). Strip planting and BP had about three times higher I_s compared to CT. Cumulative infiltration after 240 minutes increased significantly with SP and BP treatments by 71 % and 65 %, respectively, over the CT treatments. There was no significant effect of residue retention on infiltration characteristics.

Table 3.16 Effect of tillage on soil infiltration characteristics taken after wheat harvest in March 2017 at Digram, Rajshahi.

Tillage	Infiltration characteristics		
	i_i (cm min^{-1})	i_s (cm min^{-1})	I (cm)
SP	0.10	0.034	8.9
BP	0.11	0.029	8.6
CT	0.10	0.011	5.2
$LSD_{0.05}$			
Tillage	ns	0.009	2.5

i_i = initial infiltration after 10 min, i_s = Steady-state infiltration, mean of last 60 minutes infiltration rate, I= Cumulative infiltration after 240 minutes. All data are mean of four replicates. SP=Strip Planting, BP=Bed Planting, CT=Conventional Tillage.

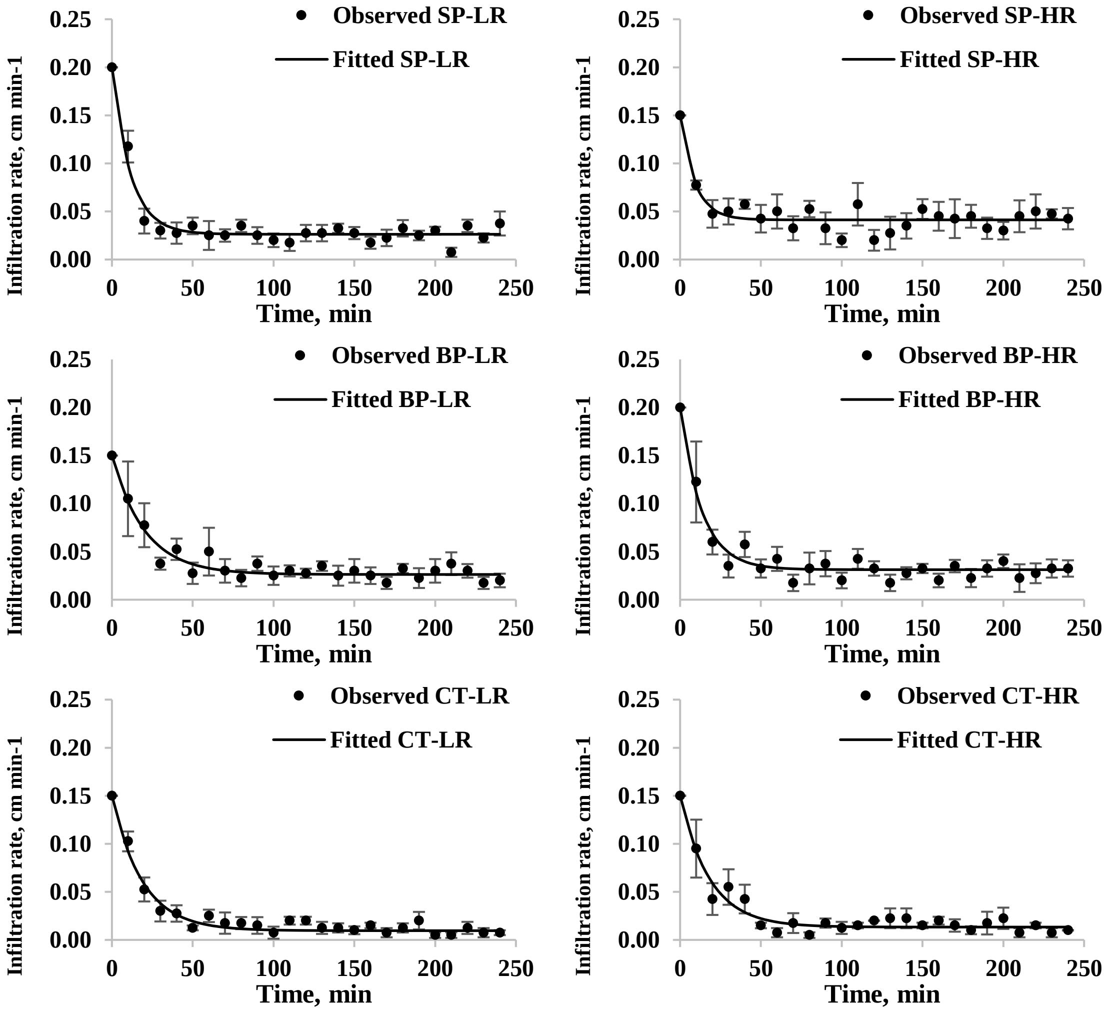


Figure 3.20 Infiltration curves for different tillage and residue retention treatments. SP-LR-Strip planting low residue, SP-HR-Strip planting high residue, BP-LR-Bed planting low residue, BP-HR-Bed planting high residue, CTLR- Conventional tillage low residue, and CT-HR-conventional tillage high residue. The infiltration data were fitted to the Horton model.

3.3.3 Soil physical properties in natural soils of five different locations

Bulk density

A plough pan under strip planting and conventional tillage were found at 10-20 cm depth at Alipur, Digram, BAU farm and Baliakandi and at 20-30 cm depth at Gouripur CA experimental plots. In contrast, soil BD was similar across all depths in natural soils of all locations, indicating no plough pan existed in the undisturbed soil profile. Soil BD of 0-10 cm of natural soil ranged from 1.32 g cm^{-3} at BAU farm to 1.39 g cm^{-3} at Digram and Baliakandi. The BD values of natural soils at 0-

10 cm soil depth were somewhat similar to those of SP and CT plots at BAU farm and Gouripur. At Digram, natural soil at 0-10 cm depth was denser than SP and CT plots. At Alipur, BD of SP plot was lower, and BD of CT plot was similar to the natural soil at 0-10 cm soil depth. At Baliakandi, BD of natural soil was similar to the SP plot but lower than the BD of the CT plot. Bulk density of the natural soil in the 10-20 cm depth was lower than that of SP and CT treatment at all locations with the highest differences in BD values at Alipur and Digram. While at 20-30 cm depth, BD of SP and CT plot was similar to the BD of natural soil.

Penetration Resistance

Penetration resistance of the natural soil was close to 0.5 MPa at all depths for all locations. At 0-10 cm depth, PR of SP and CT for all location were somewhat similar to the PR of natural soil. However, like the BD, PR of the SP and CT was higher than the PR of natural soil at 10-20 cm with the maximum differences in PR values at Alipur, Digram and BAU farm. At Gouripur and Baliakandi, the differences in PR between SP and natural soil were small. At 20-30 cm depth, PR of SP and CT was higher than that of natural soil, but the differences in PR values between the SP and natural soil were smaller than the difference between these two in the 10-20 cm soil depth.

Soil water content

Soil water content in the natural soil at the time of PR measurement was around 30 % volumetric and similar to the SP and CT plot at all locations, except at Digram where SWC in the SP and CT were around 15 %, and SWC of natural soil was about 22 %. The SWC of natural soil at 10-20 cm soil depth was nearly 27 % at all locations, while that was around 28 % at 20-30 cm soil depth.

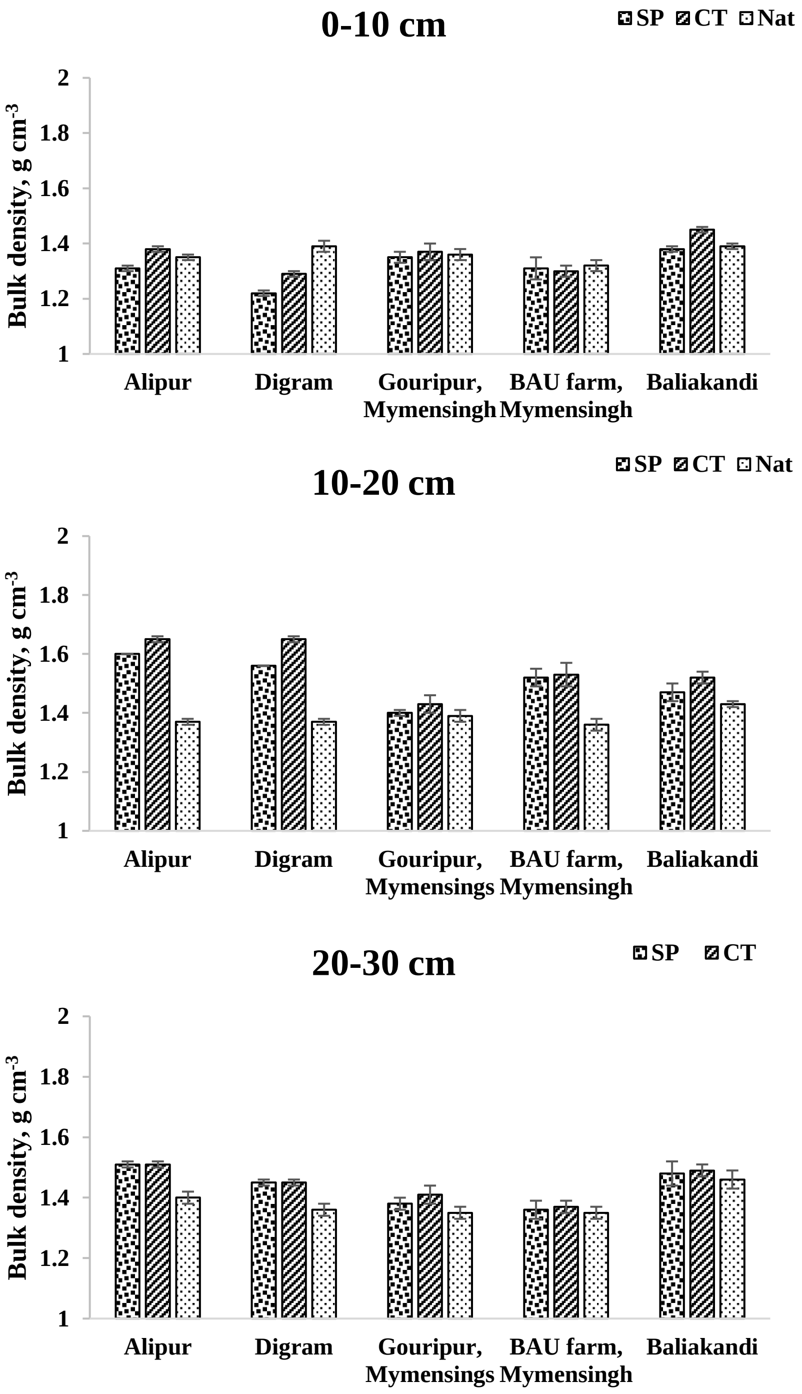


Figure 3.21 Bulk density of natural soil for five locations as compared to SP and CT tillage treatments in nearby sites.

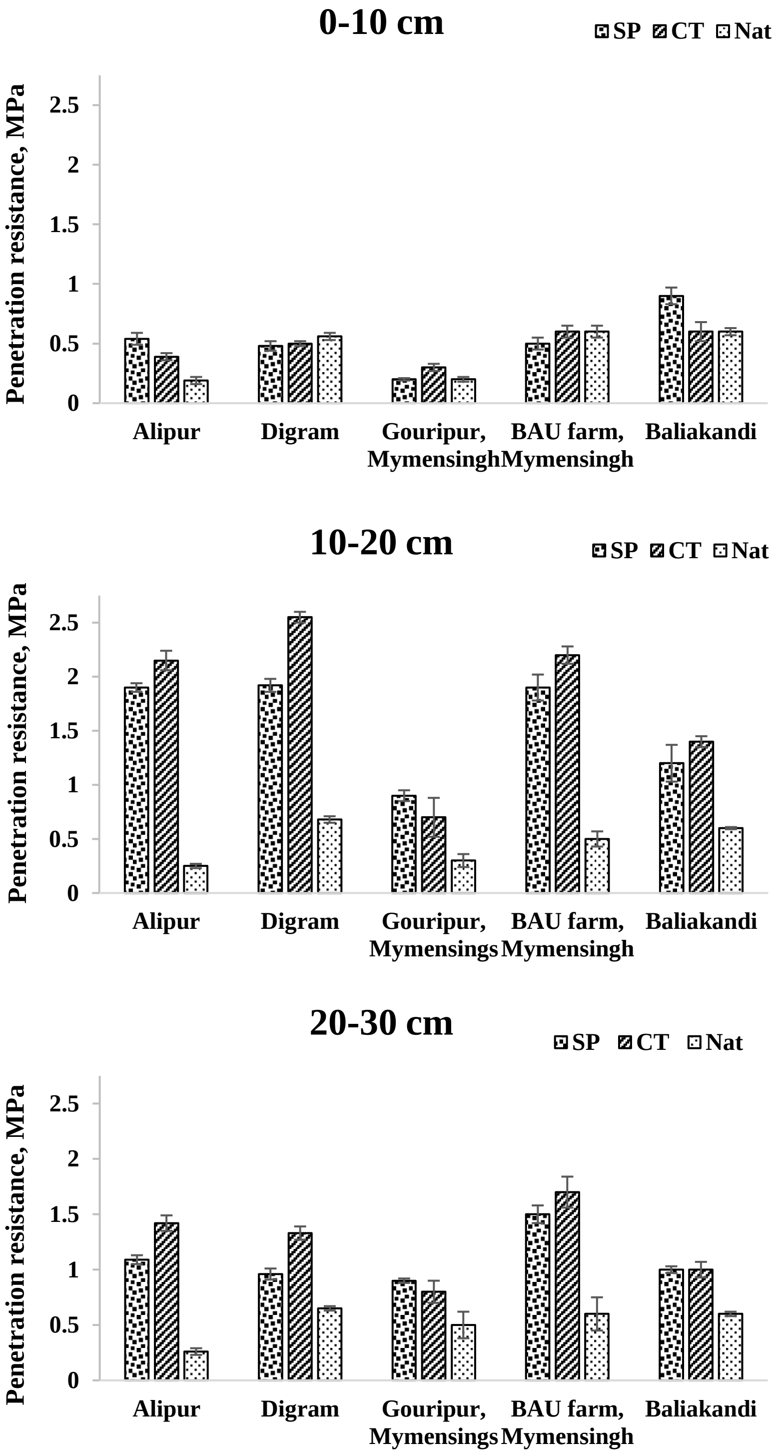


Figure 3.22 Penetration resistance of natural soil for five locations as compared to SP and CT tillage treatments at nearby sites.

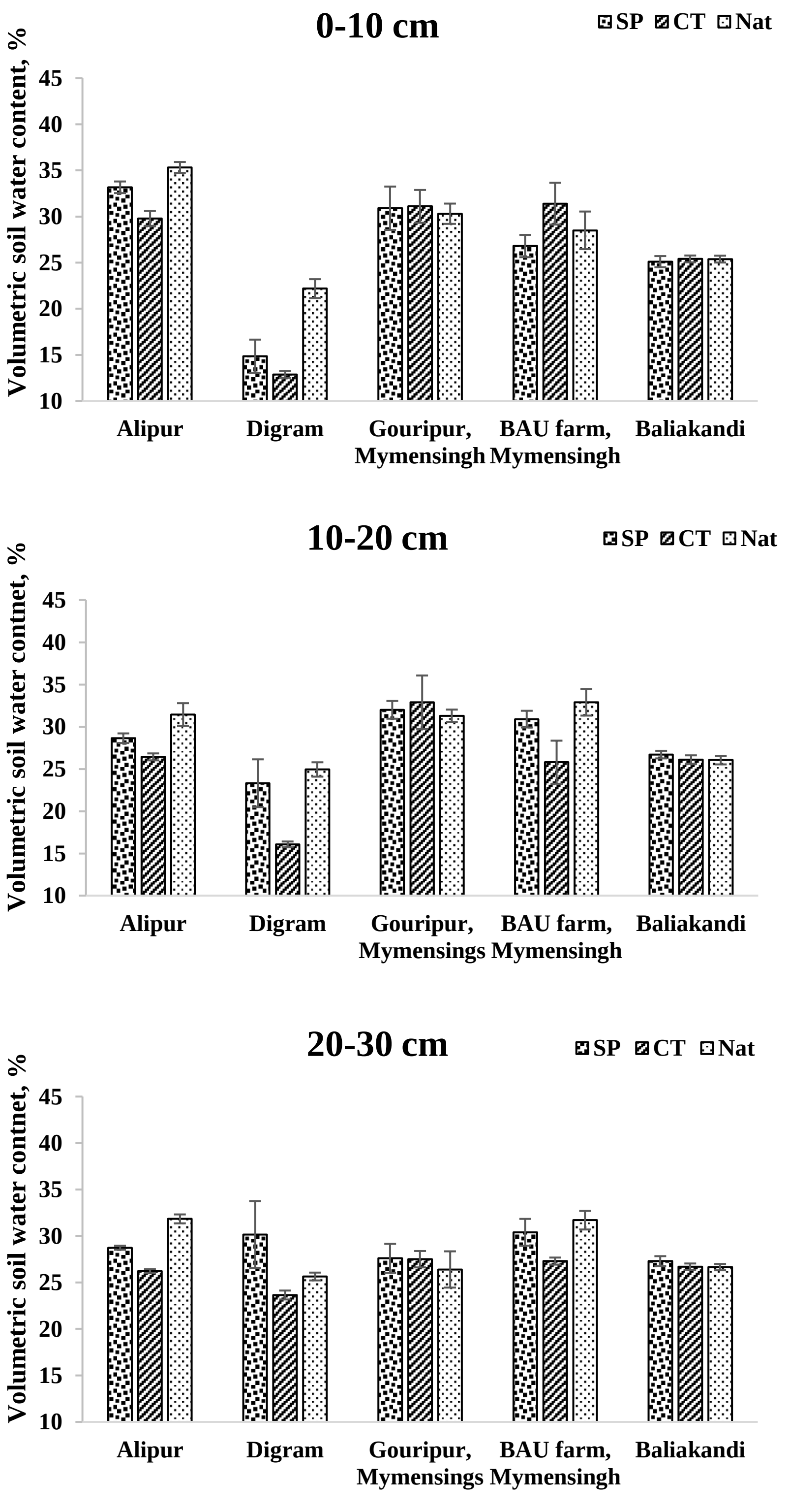


Figure 3.23 Soil water content during penetration Resistance measurements of natural soil of five locations as compared to SP and CT tillage treatments.

3.4 Discussion

In general, BD and PR in the natural soil were less than the BD and PR of SP and CT at all locations. The differences in BD and PR values between SP and the natural soil in the 10-20 cm depth were much lower than the differences in those values between CT and the natural soil. These results suggest that compaction in the plough pan under CT has been started to be restored under seven years of practice of CA. However, it is not clear whether it is potential for further restoration of the soil physical properties under CA towards values close to the natural soil and how many years it might take to reach a new equilibrium under CA practices. The beneficial changes in soil physical properties under CA may be due to the effect of increased residue retention or to minimum soil disturbance or both. The discussion below examines the effects of residue first, and then the effects of minimum soil disturbance for the CA practice and then examines the differential effects of bed formation on soil physical properties.

3.4.1 Effects of residue retention on soil physical properties

Effects on 0-10 cm depth

The remarkable decrease in BD and the increase of TP in the upper 10 cm in the HR plots corroborates earlier findings for the same tillage and residue treatments in the same experimental field (Islam, 2016; Alam *et al.*, 2018b). The reduction in BD is the reflection of an increase in soil organic carbon (SOC) content caused by the decomposition of retained crop residues over the years and less oxidation of in situ organic matter (root biomass) (Chan *et al.*, 2002). Under the same tillage and residue treatment in the same field, Alam *et al.* (2018b) reported that HR increased SOC over LR by 24 % in Alipur and 18 % in Digram irrespective of tillage treatment. Soil organic carbon has a direct impact on the BD or inversely on the porosity, as the particle density of organic matter is lower than that of mineral soil (Logsdon and Karlen, 2004). Furthermore, soil organic matter is associated with increased aggregation and permanent pore development as a result of soil biological activity (Franzluebbers *et al.*, 2000). The practice of crop residue retention has also been shown to reduce BD within the near soil surface under subhumid and humid climate (Ghuman and Sur, 2001; Bai *et al.*, 2008; Chen *et al.*, 2009) and tropical climate (Govaerts *et al.*, 2009). Under a sub-tropical and semi-arid climate in New Delhi, India, Bhattacharyya *et al.* (2015) found significantly lower topsoil BD under direct-seeded rice followed by ZT wheat with rice residue compared to puddled transplanted rice without residue followed by conventional tillage wheat without residue. In the IGP of India, Singh *et al.* (2016) found significantly lower BD under ZT direct-seeded rice followed by ZT maize, both with residue compared to conventional puddled transplanted rice followed by CT maize both without residue. Comparing Alipur and Digram soil, the result of BD values of the current study suggests that HR was more effective in the Alipur soil (BD reduced by 0.04 g cm^{-3}) than Digram soil (BD reduced by 0.03 g cm^{-3}). The result of Alam *et al.* (2018b) that SOC increased more in Alipur than in Digram also support the current result of BD reduction.

Irrespective of tillage treatments, HR retention treatment reduced PR in the 0-10 cm soil depths. Consistent with our results, Singh *et al.* (2016) reported residue retention caused a significant reduction in PR compared to without residue retention, irrespective of the crop establishment method. Crop residue retention improved SOC concentration, biological activity, and thereby improved soil structure and reduced PR in the 0-10 soil depth (Kahlon *et al.*, 2013). High residue retention treatment over LR reduced PR by 0.10 and 0.08 MPa at Alipur and Digram soil, respectively, in the 0-10 cm soil depths irrespective of tillage treatments.

For the 0-10 cm soil depth at Alipur, soil wetness measured with the undisturbed core samples at any pressure head between 0 to 30 kPa was higher under HR than LR treatment. The higher storage capacity in HR treatment than LR treatment was also reflected in the SWC at the time of PR measurement in the 0-10 cm soil depth. There are three main mechanisms by which HR could result in greater water retention capacity. Firstly, it can be attributed to the higher water absorption capacity of organic matter, which increased with HR (Blanco-Canqui and Lal, 2007a). The presence of the higher amount of organic material in HR treatment in the present study adsorbed more water and substantially increased water content at the 0-10 cm soil depth of Alipur soil. Secondly, anchored residues left on the soil surface may reduce evaporation losses, which could increase SWC at the 0-10 cm soil during PR measurements. However, at Digram soil, there was no significant differences in SWC during PR measurements under LR and HR treatment at 0-10 cm soil. The effect of increased residue retention in improving soil water retention capacity will be re-examined later while considering irrigation water savings (see Chapter 5).

Effects at 10-20 cm and 20-30 cm depths

Residue retention had no effect on BD and TP at 10-20 cm depth. In contrast to this result, He *et al.* (2011) reported 11 years of NT with all residue retained significantly reduced BD by 0.08 g cm^{-3} and increased the TP of the 10-20 cm depth by 9.0 % compared to CT without residue retained. He *et al.* (2009b) also found that 16 years of practicing NT with residue retention reduced BD by 0.11 g cm^{-3} and increased TP by 15 % in the subsurface layer (20-30 cm), despite no initial differences in values under two treatments. Soil water content measured during the measurement of PR increased in HR treatment at 10-20 cm soil depth. The higher SWC in HR treatment at 10-20 cm depth could be due to the increasing infiltration rate and decreasing runoff losses (Shipitalo *et al.*, 2000). The water that infiltrated into the 10-20 cm soil depth is less likely to evaporate quickly, and that might explain the increased soil water storage capacity at 10-20 cm soil depth for both Alipur and Digram soil. Jemai *et al.* (2013) reported after 7 years NT with residue increased SWC of 10-20 cm depth compared to CT without residue. In two different soils of Ludhiana, India, Kahlon (2014) found maximum soil water storage in the 0-30 cm soil depth under NT with residue compared to NT without residue. The HR treatment showed a reduction in PR values in the 10-20 cm depth at both Alipur and Digram, which could be attributed to the higher SWC in the 10-20 cm depth in the HR treatment compared to LR. There was no significant effect of residue retention on either BD or PR at 20-30 cm depth which might be attributed to the limited carbon input at this depth.

3.4.2 Effects of Strip Planting on soil physical properties

Effects on 0-10 cm depth

Irrespective of residue retention treatment, SP reduced BD by 0.05 g cm^{-3} at Alipur compared to the CT plot at 0-10 cm soil depth. The reduced BD under SP could be attributed to the accumulation of SOC due to minimum soil disturbance that preserved aggregate-protected carbon (Alam *et al.*, 2018b). By contrast, intensive soil disturbance under CT is known to increase the exposure of organic matter to microbial decomposition and increase the loss of labile C (SOC), and thus accelerating the break down of aggregates (Álvaro-Fuentes *et al.*, 2008; Abdollahi *et al.*, 2014; Wang *et al.*, 2015). Consistent with the present study, Choudhary *et al.* (2018b) reported 9 % lower BD under ZT compared to CT. Elsewhere, lower BD under ZT was also reported by Govaerts *et al.* (2009), Gathala *et al.* (2011b) and Parihar *et al.* (2016). In the current study, the SP vs CT comparison was made with the soil samples collected from the inter-row space in the SP treatment. Comparison between soil samples collected from inter-row space and in the strip in the SP plot reveals that BD of strips were reduced by 0.03 g cm^{-3} relative to that of inter-row space. This means that BD of strips was 0.08 g cm^{-3} lower than that of CT plot. Low BD in strips could be due to the pulverization of 0-10 cm soil depth during the SP operation. However, the mean BD value of strip and inter-row space (1.32 g cm^{-3}) can be taken to compare with the BD of CT (1.38 g cm^{-3}) since there was no fixed line for strip and inter-row and the position of the strip changed during each SP operation. At Digram, SP reduced BD by 0.07 g cm^{-3} over CT in the 0-10 cm soil depth, which suggests silty clay loam soil at Digram is more responsive to the SP treatment than the silty loam soil at Alipur.

At Alipur, PR in the inter-row space of the SP plot was higher compared to the CT plot. The lack of tillage in the inter-row space under the SP plot could result in higher PR compared to the intensively tilled soil under the CT plot. The soil sample was collected after the monsoon rice harvest at Alipur and wheat harvest at Digram. The long lag time (more than 150 days) between the most recent tillage event and the soil sampling might have also contributed to the higher PR in the inter-row space of the SP plot. Settling and reconsolidation of the untilled soil by standing water following several rainfall events (Phillips and Young, 1973) during monsoon rice could lead to compaction of the inter-row space. Nevertheless, the higher PR in the near-surface soil in the inter-row space might be seasonal. The SP operation does not essentially follow the same track every season. Thus, the high soil PR in the inter-row that was untilled in one season is likely to be minimised by making strips during the SP operation in the next season since the PR measured in the strips was lower than the PR measured in the inter-row space as found in the current study.

At Digram, there was no significant difference in PR between the inter-row space and CT plot in 0-10 cm soil depth. However, PR in the strip was lower than that in the CT plot. This result suggests that, like Alipur soil, Digram soil was also more responsive to SP in the strip than the inter-row space in 0-10 cm soil in reducing PR.

As hypothesized, reduced BD and hence increased TP under SP improved K_{sat} values by twofold relative CT plots. Better aggregate stability in the 0-10 cm depth caused by higher SOC will generally improve pore geometry and increase the connectedness of pores (Acharya and Sood, 1992; Azooz *et al.*, 1996; Bhattacharyya *et al.*, 2006a). The activity of soil organisms may have also played an important role in increasing pore continuity (Bhattacharyya *et al.*, 2008). Collectively these can lead to greater water movement within the topsoil depth in the SP plots. By contrast, loss of SOC in CT plot through repeated tillage facilitates aggregate breakdown processes; as a result slaking and disintegration of aggregates could have taken place when they were wetted under intermittent ponding (Blevins *et al.*, 1998). Since the K_{sat} measurements were taken after rice harvest at Alipur and after the wheat harvest at Digram, settling and consolidation of the dispersed aggregates over the growing season could have created a relatively impermeable topsoil depth and reduced K_{sat} in the CT plot. The higher K_{sat} in SP in the current study is in accordance with those of other researchers (Bhattacharyya *et al.*, 2006a; Rasool *et al.*, 2007; LI *et al.*, 2011), who found significantly greater K_{sat} under ZT than that under CT.

Strip planting significantly increased infiltration capacity compared to CT. This means that the increased PR in the 0-10 cm soil under the SP had no restricting effects on downward water movement. These results concur with those of Thierfelder *et al.* (2005), who indicated that minimum soil disturbance treatments tend to increase the physical stability of the topsoil while maintaining their soil hydraulic functions. Thus, it can be concluded that the higher infiltration capacity in the SP treatments could only be attributed to lower BD, and therefore to higher TP independent of PR, since SP treatments in the present study showed lower BD values compared to the CT treatment despite having higher PR values in the 0-10 cm depth.

Infiltration characteristics of the soil depend on the size distribution, geometry, continuity, and stability of the pores (Bhattacharyya *et al.*, 2008). Water transmission through the soil profile also depends on the antecedent water content, aggregation and the presence of macropore channels (Shaver *et al.*, 2002). The favourable soil structural parameter such as BD that led to increased TP under the SP in the current study might have influenced the infiltration characteristics of the soil where initial water intake and final infiltration rate (steady-state) both were improved. The higher steady-state infiltration rate observed in the plots under SP was probably due to minimum soil disturbance that maintained the continuity of water-conducting pores (Acharya and Sood, 1992) and bio channels (Azooz *et al.*, 1996). The steady-state infiltration rate is mostly governed by the soil profile and not by the soil surface (Saha *et al.*, 2010). The higher steady-state infiltration rate may also be attributed to the higher K_{sat} of the plough pan in SP. Higher steady-state infiltration rate in ZT with residue retention compared to CT without residue was also reported elsewhere (Singh *et al.*, 1996; Bhattacharyya *et al.*, 2008; Saha *et al.*, 2010).

The infiltration rate started to decline within the first 10 min after the initiation of the measurements, but the decline was steeper in the CT treatment than in the SP treatment. The infiltration rate in the CT started approaching a steady-state sooner (approximately 40 mins after the start of the run) than the SP treatment (about 80 mins). The cumulative infiltration after 240 minutes was about 60 % higher in SP compared to the values in CT treatments. Results in the present study are in close conformity with those of Shaver *et al.* (2002), Jat *et al.* (2009), Saha *et al.* (2010), who reported higher cumulative infiltration in NT than CT plots. In conclusion, the SP plot showed higher total infiltration than the CT plot at both locations, inferring that SP positively improved aggregation, and geometry, continuity and stability of the pores in the soil profile.

Minimum soil disturbance under SP improved soil water storage by the same mechanisms discussed for the residue retention, increasing soil organic material and reducing evaporation, but in addition, it can be attributed to increasing infiltration rate and decreasing runoff losses. Higher SWC at the 0-10 cm soil depth was recorded under SP compared to CT plot in both sites at the time of PR measurements, i.e. both after monsoon rice and wheat harvest. Greater water retention in the surface layer under NT than under CT was also reported (Bhattacharyya *et al.*, 2006a).

The water retention curve for Alipur showed significant differences in volumetric SWC at matric potential from 0 (saturation) to -50 kPa. At matric potential -10 kPa (field capacity), SP increased soil water storage by 2 % in the upper most 10 cm soil depth. This depth of water is small in amount but may be beneficial for post-monsoon rice dry land crop (such as mustard) during seed germination in particular. During PR measurements in the field, SP had 33 % volumetric SWC while CT had only 30 %. These values represent SWC for a matric potential of -50 kPa, i.e. below field capacity. As a result, during the drying part of the mustard season, SP can potentially supply 0.3 cm more water than CT in 0-10 cm depth where most roots are distributed. For rice, SP is also able to supply more water than CT during AWD application since the AWD irrigation method allows water to disappear above the soil surface, and volumetric SWC remains between the saturation and field capacity (-10 kPa). At Alipur, soil water retention in 0-10 cm depth was higher under SP compared to CT at 0 to -50 kPa. While at higher matric potential up to -1500 kPa, there was no difference in SWC, mostly due to the considerable variation among replicate samples under CT, indicating a relatively more effective homogenization in the topsoil under SP.

At Digram, soil water storage capacity was higher in SP than CT by about 1-3 % at -5 kPa to -1500 kPa matric potential at 0-10 cm soil depth. This means that SP can supply 0.1 to 0.3 cm more water in the 10 cm soil depth at SWC near saturation to permanent wilting point (PWP), which can beneficially reduce irrigation requirement for the wheat crop from germination to any later part of the growing season (see Chapter 5). These results are in agreement with those of Bescansa *et al.* (2006), who noticed an increase in SWC under conservation tillage compared with CT. Soil wetness at any pressure head being higher under NT was also found elsewhere (Hill *et al.*, 1985; Rasmussen, 1999; Díaz-Zorita *et al.*, 2004; Daraghmeh *et al.*, 2008). Penetration resistance at Digram was measured just after wheat harvest when SWC for SP and CT was 15 % and 13 %, respectively. According to the water retention curve for Digram, these SWC were for matric potential just above the permanent wilting point (between -392 to -1500 kPa). The difference is very small, but the evidence suggests similar SWC results from core samples in the laboratory and direct measurements in the field.

Effects on 10-20 cm depth

In the current study, soil BD increased with depth with the maximum values at the 10-20 cm soil depth and then decreased at 20-30 cm soil depth. The BD in the 10-20 cm depth were significantly higher in the CT plot compared to SP plots in both Alipur and Digram soil. These results are in conformity with those reported earlier by Jat *et al.* (2009), He *et al.* (2011), Jat *et al.* (2013), Kahlon *et al.* (2013) and Singh *et al.* (2016). The most likely reason for higher values of BD in the CT plot compared to the SP plots is the repeated wheel traffic in direct contact with the upper plough pan in the CT plot, either during tillage for dryland crops in wet soil or during puddling for rice in saturated soil, causing direct physical compaction in the plough layer. A 2-WT, even though it has a low axle load, can cause significant compaction from repeated wheel trafficking as discussed in the Chapter-4. However, a single pass wheel traffic under SP does not extend to 10-20 cm depth as the axle load of the 2-WT is low and the compaction is confined to the topsoil only (Chapter-4). Published studies revealed puddling induced high BD in the subsurface layer in rice-based system due to destruction of soil aggregates, reduction in porosity by filling of macropores with finer soil particles, and the direct physical compaction caused by the tillage implements (Sharma *et al.*, 2003; Gathala *et al.*, 2011b). The lower BD and PR in the 10-20 cm depth under SP compared to CT demonstrated that minimum soil disturbance system helped reverse sub-soil compaction in the present long-term field trials.

Published studies corroborate the present results that PR in the subsoil remains higher under CT than under ZT (Jat *et al.*, 2009; Gathala *et al.*, 2011b; Kahlon *et al.*, 2013). Nevertheless, in the current study soil, water content at the time of PR measurement was slightly but significantly higher in the SP plot than the CT plot. Thus, at least a part of the PR difference in the 10-20 cm soil depth might have been due to soil water difference.

There was a sharp decline in the K_{sat} values at the 10-20 cm depth for all tillage treatments. At this depth, there appeared a plough pan, even though the depths of the plough pan from the surface elevation of different tillage plots were different (Figure-3.3). Nevertheless, as K_{sat} measurements at the plough pan were taken at the same depth (10 cm) according to a fixed datum for all tillage treatments, K_{sat} values for the plough pan under three tillage treatments are comparable. Random tillage under CT causes compaction at 10-20 cm depth, decreasing the total porosity and microporosity, increasing BD, and thus directly decreases K_{sat}. Indirectly, puddling under CT disperses clay in floodwater, which settles over time, partially or completely clogging water transporting macropores (Sharma and De Datta, 1986; Gathala *et al.*, 2011b). Higher K_{sat} values in the 10-20 cm depth under SP plot might be attributed to the macro channels due to the decay of roots that are likely to have extended to the subsoil and preserved under minimum soil disturbance, and thereby greater producing continuity in pores and water movement. The second explanation is that shrinkage and swelling of subsoil over wetting and drying under the minimum soil disturbance plot could have created water-conducting macropores. Thus, it can be concluded that the better-connected macropores created by the minimum soil disturbance under SP have resulted in higher K_{sat} values in the 10-20 cm soil depth.

Despite having lower BD at Alipur, K_{sat} values for SP and CT in the plough pan were not different. It is worth noting that even in SP, there is a trampling effect during human involvement for different management operations in the rice field, and the number of operations was double at Alipur as at Digram since rice was grown twice in a year in Alipur and once in Digram. Nevertheless, the steady-state infiltration rate in SP was higher than that in CT. The explanation could be that during the measurement of K_{sat} with the digital infiltrometer at the plough pan, any possible crack was avoided on purpose. But random measurement of K_{sat} in the cracks showed a mean value of 5.3 cm h^{-1}.

The higher K_{sat} values in the plough pan of the SP is significant because it may facilitate faster water infiltration deep into the soil from where wheat roots can absorb water at the dry end of the season and reduce their irrigation water requirement. However, the same characteristic of a plough pan under SP can allow water to escape quickly and hinder the retention of ponded water in the rice field. These effects of SP are discussed in Chapter 4 and Chapter 5.

The water retention curve for Alipur at 10-20 cm depth showed significant differences in SWC at saturation and at matric potential from -100 kPa to -1500 kPa. At Digram, SP showed higher SWC than CT at even lower matric potential, from -10 kPa to -1500 kPa. These results suggest that SP can potentially supply significantly more water than CT in 10-20 cm depth from where at the later season, roots of wheat can absorb water (See Chapter 5).

In the plough pan, greater soil water retention under SP compared to CT can be attributed to the lower bulk density and higher mesoporosity under SP treatment (He *et al.*, 2009b). Better infiltration capacity under the SP plots was also influential in increasing water content in the deeper soil layers. Vertical and anchored residue act as barriers to water loss by evaporation and by reducing the runoff allowing the water more time to infiltrate deeply into the soil (Govaerts *et al.*, 2009). This could also contribute to the increased water content in the 10-20 cm depth under SP treatment. Higher soil water content in the deeper soil layer (30 cm) under NT compared to CT has also been reported previously (Bhattacharyya *et al.*, 2008; He *et al.*, 2009b; Thierfelder and Wall, 2009; Jemai *et al.*, 2013). These results suggest that improved infiltration capacity under minimum soil disturbance with residue retention is effective in improving available soil water at the surface soil and as well as deep in the soil profile.

3.4.3 Effects of Bed Planting on soil physical properties

Effects on 0-10 cm depth

Bed planting significantly reduced BD compared to the CT plot in the 0-10 cm depth. From the previous study, it was observed that active loosening of topsoil following the reshaping of the permanent bed caused lower BD in the 0-5 cm soil depth (Gathala *et al.*, 2011b; Islam, 2016). In the present study, for making a robust comparison between the undisturbed soil in the bed and the tilled soil in the CT plot, soil samples from the 1st soil layer of the bed was collected from +2.5 to -2.5 cm depth according to the datum (Figure 3.3). In this method, the loose soil from the top of the bed was excluded, even though the soil sampling was done after rice harvest when the loose soil was likely to be settled. Furthermore, soil samples collected from the 1st soil layer in the bed was within the depth of maximum root density, as Islam (2016) reported more than 80 % of the roots were limited to 0-10 cm in the bed. The lower BD in the bed could be attributed to the least disturbance of the SOC and plant root residues during the establishment of nonrice crops and transplanting of rice (Alam *et al.*, 2018b). Consistent with our result, Gathala *et al.* (2011b) and Parihar *et al.* (2016) reported lower BD at 0-10 cm soil in the permanent bed compared to the CT plot.

Soil BD in the 1st soil layer varied largely, with bed/furrow positions being higher in furrows and lower in beds. Higher values of BD in furrows than the bed in the upper layer have also been reported by Boulal *et al.* (2012). Under BP treatment, wheel traffic was confined to the furrows, and a 2-WT formed/reshaped one bed during each pass. Thus, each furrow has experienced direct wheel compaction twice each season since the first formation of the permanent raised bed in the year 2010. The cumulative effect of wheel trafficking could have increased the BD of the furrow bottom.

Since soil water content during PR resistance measurement in the corresponding depths of BP and CT was statistically similar (Figure 3.7), the PR values of beds and CT are comparable. Penetration resistance of beds at Alipur in the +2.5 to -2.5 cm depth was significantly higher than that in 0-10 cm depth of the CT plot. Higher PR values at depth just below the loose soil (+2.5 to -2.5 cm depth according to the datum, see Figure 3.3) of the bed could be attributed to the compaction by the roller of the bed former that took place during each reshaping operation. Furthermore, the width of the furrow bottom is 15 cm, while the maximum width of the wheel of the 2-WT is 20 cm. It is likely that the tyres used on the 2-WT caused compaction with adverse impacts on the soil properties on the side of the bed. However, as discussed above, BD values in the topsoil of the Bed was significantly lower than the corresponding BD values in the CT plot. This might be due to the fact that soil samples for the measurement of BD were collected from the centre of the bed cross-section, while the PR measurements were made along the cross-section of the bed. Five measurements, one at the centre and four at both sides of the centre with an 8 cm horizontal distance to each other, were taken and the mean was calculated and analysed. Thus, the higher PR values close to the side of the bed could have influenced the mean values compared to the mean of the CT plot at the corresponding depths. This issue has also been addressed in the research done by Kukal et al. (2006), who also suggested considering all aspects of compaction of beds using tractors with standard and narrow tyres.

Penetration resistance of the furrow followed the same trend as BD of the furrow. Penetration resistance of the furrow bottom was more than twice the PR on the beds. However, the compacted furrow bottom is beneficial in terms of water harvesting by slowing down the infiltration rates in furrows in order to let the water slowly infiltrate to the plant root zone, rather than let it escape to deeper soil layers through the cracks in the soil (Govaerts *et al.*, 2007b).

Saturated hydraulic conductivity in the 0-10 cm of bed was more than twice the values in the CT plot. In an earlier study, Choudhury and Singh (2013) reported higher K_{sat} in dry-seeded rice on raised beds compared to CT. Higher K_{sat} in the bed than CT might be due to soil aggregation that has developed more in bed than in CT. However, soil aggregation under this study was not determined. Nevertheless, there are possibilities of increasing soil aggregation in the beds since SOC have remarkably increased in BP treatment as a result of minimum soil disturbance (Alam *et al.*, 2018b). As with BD, BP performed better in increasing K_{sat} in Digram soil than Alipur soil. Saturated hydraulic conductivity increased in the bed by 250 % over CT at Digram, while the increment was 150 % at Alipur. The higher increment of K_{sat} in Digram soil could be due to more change in the pore structure of the profile, perhaps due to greater shrinkage caused by drying of the clay soil (Kirchhof and So, 1996b).

However, K_{sat} in the furrow bottom was significantly lower than that in the bed top. Lower K_{sat} in the furrow than the bed in the PRB was also reported by (Govaerts *et al.*, 2007b). Lower K_{sat} values in the furrow bottom are of importance in holding the irrigation water longer to wet the root zone rather than escaping through deep drainage. Another benefit of the compacted furrow bottom is the faster movement of irrigation water during application that decreases irrigation requirement.

Generally, cumulative infiltration for 240 minutes was about twice as high on the bed as the values in CT. Likewise, the steady-state infiltration rate was 3-times higher in the bed than in CT. More infiltration in the bed than in CT might be due to the minimum disturbance of pore continuity. Higher infiltration in the bed than in CT have also been reported elsewhere (Jat *et al.*, 2009; Gathala *et al.*, 2011b; Jat *et al.*, 2013). Soil BD was reduced, and TP was increased significantly in beds. Bed planting could have also created better-connected macropores. As a result, infiltration capacity in beds was improved.

Soil water content in BP was not significantly different from CT in the 0-10 cm depth for both Alipur and Digram during the measurement of PR. Lower SWC in bed than SP could be attributed to the rapid drying of the surface soil following the reshaping of the bed. Licht and Al-Kaisi (2005b) observed that intensive tillage pulverised soil and increased air pockets which tended to enhance evaporation and accelerated soil drying and heating.

However, the soil water retention curve for Alipur showed significantly higher SWC than CT at matric potential 0 to -50 kPa, while Digram showed higher SWC at -5 to -1500 kPa. Similar to these results, Govaerts *et al.* (2007b) also reported significantly higher water storage capacity of beds compared to CT at the permanent wilting point. The results suggest that, in the field, the topsoil of the bed could have dried quickly due to loosening, but still the soil has a potential to store more water compared to CT at the dry end of the season.

Effects on 10-20 cm depth

In the 10-20 cm (plough pan) depth, the BD of the bed was significantly lower than that in the CT plot. In the BP treatments, wheel traffic is confined to the furrows only. Thus permanent beds were uncompacted by traffic which helped to reduce BD and PR in the plough pan beneath the bed (Govaerts *et al.*, 2006). Consistent with our results, lower BD in the subsoil of the permanent bed treatment is also reported elsewhere (Jat *et al.*, 2013; Islam, 2016; Parihar *et al.*, 2016). Published studies corroborate these results that PR in the subsoil remains higher under CT than under permanent beds (Jat *et al.*, 2013; Parihar *et al.*, 2016).

Bulk density in the plough pan was significantly higher in the furrow than in the bed, which could be attributed to the undisturbed permanent bed. However, there was no significant difference between the BD or PR of the plough pan under the furrow and the respective values in the plough pan in the CT (Table 3.11), suggesting that furrow wheel passes had no additional effect on the BD of the plough pan in the furrows compared to the plough pan in the CT, despite the wheel trafficking in the furrow bottom very close to the plough pan (only 5 cm depth difference, see Figure 3.3). The most likely reason for higher values of PR in CT at the 10-20 cm is the excessive traffic during intensive tillage with an increased number of wheel passes causing compaction in the plough pan, as also evidenced in the current study (see Chapter 4).

Field saturated hydraulic conductivity decreased sharply with the increase in depth up to 10-20 cm under the bed, which corresponded with the plough pan. Field saturated hydraulic conductivity values at the plough pan underneath the bed were significantly higher compared to that under the CT plot. That puddling under CT destroys soil aggregation and drastically decreases K_{sat} is a well-known process (Sharma and De Datta, 1986). In fact, one of the objectives of puddling in rice is to slow down the infiltration rate to create standing water in rice fields (Sharma and De Datta, 1986; Sharma *et al.*, 2003). Puddling decreases infiltration directly by destroying soil aggregates, decreasing total porosity and macroporosity, increasing BD, and causing subsoil compaction. Indirectly, puddling disperses clay in floodwater, which settles over time, partially or completely blocking the macropores responsible for a majority of infiltration (Sharma and De Datta, 1986; Gathala *et al.*, 2011b). In contrast, macro channels produced from the decay of roots that have extended to the plough pan were unbroken in the bed and thereby enhanced the water movement.

However, K_{sat} values in the furrow at the plough pan were significantly lower but similar to the K_{sat} value of the plough pan in the bed and in the CT, respectively. Thus, furrow/bed position had an effect on the K_{sat} values, but wheel pass treatment in the furrows did not further reduce the K_{sat} value. The lightweight of the 2-WT and limited trafficking might have limited compaction or restored the plough pan in the furrows compared to the intensive traffic and tillage in the CT.

These results suggest that higher K_{sat} values in the bed will allow the water to infiltrate faster. In contrast, lower K_{sat} in the furrows will allow water to infiltrate slower. The outcome of these two processes on the water balance in the rice field, which influences the irrigation requirement in rice fields, will be examined in Chapter 5.

There were significant differences in soil water storage capacity in bed compared to CT at the 10-20 cm depth of Alipur soil at matric potential from -100 kPa to -1500 kPa as shown in the soil water retention curve. Digram soil performed even better than Alipur soil, where the retention curve showed significant differences in SWC at matric potential from -10 kPa to -1500 kPa. Thus, the results revealed that before an irrigation event, beds had the ability to store more water than CT at the 10-20 cm, which also would reduce the irrigation requirement in the beds.

Increased SWC in the deeper soil layer were also a reflection of the improved infiltration capacity of the bed. The standing stubble of the previous crop remaining on the top of the PRB could have induced a vertical mulching effect that resulted in higher water infiltration (Govaerts *et al.*, 2007b; Govaerts *et al.*, 2009). The water that infiltrated deep into the soil is less likely to evaporate quickly. As a result, SWC in the 10-20 cm soil depth was higher in the bed than the CT. Govaerts *et al.* (2007b) also reported that standing wheat stubble remaining on top of the permanent bed resulted in higher infiltration than in a field without residue.

3.5 Conclusions

Seven years (three crops per year since 2010) of continuous SP, BP, and CT treatments on two soils of Northwest Bangladesh have provided evidence that minimum soil disturbance and increased residue retention improved soil physical structure, structural stability, and water infiltration. The application of SP and BP with high residue retention resulted in a significant decrease in BD, increase in TP and a decrease in PR in the surface soil relative to CT. However, SP-HR outperformed BP-HR in terms of improving soil physical properties. This could be attributed to the physical compaction from additional mechanical operations required in pulverising and loosening of the topsoil of the permanent bed each time it was reshaped. High residue retention reduced BD of the topsoil in the order: CT>BP>SP.

These improvements were also found deeper in the profile, where the dense plough pan that had developed in CT was weakened under minimum soil disturbance by SP treatment. The improvements in the soil physical properties can be attributed to the absence of puddling and natural amelioration through shrinkage and swelling of subsurface during drying and wetting and by penetration of plant roots. The results also suggest that SP was more effective in the silty clay loam soil at Digram than the silty loam soil at Alipur. Strip planting reduced PR in the 10-20 cm soil depth by 10 % at Alipur but by 21 % at Digram compared to CT.

The results suggest that changes in soil physical properties by minimum soil disturbance also played an important role in changing soil hydraulic properties, namely- soil water retention, storage and transmission. The minimum level of tillage disruption in SP treatment allowed the stabilisation of pore continuity that significantly contributed toward greater water infiltration and enhanced water storage in the profile. Saturated hydraulic conductivity of the plough pan under SP was twice as high as under CT, while cumulative infiltration under SP was 60 % greater than that under CT. Therefore, the first hypothesis of the current study, which stated that "Continuous use of long-term (7 years) minimum soil disturbance with residue retention can change the soil physical properties such that they can also alter the soil hydrologic properties in the plant root zone depths”, is supported. Furthermore, the changes in soil physical properties and water infiltration under minimum soil disturbance have profound implications for crop production in the rice-based rotations. The higher value of infiltration observed in the minimum soil disturbance plot may alter the water balance, which is of particular importance for both rice and dry season crops such as wheat (see Chapter 5 for rice and Chapter 6 for wheat).

4 Compaction by 2-wheel tractor wheeling under controlled-traffic strip planting: characterisation of changes in soil physical properties by least limiting water range, and chickpea emergence

4.1 Introduction

Soil compaction by machinery traffic has become a major problem worldwide in agriculture (Håkansson *et al.*, 1988; Håkansson, 1990; Raghavan *et al.*, 1990; Servadio *et al.*, 2001; Horn and Fleige, 2003; Hamza and Anderson, 2005; Servadio *et al.*, 2005; Chan *et al.*, 2006; Soane and van Ouwerkerk, 2013). It is defined as "the process by which soil grains are rearranged to decrease void space and bring them into closer contact with one another, thereby increasing the bulk density" (SSSA, 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 (Ball and Ritchie, 1999; Chamen *et al.*, 2003; Chan *et al.*, 2006; Radford *et al.*, 2007). Soil compaction induced by vehicle traffic has a hostile effect on a number of soil physical properties such as BD, PR, porosity, and hydraulic conductivity (Radford *et al.*, 2000; Hamza and Anderson, 2005). From a soil management perspective, compaction problems can be divided into topsoil and subsoil. Compacted topsoil is the formation of densified layers with high PR within the depth of the cultivated zone caused during the soil preparation cycle (Jorajuria *et al.*, 1997). Annual tillage can return the compacted topsoil to its low resistance. By contrast, subsoil compaction is the result of annual cumulative densification effects appearing at depths below the cultivated horizon. Amelioration of compacted subsoil needs the application of special tillage techniques such as subsoiling or deep tillage that are very expensive

The number of passes by the agricultural vehicle wheels plays an important role in soil compaction. The number of passes affects the number of loading events and the coverage, intensity and distribution of wheel traffic. Although soil compaction was reported following the use of heavy vehicles (> 100 kiloNewtons (kN)), high frequency and random trafficking by a light tractor can cause just as much damage (Chamen, 2011) or even greater damage than a heavier tractor with fewer passes (Chygarev and Lodyata, 2000). Etana and Håkansson (1996) reported that one pass by a 990 kN wheel loader increased the degree of compactness by almost as much as three passes by a 540 kN tractor.

There is evidence that topsoil compaction is related to ground pressure, while subsoil compaction is related to total axle load independently of ground pressure (Becerra *et al.*, 2010). A wide range of four-wheel tractors (4-WT) is used around the world with different axle load ranging from 5.4 kN to over 100 kN with a wide range of ground pressure. For example, a commonly used 4-WT with an axle load of 18.5 kN has a ground pressure of 135 kPa (Zhang *et al.*, 2006). In comparison to 4-WT, a two-wheel tractor (2-WT) has an axle load of 3 kN and exerts a ground pressure of 85 kPa. Although the 2-WT axle load is low and the ground pressure is lower than that for a 4-WT, the repeated traffic by a 2-WT, as discussed previously, may lead to soil compaction. Traffic frequency impacts by a 2-WT on soil compaction has not been addressed in the literature.

Two-wheel tractors are used in smallholders in South Asia and other parts of the world as the main means of land preparation and other farm operations due to small farm and field size combined with an affordable price. Two-wheel tractors have become very popular in Bangladesh: in 1996, there were only 100,000 units of 2-WT; in 2010, the figure increased to 550,000 units (Ahmmed, 2014; Ziauddin and Zia, 2014), and by 2013 over 700,000 units were operating (Mandal, 2014). The most serious source of subsoil compaction in Bangladesh is attributed to conventional tillage (CT) by a 2-WT that repeatedly cultivates the soil under unfavourable, high soil water conditions. The commencement of field operation is suitable when SWC is 70-90 % of field capacity depending on the soil texture (Nugis *et al.*, 2004). Above this water content, the load support capacity of the soil is reduced (Kondo and Junior, 1999) even when a 2-WT with a low ground pressure is used. During CT operation for a non-rice dryland crop, tractor wheels are repeatedly run on the intensively pulverised loose soil or the open-wheel ways in the same wheel tracks. During CT for rice, puddling is done with random wheel trafficking across the field with SWC between field capacity and saturation to create a plastic condition (Sharma and De Datta, 1985). During both tillage operations, tractor tines do not reach the upper part of the subsoil; rather the wheels of the tractor directly run on the upper part of the subsoil and likely cause the compaction of the subsoil.

The major management tools for the prevention or alleviation of soil compaction is the selection of tractor and their operations. The ground contact pressure can be reduced by increasing the number, kind, size and inflation pressure of tractor tires (Chamen *et al.*, 2003). Speed of tractor operation, number of wheel passes and soil water content at the time of operations are important in minimizing soil compaction. Agronomic practices for alleviation of compaction include crop rotations, cultivating crops that produce abundant organic materials (Larson *et al.*, 1994). Deep loosening is another option, but it is expensive, rarely fully ameliorates the compacted soil, and loosened soil is often recompacted within a few years (Kooistra and Boersma, 1994). The controlled traffic farming system may be a desirable option for the amelioration of degraded soil, where vehicle wheels are confined to a single line and traffic follow the same track (Tullberg, 2001). However, these techniques are not being used in the smallholder farms in SE and S Asia.

In this study, it was hypothesised that a light tractor could cause much damage to soil physical properties when used with an increased number of passes. Therefore, while active tilling alone may contribute to the formation of a plough pan, frequent loading events, even with a low ground pressure, transmitted into the soil during repeated wheel trafficking has a major influence on the plough pan. The objectives of the study were:

i) to evaluate the response of soil physical properties such as BD, PR, infiltration and hydraulic conductivity to tractor wheel tracks under different compaction treatments and CT,

ii) to characterize the trafficking effects on the soil by changes in water availability, soil resistance to root penetration and soil aeration, i.e. by least limiting water range (LLWR),

iii) to evaluate the response of chickpea emergence in differently compacted soil.

4.2 Materials and methods

4.2.1 Experimental site and soil texture

The study consisted of four experiments in 2015, 2016 and 2017 (Table 4.1). In 2015, Exp. 1 was done in the field 200 m from the Conservation Agriculture long-term experiment (see Chapter 3 for details) located at Alipur of Durgapur, Rajshahi, Bangladesh (24^{o} 29’ 04.35” N 88^{o} 47’ 19.65” E). The recent cropping history for the experimental field was cool, dry season rice in 2014, followed by monsoon rice in 2014 and winter mustard in 2015. The experiment was commenced after the mustard harvest in February, and there was no-tillage or deep tillage done prior to the tillage or traffic operation. In 2016, Exp. 2 was done on the same field as in Exp. 1 at Alipur, with the trafficking direction of Exp. 2 perpendiculars to the direction of Exp. 1 in 2015. Experiment 2 was started ten months after Exp. 1, and between these two experiments, there was no-tillage. However, the field was inundated by rain water for three months that caused the clays to expand and then shrink when the soil drained and dried. Therefore, compaction effects carrying over from the Exp. 1 were minimised. In 2016, Exp. 3 was conducted in the field adjacent to the Conservation Agriculture long-term experiment (see Chapter 3 for details) located at Digram of Godagari, Rajshahi, Bangladesh (24°31'31.73"N 88°22'33.05"E). In the adjacent field, strip planting was practised since 2010. At Digram, the tillage or traffic operation was done after a rain event in March 2016. In 2017, Exp. 4 was done at a farmer’s field located 20 km from Thakurgaon district centre, Bangladesh. Exp. 4 consisted of three adjacent fields where wheel trafficking was performed at three volumetric SWCs. Soil textural class of Alipur, Digram and Thakurgaon are sandy clay loam, silty clay loam and sandy loam, respectively. An existing plough pan was found at 8-13 cm depth at Alipur and 10-15 cm depth at Digram. Details of the initial soil physical parameters are given in Table 4.1.

Table 4.1 Soil physical parameters measured before wheel trafficking experiments at three locations and different depths. SWC was the residual water content after the monsoon rice harvest at Alipur measured in February. At Digram SWC was the residual water content after wheat harvest in March. At Thakurgaon, SWC was the residual water content after the monsoon rice harvest measured in January.

Exp. Number	Location	Depth, cm	% Sand	% Silt	% Clay	SWC, %	BD g cm^3	K_{sat} cm h^{-1}
1 and 2	Alipur	0-5	50.1	26.0	23.8	26	1.30	1.89
		8-13	63.8	10.4	25.8	26.7	1.58	0.76
		10-15	61.4	12.7	25.8	27	1.55	-
3	Digram	0-5	20.4	48.2	31.4	26.4	1.37	1.16
		5-10	19.7	47.9	32.4	27.1	1.59	-
		10-15	19.1	48.7	33	27.5	1.66	0.40
4	Thakurgaon	0-5	60.0	31.3	8.7	21, 26, 29*	1.32	-

SWC= Soil water content at the time of wheel trafficking experiment, BD= Bulk density, K_{sat}= Saturated hydraulic conductivity. * At Thakurgaon, tillage and wheel trafficking experiments were done in three plots with three SMC.

4.2.2 Experimental treatments and layout

The field-test for wheel trafficking was carried using a Versatile Multi-crop planter (VMP) mounted on a Chinese Saifeng 2-WT of about 8.95 KW output power at 2000 revolution per minute. The tractor had wheels of standard size 6.00-12.00 (Wheel width-wheel rim diameter) rubber tyres with inflation pressure 145 kPa. The speed of the vehicle was 1.5 km h^{-1} during field test operating in a low-speed second gear position. This tyre pressure and the vehicle speed were within the range practised by the local farmers. Conventional tillage was done with a Saifeng 2-WT by random trafficking. The technical specifications were the same for all treatments, so that the axle load was the only experimental variable related to the ground pressure. For the treatments with increased ground pressure, extra axle weight was obtained by loading sacks of soil on a metal frame on the tractor in such a position that the centre of gravity of the loading and the centre of wheels lies in the same line perpendicular to the ground surface. The weight distribution of the tractor was balanced in such a way that there was a negligible weight on the press wheel of the VMP. The tyre-soil contact area was measured using the following procedure: the tractor was raised by using a hydraulic lift, and the area around the tyre was sprayed with black paint (Figure 4.1). Then an impression of the wheel was made by lowering the tractor on a white sheet of paper, which was placed on a flat wood board. Finally, the tyre-soil contact area was determined by making an ellipse around the wheel impression, and the area of the ellipse was measured with a planimeter. The ground pressure was calculated as the ratio of axle load and the tyre-soil contact area. The treatment combinations with the ground pressure of all experiments of the study are presented in Table 4.2. The treatments of strip tillage with or without loading with single and multiple wheel passes has been defined as the loading weight and number of wheel passes treatments. Whereas the conventional tillage with single or multiple wheel passes has been defined as the tillage treatments (Table 4.2). The field view of lands prepared by different treatments is also presented in Figure 4.2.

Figure 4.1 Determination of tyre soil contact area by taking an impression of the tyre on a sheet of paper. Inset is the impression of the tyre.

Table 4.2 Treatment identification and tyre/axle configuration

Year	Exp. #	Treatment definitions	Treatments	Number of wheel passes	Code	Axle load, kN	Tyre-soil Contact area, m^2	Ground Pressure, kPa
2015	1	Loading weight treatments	Strip Tillage	1	ST-1Pass	4.02	0.0166	121.0
			Strip Tillage	2	ST-2Pass	4.02	0.0166	121.0
			Strip Tillage + 100 kg load	1	ST100-1Pass	4.70	0.0169	138.7
			Strip Tillage + 100 kg load	2	ST100-2Pass	4.70	0.0169	138.7
		Tillage treatments	Conventional tillage	1	CT-1Pass	2.64	0.0154	85.7
			Conventional tillage	2	CT-2Pass	2.64	0.0154	85.7
		No traffic	No traffic	0	No traffic	-	-	
2016	2, 3 and 4	Loading weight treatments	Strip Tillage	1	ST-1Pass	4.02	0.0166	121.0
			Strip Tillage	4	ST-4Pass	4.02	0.0166	121.0
			Strip Tillage + 200 kg load	1	ST200-1Pass	5.98	0.0173	172.2
			Strip Tillage + 200 kg load	4	ST200-4Pass	5.98	0.0173	172.2
		Tillage treatments	Conventional tillage	1	CT-1Pass	2.64	0.0154	85.7
			Conventional tillage	4	CT-4Pass	2.64	0.0154	85.7
		No traffic	No traffic	0	No traffic	-	-	-

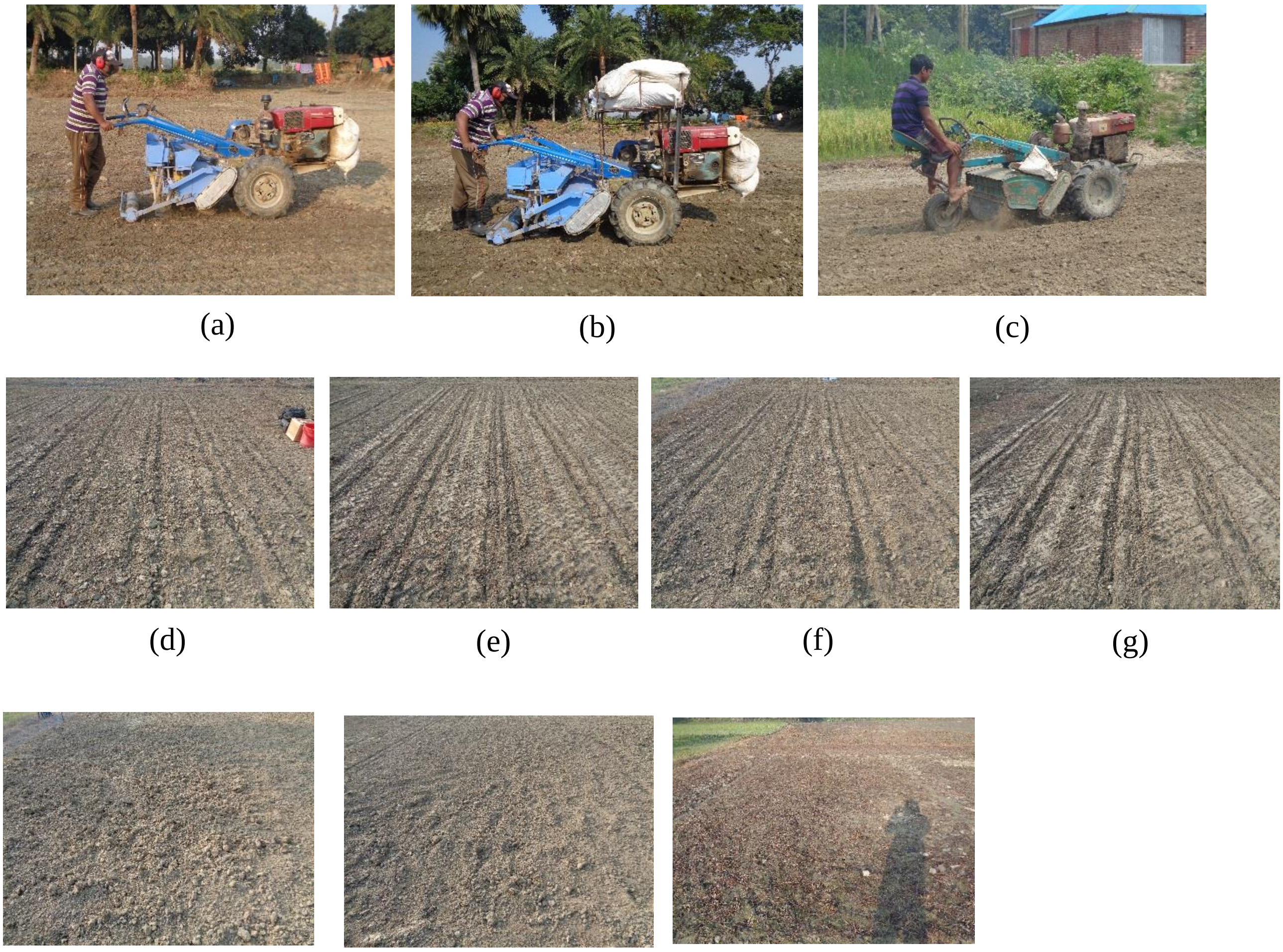

(a) (b) (c)
(d) (e) (f) (g)
(h) (i) (j)

Figure 4.2 Field view of tillage, loading weight, and number of wheel passes treatment operations: (a) strip tillage without loading (b) strip tillage with 200 kg loading (c) conventional tillage. Soil condition after treatment operations: (d) strip tillage single pass where wheel tracks are not visible due to coverage by pulverised soil which was removed during soil sample collection, (e) strip tillage four passes, (f) strip tillage with loading single pass, (g) strip tillage with loading four passes, (h) conventional tillage single pass, (i) convention tillage four passes, (j) undisturbed soil with no traffic no passing (control).

4.2.3 Soil sampling

Undisturbed soil cores (5 cm depth × 7.5 cm diameter) were collected one day after the wheeling operation with a hammer-driven sampler at 26 % mean volumetric SWC (Table 4.1) from each compaction treatments in each of the four trenches. Two trenches were dug 5 m apart along an 8 m wheel track. Thus, for wheel traffic plots, soil samples were collected from four trenches from two-wheel tracks. Core soil samples were collected from the centrelines of the tyre tracks because this is where the compressive effects tend to concentrate (Sohne, 1958). For CT treatment and No traffic plots, trenches were made randomly at a 1 m distance from the border of each plot. From each trench, three cores were taken for three depths of 0-5 cm, 5-10 cm and 10-15 cm from three different grids, as shown in Figure 4.3. Thus, 12 cores were taken from each plot. However, for Alipur, the soil sampling increments were 0-5, 8-13, and 10-15 cm. This was because there was a plough pan that existed at Alipur at 8-13 cm depth prior to the initiation of the experiments. Soil samples were taken from the 8-13 cm depth to characterize the physical properties of the plough pan before and after the wheel traffic. No soil samples were taken from the 5-8 cm depth of Alipur, since the samples taken from the 0-5 cm depth would represent the physical properties of the 5-8 cm depth. Furthermore, there was overlap among the 8-13 cm and 10-15 cm depth. Soil samples from the third layer of Alipur soil were taken from 10-15 cm depth, not from 13-18 cm, to compare the physical properties and the response to treatments of this layer to the same layer of Digram soil (10-15 cm depth).

All the cores collected were used for PR and BD measurements. Bulk density was determined after taking PR measurements (described later) on a soil oven-dry mass basis by drying each core in a fan-forced oven set at 105° C for 24 h (Blake and Hartge, 1986). From each plot, a different set of cores (2 cm depth × 5 cm diameter) from the same three depths were also collected for matric potential measurements to determine the soil water retention curve.

Figure 4.3 Sample core collection from three depths (0-5 cm, 5-10 cm and 10-15 cm) of a trench for bulk density and penetration resistance measurements at Digram. For Alipur the soil sampling increments were 0-5, 8-13, and 10-15 cm.

4.2.4 Penetration resistance measurements in the trench

Soil water content and PR were measured in the same trench after BD soil samples were collected. In the trenches, volumetric SWC was measured by the MP406 probe (ICT international, Australia), which was calibrated first in 2015. Four trenches were dug (as described above) in each replication; altogether, 16 measurements were taken for each treatment. Penetration resistance and SWC were measured for three depths 0-5 cm, 8-13 cm and 10-15 cm at Alipur. Details of the calibration of the moisture probe and the measurements of PR in the trench have been given in Chapter 3. Penetration resistance was measured with a force gauge (Dillon, model: GL250, origin: USA) with an 8.85 mm diameter 30^0 semi-angle cone. No laboratory measurements of PR were done in 2015.

Figure 4.4 Measurements of soil water content and penetration resistance in the trench after wheel compaction operations at Alipur in 2015.

4.2.5 Penetration resistance measurements in the laboratory

Penetration resistance of each soil samples was measured in 2016 on the intact soil cores with a dynamic cone penetrometer that was fabricated in the farm machinery workshop at Bangladesh Rice Research Institute (Figure 4.6). A force gauge (Dillon, model: GL250, origin: USA) of 250 N capacity with a precision of 0.1 N was mounted on the motorised test stand. The test stand has a downward speed of 1 to 15 mm min^{-1}. The PR was determined with a 2 mm diameter 30^{o} semi-angle cone with a base area of 3.14 mm^{2}. Behind the cone, the shaft was 1 mm in diameter. The penetration speed used was 3 mm min$^{-1,}$ and the penetration force was measured when the cone had penetrated a distance of 4 mm from the top of each core (Dexter, 1986). Soil PR was calculated by dividing the axial penetration force by the base area of the cone. Penetration resistance of the cores was measured at five water contents. Cores were slowly saturated for 24 hours and let to drain for 24 hours (Figure 4.5). The first PR was measured at the field capacity. The soil cores were then weighed and left to dry on the bench at constant room temperature until the predetermined weight was reached. The soil cores were then wrapped in plastic and placed in an airtight bag until equilibrium was reached in the soil core. Volumetric water contents of the five penetration measurements were approximately 33-37, 27-30, 25-27, 21-25 and 18-20 %. Two measurements of PR per soil core per water content were performed, and the mean was calculated.

Then, the soil cores were oven-dried at 105° C for 24 hrs to determine the volumetric water content and BD (Blake and Hartge, 1986). No field measurements of PR were done in 2016.


(a) (b) (c)

Figure 4.5 (a) Saturating the soil samples for 24 hrs (b) draining the soil samples to reach field capacity. Cores were placed on cloths to prevent the loss of soil (c) equilibrating the soil samples for water content by wrapping after a drying event.

(a) (b) (c)

Figure 4.6 (a) A dynamic cone penetrometer used for measuring PR, (b) 2 mm diameter 300 cones used, (c) a core soil sample after measurement of penetration resistance illustrating the distance between each point of measurement.

4.2.6 Penetration resistance for θ_{FC}, θ_{PWP} and water content at sowing

The correlation between the volumetric water content and the PR values was established to compensate for the variation of PR due to variation in SWC. Volumetric water content and the corresponding PR values for all 16 soil samples from one treatment were plotted and fitted to an exponential curve (Table 4.5 to Table 4.7 for Alipur and Table 4.10 to Table 4.12 for Digram). Penetration resistance values for soil water content at field capacity, permanent wilting point and the water content at sowing were calculated from the exponential equations. The method was repeated for all tillage, loading weight, and number of wheel passes treatments. The curve was also used to calculate the corresponding value of volumetric water content at the critical value of PR for root growth (2.5 MPa) to determine the least limiting water range (LLWR) (Table 4.8 and Table 4.13 for Alipur and Digram, respectively).

4.2.7 Soil water retention curve

For determination of the water retention curve, core samples were saturated for 24 hrs and then weighed. Then water content of the soil cores was determined at -5, -10, -30, -50, -100, -200, -392, -1500 kPa tension using a pressure plate apparatus (Soilmoisture Equipment Corp., USA) (Dane and Hopmans, 2002). At equilibrium, the soil cores were weighed at each matric potential. Then, the cores were oven-dried at 105^{o} C for 24 hrs to determine the volumetric water content (Grossman and Reinsch, 2002). Gravimetric water content was converted to volumetric water content using the BD of the corresponding soil samples. Volumetric water content at matric potential -10 kPa and -1500 kPa was considered as the volumetric water content at field capacity (θ_{FC}) and permanent wilting point (θ_{PWP}), respectively. Soil water retention curves were established for each treatment and soil type using the RETC computer program (Van Genuchten *et al.*, 1991). The equation from Van Genuchten (1980) was used to model the water retention curve:

$$\theta_v = \theta_r + \frac{(\theta_s - \theta_r)}{\{1 + (\alpha\psi)^n\}^m}$$

Where θ_v is the volumetric water content (%), θ_r is the residual water content (%), θ_s is the saturated water content (%), ψ is the water potential (cm), and α, n and m are constants that affect the slope of the retention curve: α approximates the inverse of the air-entry potential of the water retention curve, and n and m are parameters that control the slope of the curve (Reutenauer and

Ambroise, 1992). As in (Van Genuchten, 1980), the Mualem model was used and m restricted to be:

$$m = 1 - \frac{1}{n}$$

4.2.8 Infiltration measurements in the field

For the current study, a ring of 15 cm in diameter was used since the width of the compacted zone by traffic wheels were about 17-20 cm. Ring infiltrometer was inserted into the unsaturated soil to a depth of 5 cm. The depth of water ponding was 10 cm, which was maintained by connecting a Mariotte reservoir to the infiltrometer. The height of the Mariotte reservoir was adjusted to set the depth of ponding. The rate of fall of the water level in the Mariotte reservoir was monitored at 10 minutes interval to determine the infiltration rate into the soil. After some preliminary tests, 4 hours duration of the measurement was chosen since this duration was found to be adequate to detect the apparent steady-state condition. Steady-state was reached after an average of 3 hours. The criterion used for attaining steady-state infiltration was that the 10 min infiltration volume during a 60 min record remained effectively constant. This method was used by Mertens *et al.* (2002), except they used the 5 min infiltration volume during a 30 min record. The observed data of infiltration measurements were also fitted to Horton’s model as in Chapter 3. The details of the infiltration measurements have been given in Chapter 3.

4.2.9 Measurements of saturated hydraulic conductivity

Saturated hydraulic conductivity in the field was measured with a constant head digital infiltrometer (Meter group, USA) Figure 4.7. The infiltration rate resolution of the machine was 0.0038 cm h^{-1}. The machine was operated for 2.5 to 3 hours, depending on the compactness of the soil profile. The hydraulic head during the K_{sat} measurement was kept 10 cm. One K_{sat} measurements were taken for one replication of each treatment. Thus, total of four measurements were taken for each treatment. For compaction treatments (ST-1Pass, ST-4Pass, ST200-1Pass and

ST200-4Pass), measurements were taken for two depths of the wheel tracks. For CT, two measurements were taken randomly for two depths.

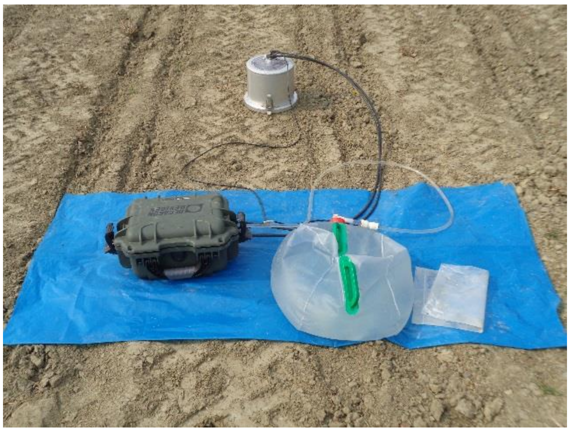


Figure 4.7 Field measurement of saturated hydraulic conductivity with a constant head digital infiltrometer (Meter group, USA). Picture showing measurements in the wheel tracks.

4.2.10 Chickpea emergence

Chickpea seeds were sown in February at Alipur and March at Digram in 2016, one day after tillage or traffic treatments operations. Chickpea (*Cicer arietinum*) seeds were first primed by soaking in water for 24 hrs. Eight mm diameter and 15 mm deep small holes with a sharp stick were made by hand dibbing 8 cm seed to seed distance on the wheel tracks for compaction treatments and on rows for CT. There was a 15 cm row to row distance for CT. This way, the number of holes in each plot were the same irrespective of treatments. One seed was then placed in one hole and covered with loose soil with a gentle pressing (Figure 4.8). At the time of chickpea sowing, soil temperature was about 15 to 18^0 C at Alipur and 20 to 25^0 C at Digram. Soil water content at the time of sowing was 26 % at Alipur and 27 % at Digram. Two weeks after seeding, emerged chickpea plants were counted, and their percentage was determined.

Figure 4.8 Hand dibbing of chickpea seeds at Alipur in 2016.

4.2.11 Statistical analysis

The field layout was designed as split-plot where strip tillage, strip tillage with loading and the CT had two levels of wheel passes treatments, namely, single pass and multiple passes. The No traffic plot, i.e. the undisturbed plot, had no passing treatment. All treatment combinations had an equal number of replications but were considered unbalanced because of the unequal level of wheel passes. Hence, all parameters were analysed by Residual Maximum Likelihood (REML). The estimated means from the model and the average least significant difference (LSD) at the 5 % level of significance was used for all main effect and the interaction effect and reported to distinguish differences between means. All analysis was carried out with GenStat version 18.0 (VSN international Ltd. United Kingdom).

4.3 Results

Experiment 1

4.3.1 Aipur 2015

Effect of tillage, loading weight and number of wheel passes on bulk density

In the 0-5 cm soil depth, taking an average across the number of passes, ST100 treatment significantly ($P<0.001$) increased BD by 0.09 g cm^{-3} compared to No traffic plot, while ST increased BD by 0.08 g cm^{-3} compared to No traffic. In contrast, CT significantly decreased BD by 0.04 g cm^{-3} compared to No traffic plot. There were no significant differences in BD values between ST and ST100 treatments. Taking an average of two compaction treatments (ST and ST100), two passes did not significantly increase BD over single pass. In the 8-13 cm and 10-15 cm soil depth, there was no significant effect of tillage, loading weight, or number of wheel passes on BD. In 2016, a compaction experiment was done with 200 kg extra load and four number of wheel passes (results are given later).

Table 4.3 Mean soil bulk density (g cm^{-3}) values under different tillage, loading weight, and number of wheel passes treatments taken in 2015 Alipur, Rajshahi.

Treatment	BD 0-5 cm		BD 8-13 cm		BD 10-15 cm	
	1 pass	2 pass	1 pass	2 pass	1 pass	2 pass
ST	1.37	1.40	1.60	1.61	1.57	1.58
ST100	1.39	1.40	1.59	1.61	1.59	1.59
CT	1.27	1.26	1.62	1.62	1.57	1.61
No traffic	1.31		1.61		1.59	
P_{Load}	<0.001		ns		ns	
P_{Pass}	Ns		ns		ns	
$P_{Load \times Pass}$	Ns		ns		ns	
$LSD_{0.05}$ Average	0.04		ns		ns	

ST=Strip tillage, ST100=Strip tillage with 100 kg load, CT=Conventional Tillage. $LSD_{0.05}$= Least significant difference.

Effect of tillage, loading weight, and number of wheel passes on PR measured in the trench

In 2015, There was no significant effect of tillage, loading weight or number of wheel passes on the BD of 0-5 cm, 8-13 cm and 10-15 cm soil depth. Penetration resistance under two passes was slightly higher than the PR under single pass in the 0-5 cm soil, but the difference was not significant. Averaging across all treatments, mean PR in 0-5 cm, 8-13 cm and 10-15 cm depth was 1.1, 2.2 and 1.8 MPa, respectively. The higher PR in the 8-13 cm suggests that there was a plough pan at this depth.

Table 4.4 Penetration resistance (MPa) measured in the trench under different tillage, loading weight, and number of wheel passes treatments in 2015, Alipur, Rajshahi.

Treatment	0-5 cm		8-13 cm		10-15 cm	
	SWC	**PR**	**SWC**	**PR**	**SWC**	**PR**
ST-1Pass	26.5	1.1	28.0	2.2	27.3	1.8
ST-2Pass	26.1	1.3	28.1	2.4	28.9	1.8
ST100-1Pass	26.8	1.2	27.8	2.1	30.2	1.8
ST100-2Pass	26.3	1.3	27.8	2.2	28.1	1.8
CT-1Pass	26.7	1.1	28.3	2.1	29.3	1.9
CT-2Pass	26.5	0.9	28.4	2.1	29.1	1.7
No traffic	26.8	1.1	27.7	2.2	28.3	1.8
P_{Load}	Ns	ns	ns	ns	ns	ns
P_{Pass}	Ns	ns	ns	ns	ns	ns
$P_{Load \times Pass}$	Ns	ns	ns	ns	ns	ns
$LSD_{0.05}$ Average	Ns	ns	ns	ns	ns	ns

SWC= soil water content (%, w/w), PR= penetration resistance, ST=Strip tillage, ST100=Strip tillage with 100 kg load, CT=Conventional Tillage.

Experiment 2

4.3.2 **Alipur 2016**

Effect of tillage, loading weight, and number of wheel passes treatments on bulk density

There was a significant ($P<0.05$) interaction of loading weight × the number of wheel passes on BD at the 0-5 cm depth (Figure 4.9). The ST200-4Pass treatment increased BD by 0.15 g cm^{-3} compared to No traffic, while ST200-1Pass increased BD by 0.1 g cm^{-1} over No traffic. This means that the extra three passes increased BD by 0.05 g cm^{-3}. Treatment ST200-4Pass increased BD by 0.15 g cm^{-3} compared to No traffic, while ST-4Pass increased BD by 0.14 g $cm^{-3,}$ suggesting extra 200 kg load increased BD by 0.01 g cm^{-3}. In contrast to compaction treatments, CT-4Pass reduce BD by 0.08 g cm^{-3} compared to CT-1Pass. There was no significant effect of tillage, loading weight, or number of wheel passes treatments on the BD of the plough pan (8-13 cm) and 10-15 cm soil depth.

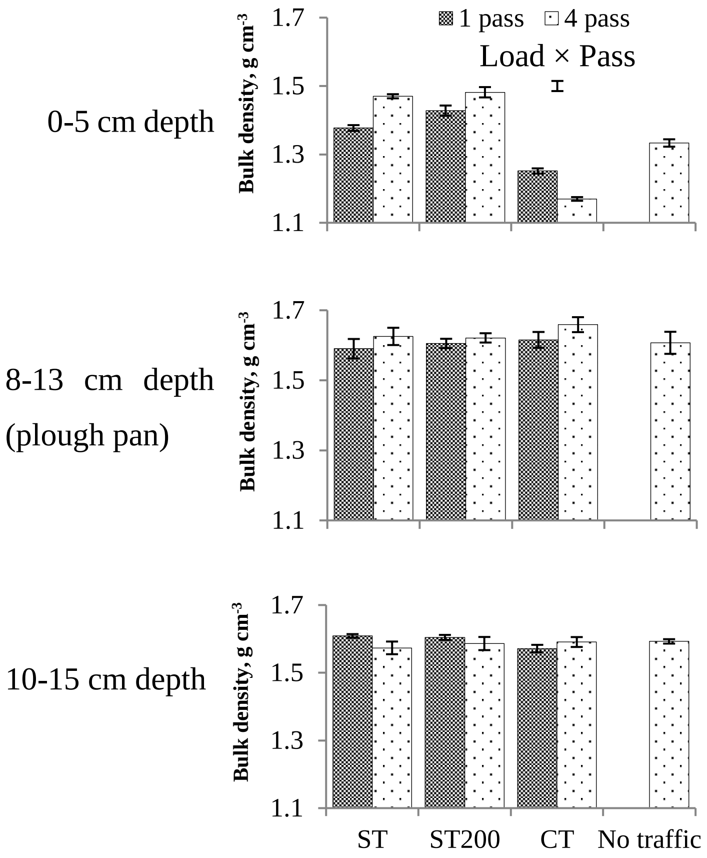


Figure 4.9 Mean soil bulk density at Alipur in 2016 as affected by different tillage, loading weight, and number of wheel passes treatments at three depths. ST= Strip Tillage, ST200= Strip tillage with 200 kg load, CT= Conventional tillage, No Traffic= Undisturbed soil (control).

Bulk density results from two experiments done separately in 2015 and 2016 in the same field at Alipur are presented in Figure 4.9. As the loading weight and number of wheel passes and tillage operations were done in relatively the same SWC, the results from two years' experiments were compared for ST single pass, two passes and four passes. The result shows that BD increased linearly with the increase in number of passes. A comparison is also made for the increase in BD due to the increase in ground pressure. In this case, the BD was also linearly increased with the increase in ground pressure. The regression coefficient is significant (P<0.01) for both cases. However, the trend line for the first one is steeper than the second one. This result confirms that greater compaction in the topsoil is achieved more by increasing the number of passes than increasing the loading.

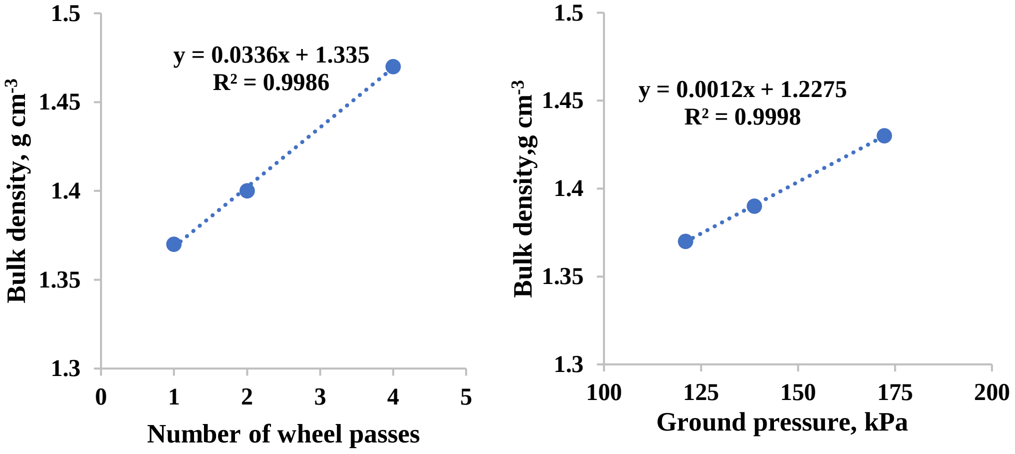


Figure 4.10 Relationship between (a) bulk density (BD) vs number of wheel passes (b) BD vs ground pressure by the wheel traffic of the 2-WT on 0-5 cm soil at Alipur.

Relationship between penetration resistance measured in the laboratory and soil water content

Penetration resistance values measured in the laboratory were significantly correlated with SWC (Figure 4.11 to Figure 4.13). Penetration resistance decreased with increasing SWC ($P<0.05$) (Figure 4.11) for all treatments and depths. An exponential model of PR with SWC was able to explain around 80 % of the variability in PR.

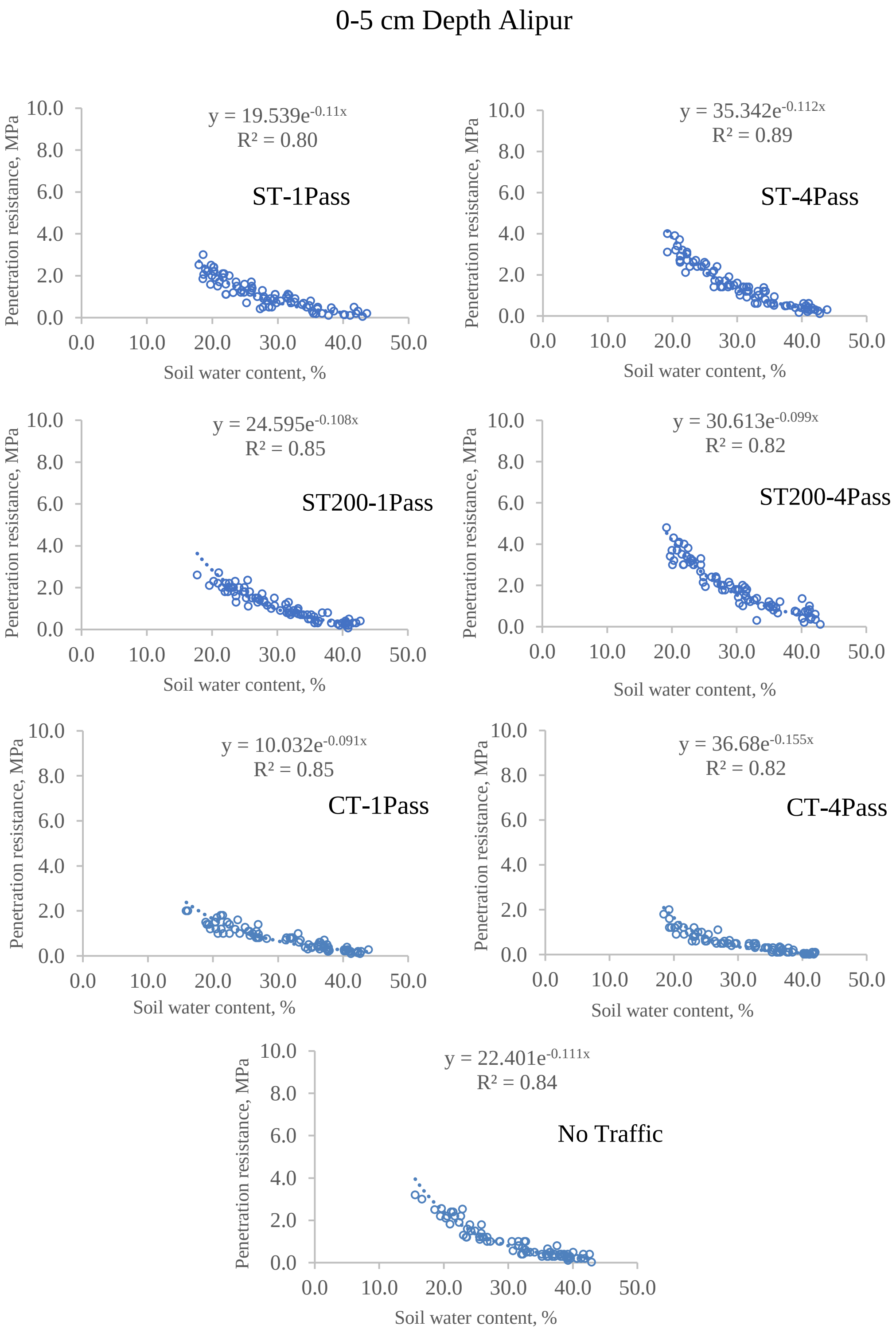


Figure 4.11 Penetration resistance values plotted against soil water content for 0-5 cm depth at Alipur 2016. ST=Strip tillage, ST200=Strip tillage with 200 kg load, CT= Conventional tillage.

8-13 cm depth Alipur

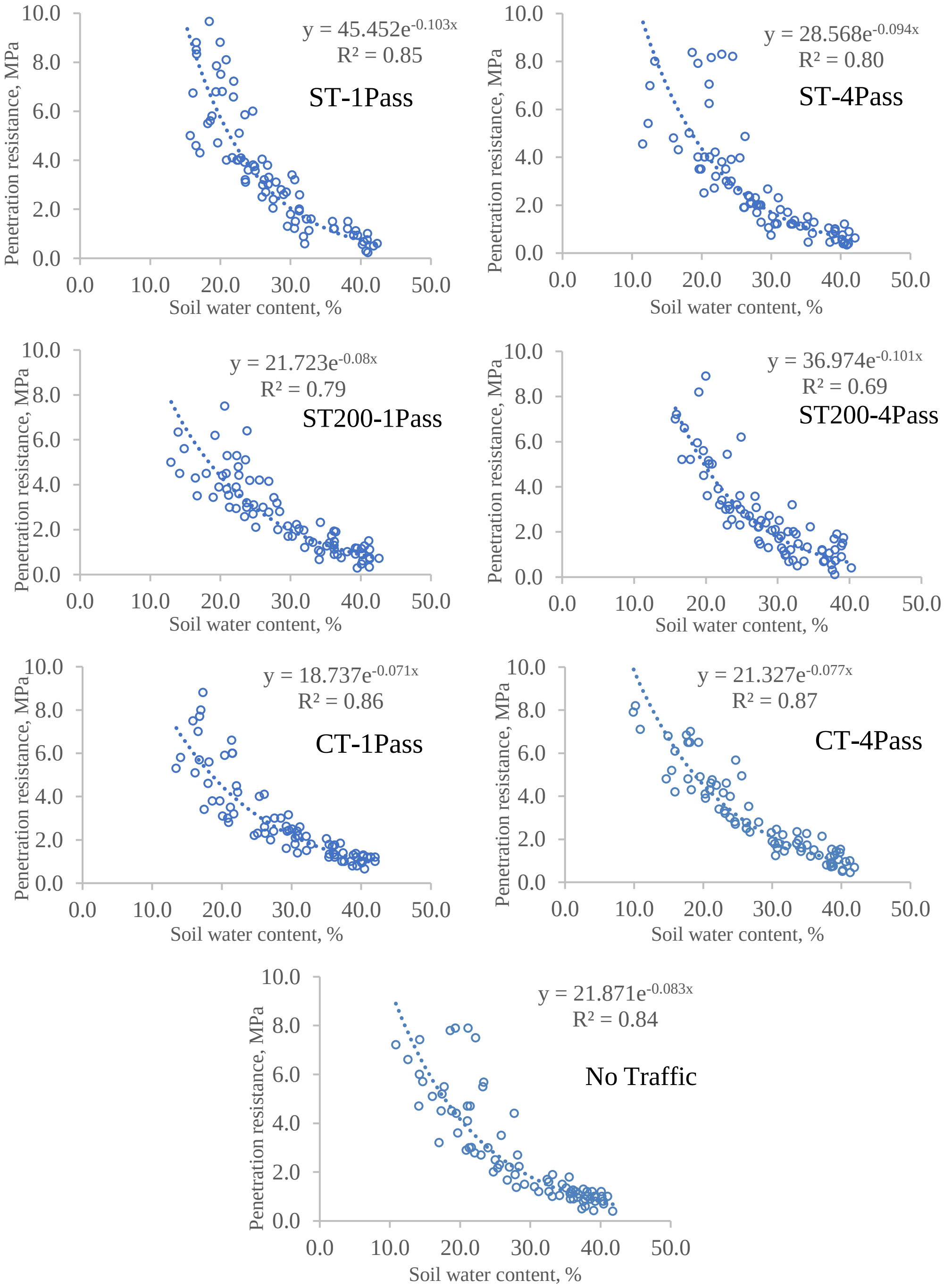


Figure 4.12 Penetration resistance values plotted against soil water content for 8-13 cm depth at Alipur 2016. ST=Strip tillage, ST200=Strip tillage with 200 kg load, CT= Conventional tillage.

10-15 cm depth Alipur

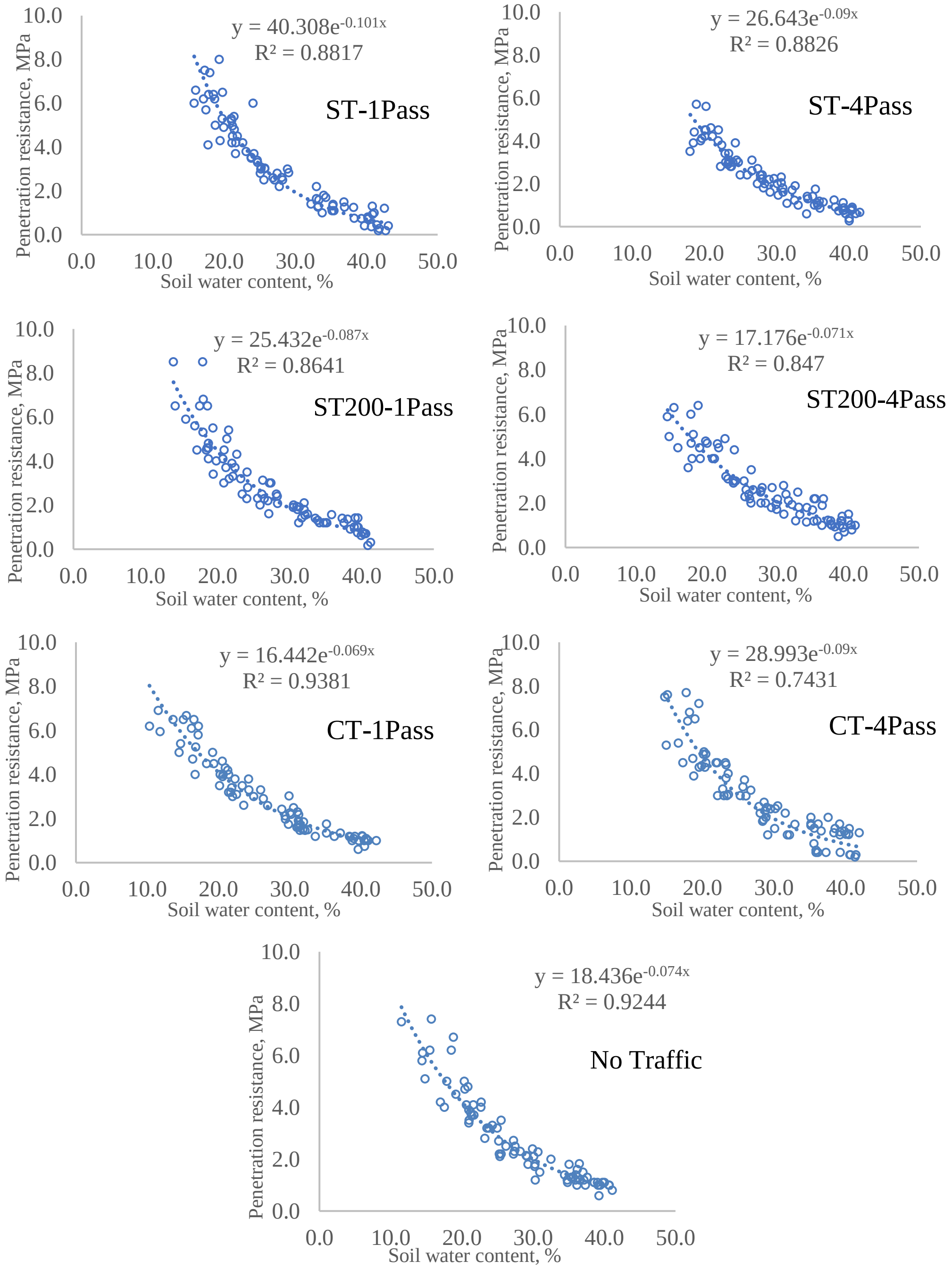
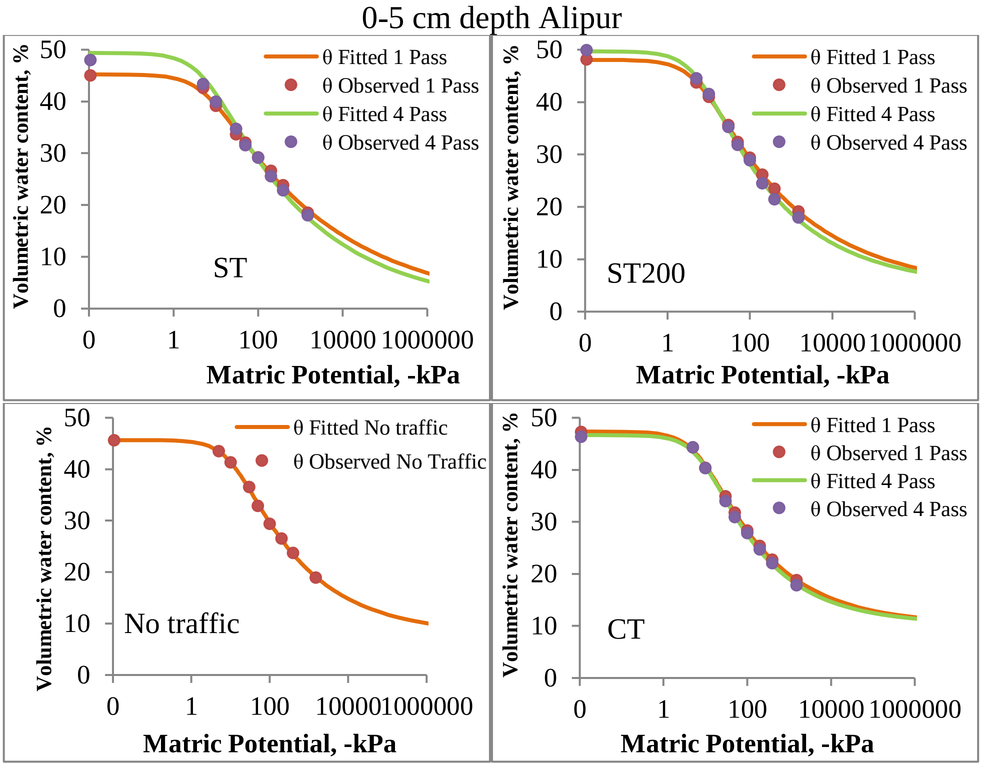


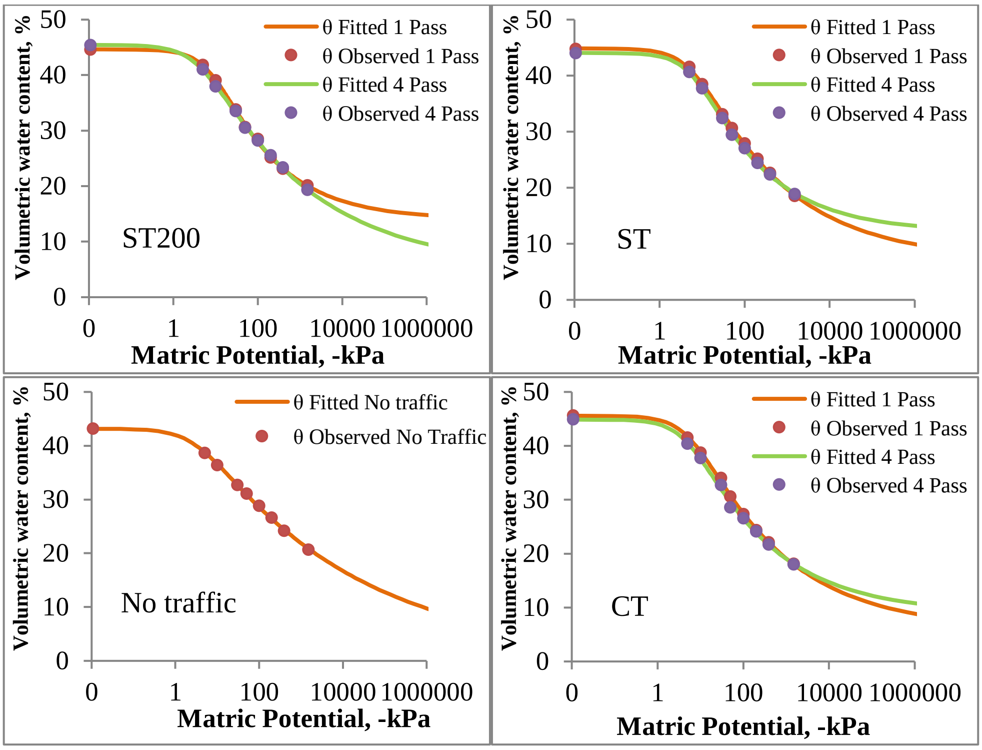
Figure 4.13 Penetration resistance values plotted against soil water content for 10-15 cm depth at Alipur 2016. ST= Strip tillage, ST2000=Strip tillage with 200 kg Load, CT= Conventional tillage.

Soil water retention curve

The soil water retention curves obtained at different tillage, loading weight, and number of wheel pass treatments for Alipur soil are shown in Figure 4.14. The results show that the main effect of treatments was significant on water content between 0 to –10 kPa matric potential but not at a lower (more negative) potential. At –10 kPa matric potential, the water content of ST200 was significantly higher than the water content of ST. The results suggest that increased BD by ST200 increased the water content at –10 kPa. On a volumetric basis, the effect of compaction by extra loading and increased wheel passes on the water retention curve tended to be reflected in an increase in water content due to the increase in BD. However, despite the significant BD difference, there was no significant difference in water content between the ST200 soil and the No traffic at – 10 kPa matric potential. There was no significant effect of tillage, loading weight, or number of wheel passes on water retention across the whole measured tension range in the 8-13 cm or 10-15 cm soil depths.



8-13 cm depth Alipur



10-15 cm depth Alipur

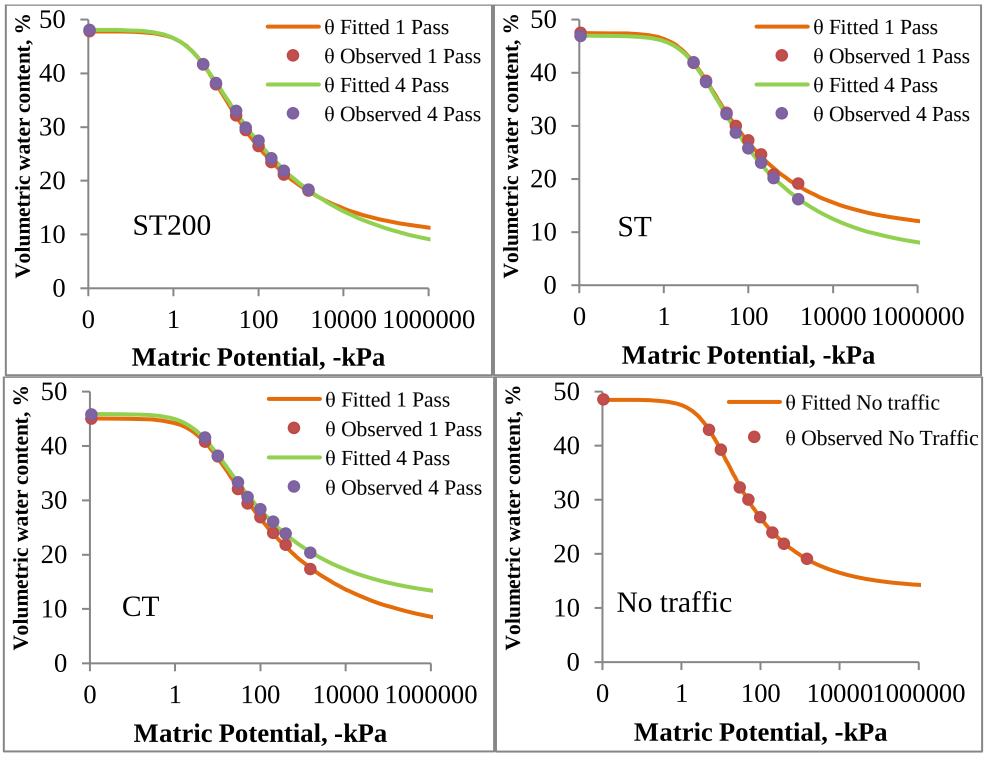


Figure 4.14 Water retention curve under different treatments in three depths at Alipur 2016. ST=Strip tillage, ST200=Strip tillage with 200 kg load, CT= Conventional tillage.

Penetration resistance at soil water contents at sowing, field capacity, and permanent wilting point

The relationships in Figure 4.11, Figure 4.12, and Figure 4.13 were used to estimate the PR of each treatment and soil depth at SWC at sowing (θ_{Sow}), field capacity (θ_{FC}) and permanent wilting point (θ_{PWP}). Given the effect of soil water on soil strength, treatment comparisons are possible if soil water is standardised to field capacity and permanent wilting point. Comparison of these estimated PR values for different tillage, loading weight, and number of wheel passes treatments at θ_{Sow}, θ_{FC} and θ_{PWP} are presented in Table 4.5, Table 4.6, and Table 4.7.

Penetration resistance at 0-5 cm depth estimated from the PR vs SWC relationship

Penetration resistance estimated for θ_{Sow}

The PR value at θ_{Sow} was intermediate between the PR at θ_{FC} and θ_{PWP} for all tillage, loading weight, and number of wheel passes treatments. Tillage or the loading weight × number of wheel passes interaction significantly influenced PR at θ_{Sow}. Penetration resistance value at θ_{Sow} followed the same trend as PR at θ_{FC}. For example, the maximum value of PR was induced by ST200-4Pass, while the minimum value was found in CT-4Pass. Among the four loading weights and number of wheel passes treatments, PR was in the order of ST200-4Pass>ST-4Pass>ST200-1Pass>ST-1Pass. Nevertheless, the difference in PR values between the two treatments was larger at θ_{Sow} than the difference in PR values between the two treatments at θ_{FC}.

Penetration resistance estimated for θ_{FC}

At the 0-5 cm depth, the interaction effect of tillage or loading weight × number of wheel passes on PR at θ_{FC} was significant (Table 4.5). Among the seven treatments, PR tended to be the maximum in ST200-4Pass and the minimum in CT-4Pass. While among the four loading weight treatments, PR values were in the order of ST200-4Pass>ST-4Pass>ST200-1Pass=ST-1Pass. The ST200-4Pass treatment increased PR by 0.5 MPa relative to ST200-1Pass, while ST-4Pass increased PR by 0.3 MPa compared to ST-1Pass. The differences in PR between ST200-4Pass and ST-4Pass was 0.2 MPa, while there was no difference in PR between ST200-1Pass and ST-1Pass.

Penetration resistance estimated for θ_{PWP}

Taking the average across the number of wheel passes, ST200 increased PR by 0.4 MPa over ST. For the average across two loading weight treatments (ST and ST200), four passes increased PR by 1.8 MPa compared to single passes. Penetration resistance under CT-4Pass was not significantly different than that under CT-1Pass, and the mean value of these two (2.6 MPa) was significantly lower than the mean value of loading weight treatments (4.0 MPa).

Penetration resistance at 8-13 cm depth estimated from the PR vs SWC relationship

There was no significant effect of tillage, loading weight, and number of wheel passes treatment for 8-13 cm depth at either of θ_{Sow}, $\theta_{FC,}$ or θ_{PWP}. Nevertheless, the higher PR values in 8-13 cm soil depth than the PR values in 0-5 cm depth under the uncompacted No traffic treatment suggest the presence of a plough pan at this depth. The mean PR value of all treatments was 1.5 MPa, 5.6 MPa and 2.9 MPa for $\theta_{FC,}$ θ_{PWP} and θ_{Sow}, respectively.

Penetration resistance at 10-15 cm depth estimated from the PR vs SWC relationship

Taking averages across all treatments, PR values at $\theta_{FC,}$ $\theta_{PWP,}$ and θ_{Sow} were 1.6 MPa, 5.4 MPa and 2.8 MPa, respectively, suggesting soil PR in the 10-15 cm depth was similar to the 8-13 cm depth.

Table 4.5 Penetration resistance for different tillage, loading weight, and number of wheel passes treatment at different soil water content in the 0-5 cm soil, Alipur 2016.

Depth 0-5 cm, θ_{sow} = 26 % volumetric

Treatments	**PR_{sow}, MPa**	**θ_{FC}, %**	**PR_{FC}, MPa**	**θ_{WP}, %**	**PR_{PWP}, MPa**
ST-1 Pass	1.2	39.1	0.5	18.5	2.8
ST-4 Pass	1.9	39.9	0.8	18.0	4.7
ST200-1Pass	1.5	41.0	0.5	19.1	3.4
ST200-4Pass	2.3	41.5	1.0	17.9	5.0
CT-1Pass	0.9	40.3	0.4	18.8	2.0
CT-4Pass	0.6	40.3	0.2	17.7	2.4
No traffic	1.3	41.3	0.4	18.9	2.8
P_{Load}	<0.001	0.038	<0.001	Ns	<0.001
P_{Pass}	<0.001	ns	<0.001	Ns	<0.001
$P_{Load \times Pass}$	<0.001	ns	<0.001	Ns	ns
$LSD_{0.05}$ Average	0.19	1.7	0.14	Ns	1.03

$LSD_{0.05}$=Average least significant difference for Residual Maximum Likelihood (REML) for all main and interaction effect (see section for statistical method), θ_{FC}= Soil water content at field capacity, PR_{FC}=Penetration resistance at θ_{FC}, θ_{PWP}= Soil water content at permanent wilting point, PR_{PWP}= Penetration resistance at θ_{PWP}, PR_{sow}= Penetration resistance for soil water content at sowing.

Table 4.6 Penetration resistance for different tillage, loading weight, and number of wheel passes treatment at different soil water content in the 8-13 cm soil, Alipur 2016.

Depth 8-13 cm, θ_{sow} = 26.7 % volumetric

Treatments	PR_{sow}, MPa	θ_{FC}, %	PR_{FC}, MPa	θ_{PWP}, %	PR_{PWP}, MPa
ST-1 Pass	3.2	38.5	1.5	18.5	6.9
ST-4 Pass	2.7	37.7	1.4	18.9	5.6
ST200-1Pass	3.0	39.1	1.5	20.1	5.5
ST200-4Pass	2.8	38.0	1.4	19.3	5.3
CT-1Pass	3.0	38.8	1.6	18.1	5.5
CT-4Pass	2.9	37.7	1.7	18	5.5
No traffic	2.7	36.4	1.5	20.7	4.6
P_{Load}	ns		ns		ns
P_{Pass}	ns		ns		ns
$P_{Load \times Pass}$	ns		ns		ns
$LSD_{0.05}$ Average	ns		ns		ns

$LSD_{0.05}$=Average least significant difference for Residual Maximum Likelihood (REML) for all main and interaction effect (see section for statistical method), θ_{FC}= Soil water content at field capacity, PR_{FC}=Penetration resistance at θ_{FC}, θ_{PWP}= Soil water content at permanent wilting point, PR_{PWP}= Penetration resistance at θ_{PWP}, PR_{sow}= Penetration resistance for soil water content at sowing.

Table 4.7 Penetration resistance for different tillage, loading weight, and number of wheel passes treatment at different soil water content in the 10-15 cm soil, Alipur 2016.

Depth 10-15 cm, θ_{sow} = 27 % vol

Treatments	PR_{sow}, MPa	θ_{FC}, %	PR_{FC}, MPa	θ_{PWP}, %	PR_{PWP}, MPa
ST-1 Pass	2.9	38.5	1.5	19.2	6.0
ST-4 Pass	2.6	38.3	1.5	16.2	6.5
ST200-1Pass	2.7	38.0	1.6	18.2	5.3
ST200-4Pass	2.8	38.2	1.7	18.4	5.1
CT-1Pass	2.7	38.0	1.8	17.4	5.2
CT-4Pass	2.9	38.2	1.6	20.3	5.2
No traffic	2.7	39.3	1.7	19.1	4.6
P_{Load}	ns		ns		ns
P_{Pass}	ns		ns		ns
$P_{Load \times Pass}$	ns		ns		ns
$LSD_{0.05}$ Average	ns		ns		ns

θ_{FC}= Soil water content at field capacity, PR_{FC}=Penetration resistance at θ_{FC}, θ_{PWP}= Soil water content at permanent wilting point, PR_{PWP}= Penetration resistance at θ_{PWP}, PR_{sow}= Penetration resistance for soil water content at sowing.

Least limiting water range and plant available water content for mean bulk density values

Table 4.8 presents LLWR for Alipur soil under seven treatments and three soil depths. The parameters of θ_{FC}, θ_{AFP}, θ_{PWP} and θ_{PR} used to calculate the LLWR, PAW and the percentage reduction in PAW with respect to LLWR are also presented. The numbers in bold type were used to calculate the LLWR. The θ_{AFP} and θ_{PR} were the limiting factors for LLWR for all treatments and depths except under CT-1Pass and CT-4Pass at the surface soil where $\theta_{FC,}$ and θ_{PWP} were, respectively, the upper and the lower limits.

Irrespective of tillage, loading weight, and number of wheel passes treatments, 0-5 cm depth exhibit wider LLWR values compared to the other two depths. Comparing all treatments, LLWR of 0-5 cm depth under ST200-4Pass treatment, the most compacted soil, were 61 % lower than the LLWR values under CT-4Pass treatment, the most tilled soil. The ST-1Pass treatment gave a similar LLWR value compared to No traffic treatment. However, ST-4Pass treatment reduced LLWR by 45 % compared to No traffic treatment. Furthermore, CT-4Pass increased LLWR by 13 % compared to No traffic. The results also suggest that the difference in LLWR values between ST-1Pass and CT-1Pass was only 10 %, and comparing ST-1Pass and CT-4Pass; the difference increased to 14 %.

Comparing loading weight and number of wheel passes treatments (for treatment details, see Table 4.2), shifting from ST-1Pass to ST-4Pass LLWR values reduced by 44 %. Similarly, shifting from ST200-1Pass to ST200-4Pass reduced LLWR values by 41 %. Again adding an extra 200 kg load to ST-1Pass, ST200-1Pass treatment reduced LLWR value by 23 %. Similarly, adding an extra 200 kg load to ST-4Pass, ST200-4Pass treatment reduced LLWR value by 19 %.

There was a sharp decline in LLWR in the 8-13 cm soil depth and 10-15 cm soil depth. The LLWR in the 8-13 cm soil depth (plough pan) was less than 4 % regardless of treatments and tended to be negative under CT-4Pass treatment. However, there were no significant differences in LLWR values between 8-13 cm and 10-15 cm soil depth.

In 0-5 cm depth, the percentage reduction in PAW ranged from 0-62 % considering all treatments. Under CT, the percentage reduction in PAW was 0 % since the PAW was equal to LLWR, where θ_{FC} and θ_{PWP} were the limiting factors for root growth. Under CT at depth 8-13 cm depth where the LLWR was negative, the percentage reduction was >100 %.

Table 4.8 The least limiting water range (LLWR) and the limits of volumetric water content used in the calculation of the LLWR Alipur.

Treatments	Depth	θ_{FC}, %	θ_{AFP}, %	θ_{PWP}, %	θ_{PR}, %	LLWR, %	PAW, %	Reduction to PAW %
ST-1Pass	1	39.14	**38.03**	18.48	**18.69**	19.34	20.67	6.41
	2	38.47	**29.99**	18.54	**28.16**	1.83	19.93	90.81
	3	38.46	**29.29**	19.16	**27.31**	1.98	19.30	89.73
ST-4Pass	1	39.92	**34.53**	17.96	**23.65**	10.88	21.96	50.46
	2	37.73	**28.66**	18.89	**25.91**	2.75	18.84	85.40
	3	38.25	**30.62**	16.20	**26.29**	4.33	22.04	80.36
ST200-1Pass	1	40.95	**36.11**	19.05	**21.17**	14.94	21.90	31.75
	2	39.07	**29.42**	20.12	**27.27**	2.15	18.95	88.65
	3	37.95	**29.46**	18.19	**26.66**	2.79	19.76	85.86
ST200-4Pass	1	41.51	**34.09**	17.91	**25.30**	8.78	23.60	62.78
	2	37.98	**28.82**	19.32	**26.67**	2.15	18.65	88.47
	3	38.21	**30.14**	18.37	**27.14**	3.00	19.84	84.89
CT-1Pass	1	**40.32**	42.77	**18.76**	15.27	21.56	21.56	0.00
	2	38.76	**29.04**	18.13	**28.37**	0.67	20.63	96.74
	3	38.03	**30.70**	17.35	**27.30**	3.40	20.68	83.55
CT-4Pass	1	**40.29**	45.86	**17.74**	17.33	22.55	22.55	0.00
	2	37.74	**27.40**	18.00	**27.75**	-0.35	19.75	101.77
	3	38.16	**31.70**	20.31	**27.23**	4.47	17.85	74.97
No traffic	1	41.30	**39.69**	18.89	**19.76**	19.93	22.41	11.04
	2	36.40	**29.35**	20.68	**26.13**	3.22	15.72	79.49
	3	39.25	**29.90**	19.07	**27.00**	2.90	20.18	85.63

θ_{FC}= Soil water content at field capacity, determined from the water retention curve, θ_{AFP}=Soil water content at 10 % air-filled porosity, θ_{PWP}= soil water content at permanent wilting point, determined from the water retention curve, θ_{PR}= Soil water content at PR value of 2.5 MPa, calculated from the SWC vs PR relationship. LLWR= Least limiting water range, PAW= Plant available water content.

The LLWR was negatively related to BD values for all treatments and at all depths (Figure 4.15). However, the slope of the trend line for 0-5 cm depth was steeper compared to that for the other two depths. In the plough pan (8-13 cm depth), the LLWR value became negative with BD values equal to 1.66 g cm^{-3} under CT-4Pass. Da Silva *et al.* (1994) considered soil with a negative LLWR to have zero LLWR.

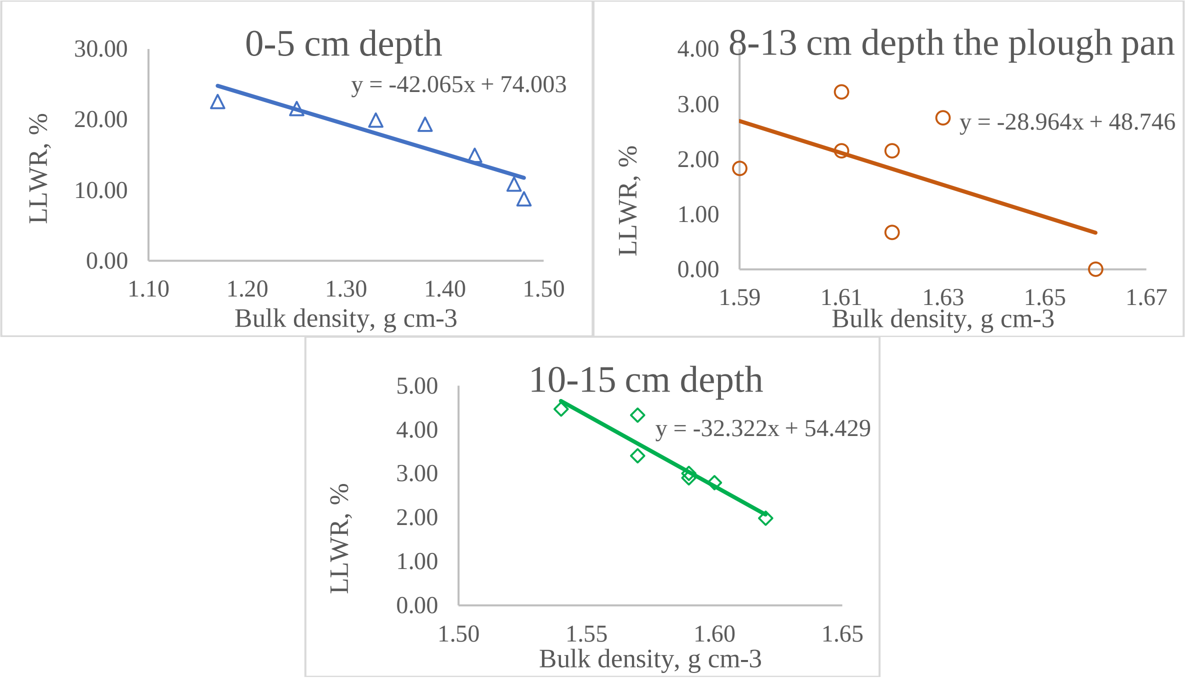


Figure 4.15 Relationship of least limiting water range (LLWR) to bulk density for 0-5 cm, 8-13 cm and 10-15 cm soil depths for different tillage, loading weight and number of wheel passes treatments in Alipur.

Saturated hydraulic conductivity

Tillage or loading weight × number of wheel passes interaction significantly affected the saturated hydraulic conductivity (K_{sat}) at the 0-5 cm soil depth (Figure 4.16). The saturated hydraulic conductivity of ST-1 Pass was 1.98 cm h$^{-1,}$ which was reduced sharply to 0.47 cm h^{-1} under ST-4Pass. By adding an extra 200 kg load on the vehicle, 2-WT reduced the K_{sat} to 0.74 cm h^{-1} with a single pass, which was further reduced to 0.30 cm h^{-1} with four passes. Saturated hydraulic conductivity under ST200-4 Pass was also significantly lower than that under the No traffic treatment and than either CT-1Pass or CT-4Pass. The results suggest that K_{sat} was highest with the most tilled soil under CT-4 Pass and was the lowest with the most compacted soil under ST200-4 Pass. Treatment differences in the plough pan (8-13 cm) were not significant.

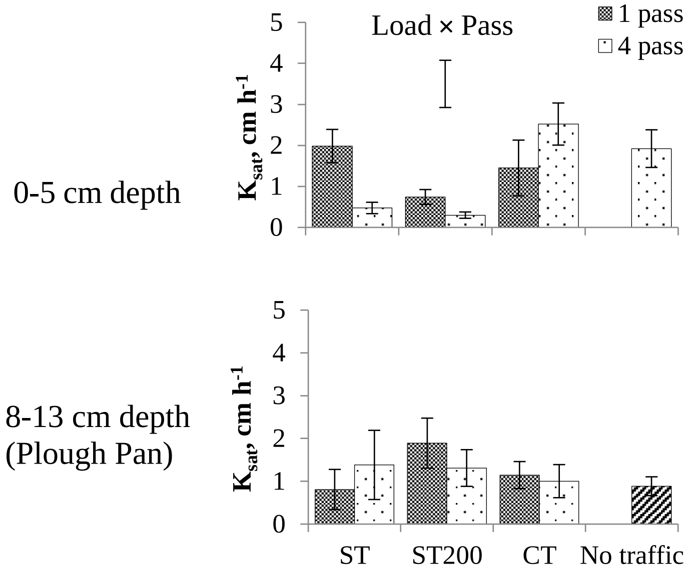


Figure 4.16 Tillage, loading weight, and number of wheel passes effects on Saturated hydraulic conductivity (K_{sat}) at Alipur in 2016. ST= strip tillage, ST200= strip tillage with 200 kg load, CT= conventional tillage, No Traffic= undisturbed soil (control). Floating bar indicates the average least significant difference at 5 % level of significance.

Infiltration rate and cumulative infiltration

Infiltration rates were significantly lower in the four pass treatments than in the single pass under both ST and ST200 treatments (Table 4.9). The highest mean initial infiltration rate after 10 minutes was obtained in the plots under CT-1Pass and CT-4Pass, whereas the lowest was obtained in the ST200-4Pass treatment. After 10 min, there was a steeper reduction in infiltration rates in the ST and ST200 treatments than in the CT treatments. In the ST and ST200 treatments, the initial infiltration rates under four passes started approaching a steady value sooner (approximately 30 min after the start of the run) than the single pass (about 50 min) (Figure 4.17). In the case of CT and the No traffic plot, the infiltration rates started approaching the steady-state after approximately 70 min. Under ST and ST200 treatments, the steady-state infiltration rate in single wheel pass treatment was twice as high as the final infiltration rate in four wheel pass treatment. The mean steady-state infiltration rate was significantly higher under CT plots than under ST and ST200 plots. The mean cumulative infiltration at the end of 240 min was also higher in the CT plots than under the ST and ST200 plots. Cumulative infiltration decreased significantly under ST-4Pass and ST200-4Pass by 57 % and 63 %, respectively, over No traffic treatment (Table 4.9).

Table 4.9 Effect of tillage, loading weight, and number of wheel passes on soil infiltration characteristics taken in 2016 at Alipur, Rajshahi.

Tillage or loading weight treatments	**Infiltration characteristics**					
	Initial (i_i) (cm min^{-1})		**Steady-state (i_s) (cm min^{-1})**		**Cumulative (I) (cm)**	
	1 Pass	**4 Pass**	**1 Pass**	**4 Pass**	**1 Pass**	**4 Pass**
ST	0.31	0.16	0.11	0.04	31.8	15.0
ST200	0.30	0.12	0.11	0.05	30.0	13.0
CT	0.45	0.45	0.13	0.17	43.0	50.4
No traffic	0.38		0.12		34.6	
P_{Load}	<0.001		<0.001		<0.001	
P_{Pass}	<0.001		0.036		0.01	
$P_{Load \times Pass}$	0.035		0.008		0.005	
$LSD_{0.05}$ Average	0.10		0.05		10.8	

i_i = initial infiltration after 10 min, i_s = Steady-state infiltration, mean of last 60 minutes infiltration rate, I= Cumulative infiltration after 240 minutes. All data are mean of four replicates. ST= Strip tillage, ST200=Strip tillage with 200 kg load, CT= Conventional tillage, $LSD_{0.05}$=Average least significant difference for Residual Maximum Likelihood (REML) for all main and interaction effect (see the section for statistical method).

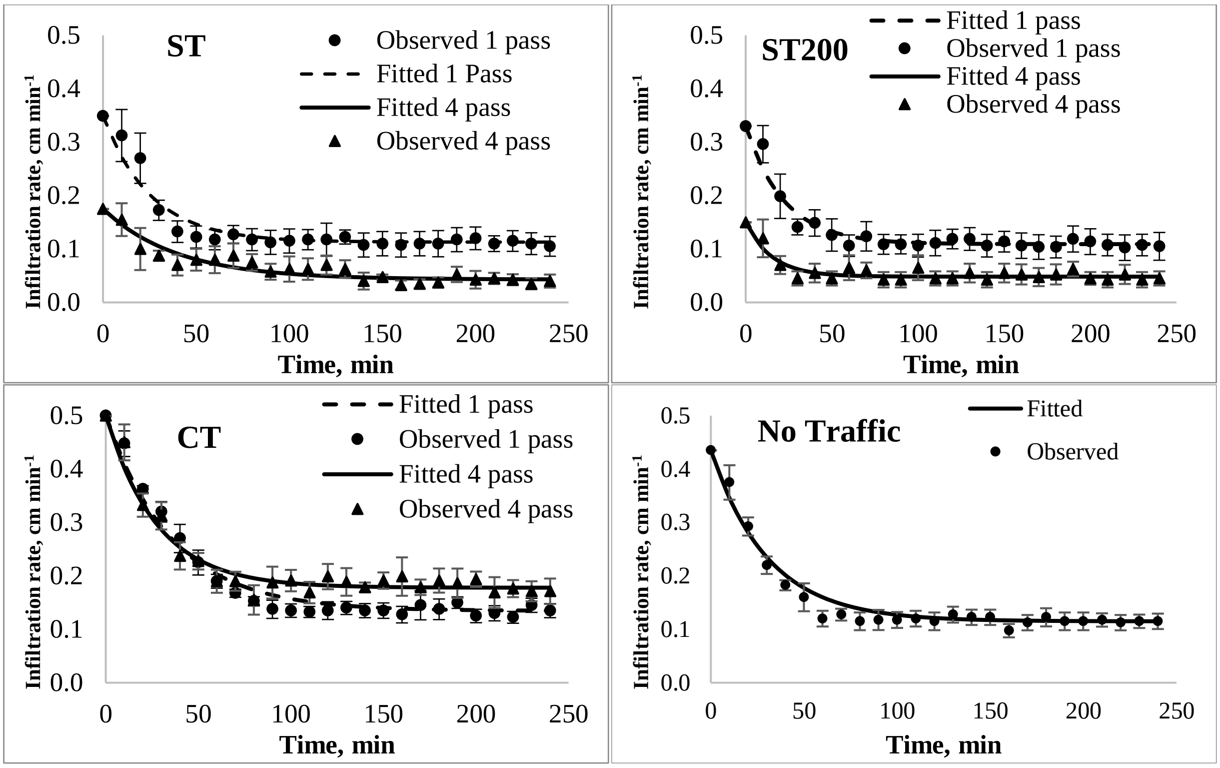


Figure 4.17 Infiltration curves for tillage, loading weight, and number of wheel passes treatments. ST-strip tillage, ST200-strip tillage with 200 kg load, CT-conventional tillage, No traffic- undisturbed soil in 2016 at Alipur, Rajshahi . The infiltration data were fitted to Horton's model.

Chickpea emergence

Chickpea plant emergence was significantly ($P<0.05$) affected by the main effects of tillage or loading weight and the main effect of number of wheel passes at Alipur in 2016 (Figure 4.18). Percent plant emergence was significantly higher under CT (83 %) than that under ST (71 %) and ST200 (67 %). Furthermore, CT gave higher plant emergence compared to the No traffic plot (72 %). There were no significant differences in plant emergence values under ST vs ST200, ST vs No traffic and ST200 vs No traffic. The ST200 -4Pass treatment gave significantly lower plant emergence (64 %) than the No traffic plot. The ST-4Pass treatment (67 %) gave a statistically similar plant emergence compared to No traffic plot.

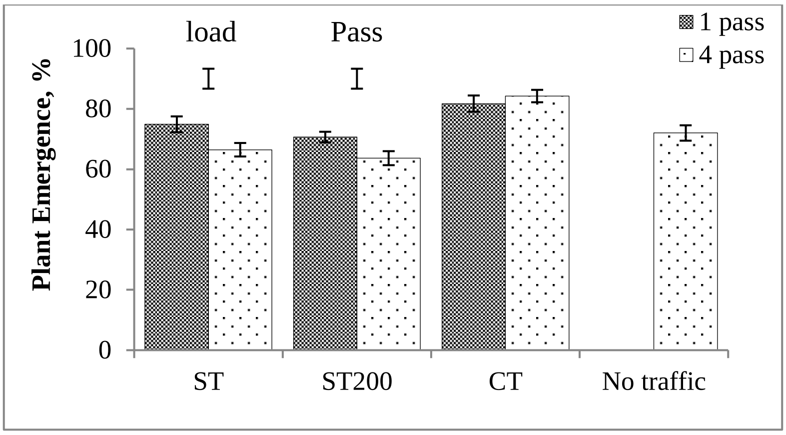


Figure 4.18 Tillage, loading weight, and number of wheel passes treatment effects on chickpea plant emergence (%) at Alipur in 2016 . ST= Strip tillage, ST200= Strip tillage with 200 kg load, CT= Conventional tillage, No Traffic= Undisturbed soil (control). (percentage plant emergence was calculated from 710 seeds sown on each plot). The floating bar indicates the average least significant difference at 5 % level of significance.

Experiment 3

4.3.3 Digram 2016

Effect of tillage, loading weight and number of wheel passes on bulk density

The soil BD was affected significantly ($P<0.05$) by the loading weight × number of wheel passes interaction in the 0-5 cm depth (Figure 4.19). The ST-4Pass treatment induced an increase in soil BD by 0.08 g cm^{-3} over the ST-1Pass. Similarly, ST200-4Pass treatment increased soil BD by 0.07 g cm^{-3} compared to ST200-1Pass treatment. However, adding an extra 200 kg load to the ST, i.e. the ST200 treatment, increased BD by 0.04 g cm^{-3}. The CT-4Pass treatment reduced BD by 0.03 g cm^{-3} over CT-1Pass. Furthermore, all loading weights and number of wheel passes increased BD compared to No traffic, while both CT-1Pass and CT-4Pass decreased BD compared to No traffic plot.

In the 5-10 cm depth, the CT-1Pass treatment increased BD by 0.06 g cm^{-3} with a further increment of 0.09 g cm^{-3} under CT-4Pass treatment compared to undisturbed soil under No traffic treatment. The ST-4Pass treatment increased BD by 0.06 g cm^{-3} over ST-1Pass, and ST200-4Pass increased BD by 0.04 g cm^{-3} over ST200-1Pass. The CT-4Pass treatment increased BD by 0.03 g cm^{-3} over CT-1Pass. There was no significant effect of tillage, loading weight, or number of wheel passes treatments on the BD in the 10-15 soil depth.

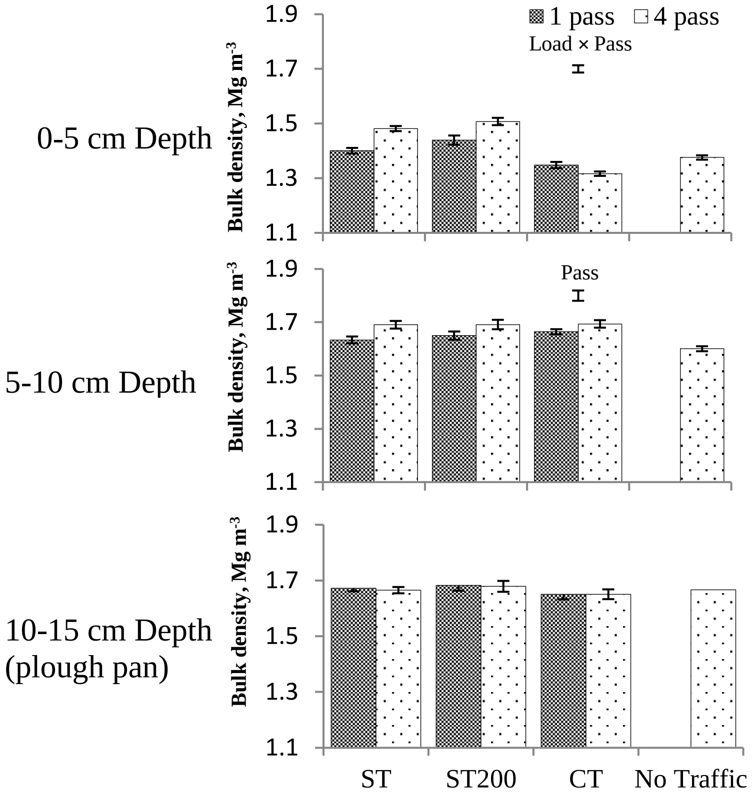


Figure 4.19 Mean bulk density of Digram soil as affected by different tillage, loading weight, and number of wheel passes treatments at three depths. ST= Strip tillage, ST200= Strip tillage with 200 kg load, CT= Conventional tillage, No traffic= Undisturbed soil (control).

Relationship between penetration resistance measured in the laboratory and soil water content

As in the Alipur soil, PR values for Digram soil was also significantly correlated to SWC (Figure 4.20 to Figure 4.22). The PR decreased with an increase in SWC, as expected. An exponential model of PR and SWC were able to explain 70-90 % of the variability in PR.

0-5 cm Digram

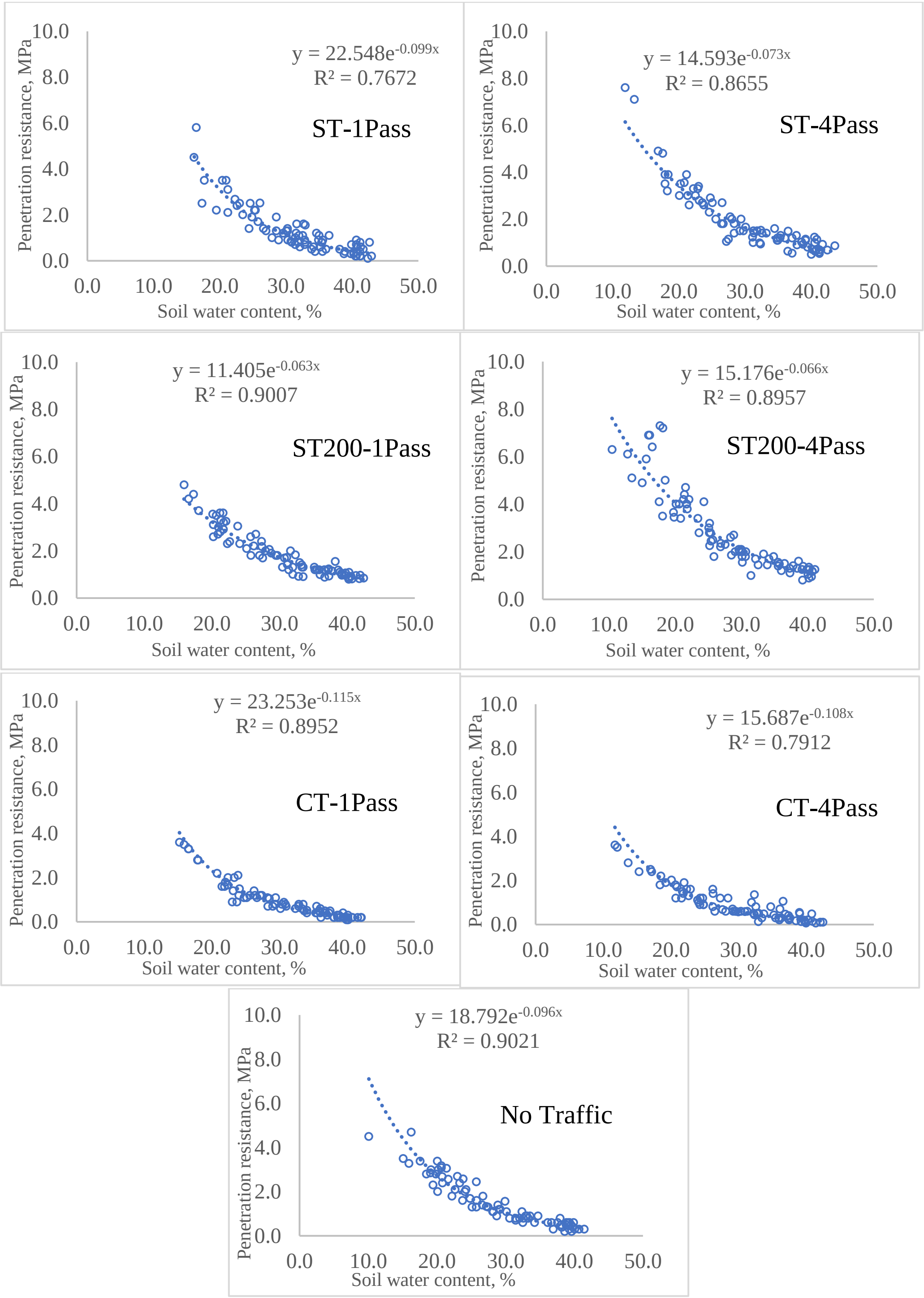


Figure 4.20 Penetration resistance values plotted against soil water content for 0-5 cm depth at Digram 2016. ST= Strip tillage, ST200=Strip tillage with 200 kg load, CT= Conventional tillage.

5-10 cm Digram

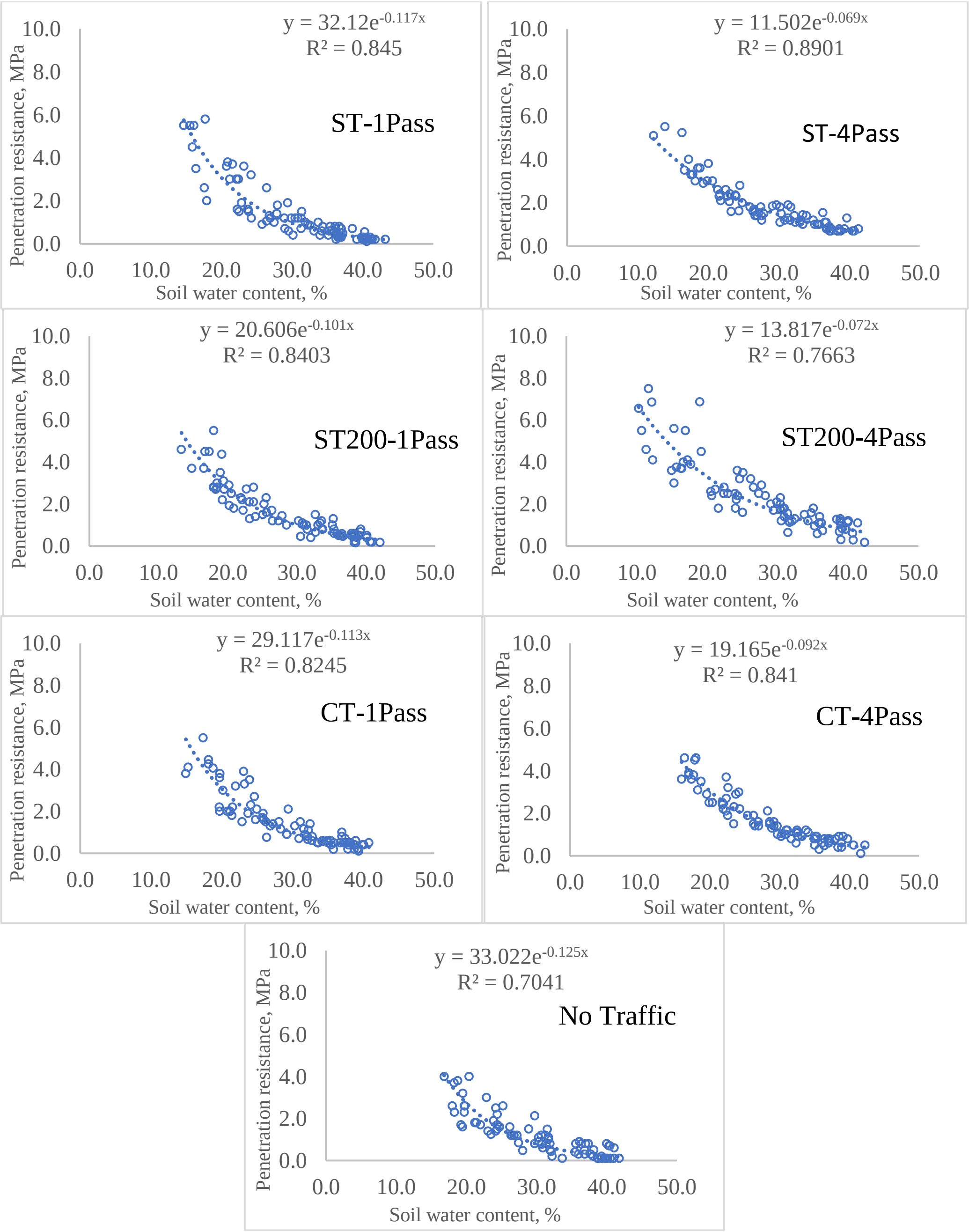


Figure 4.21 Penetration resistance values plotted against soil water content for 5-10 cm depth at Digram 2016. ST= Strip tillage, ST200=Strip tillage with 200 kg load, CT= Conventional tillage.

10-15 cm Digram

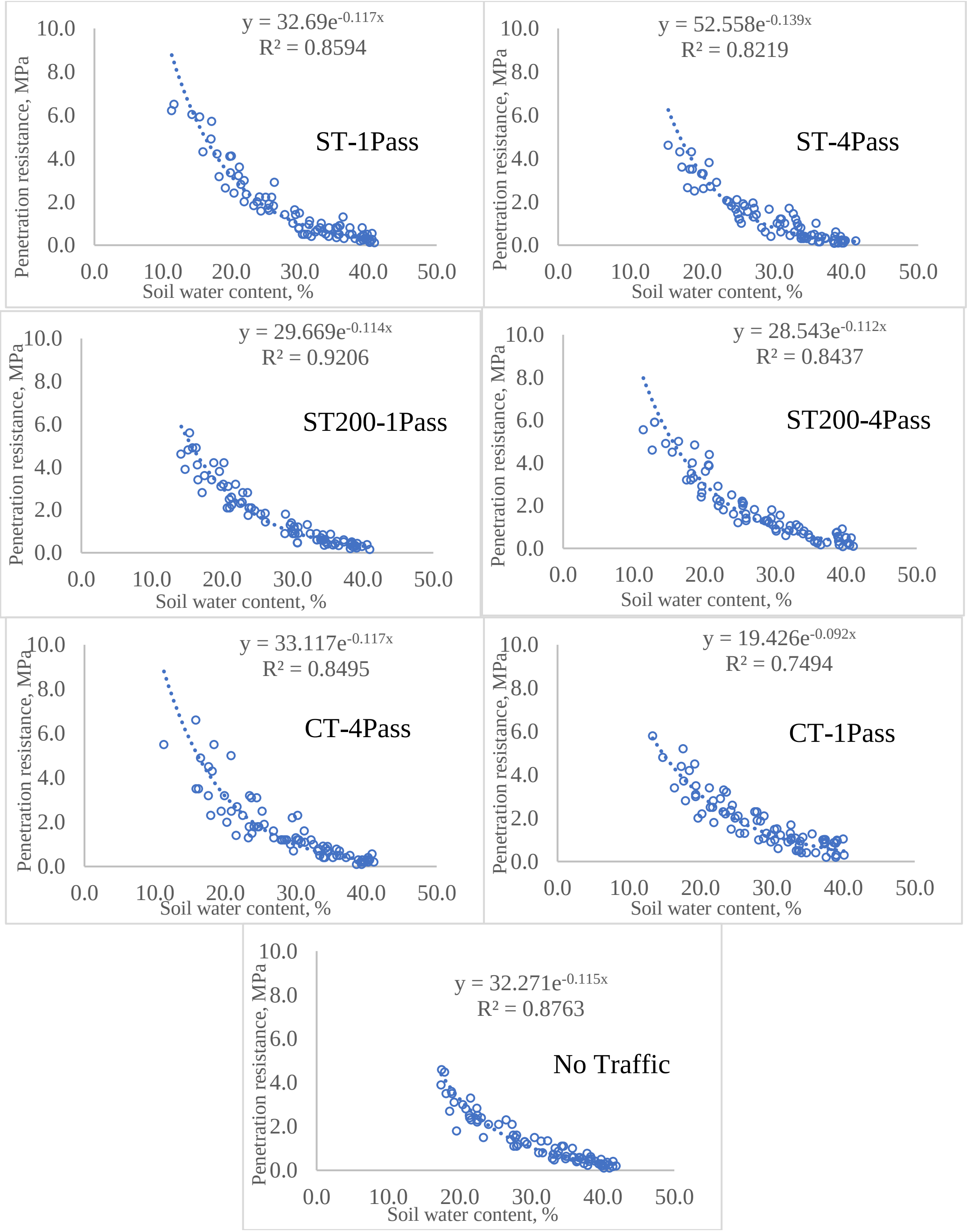


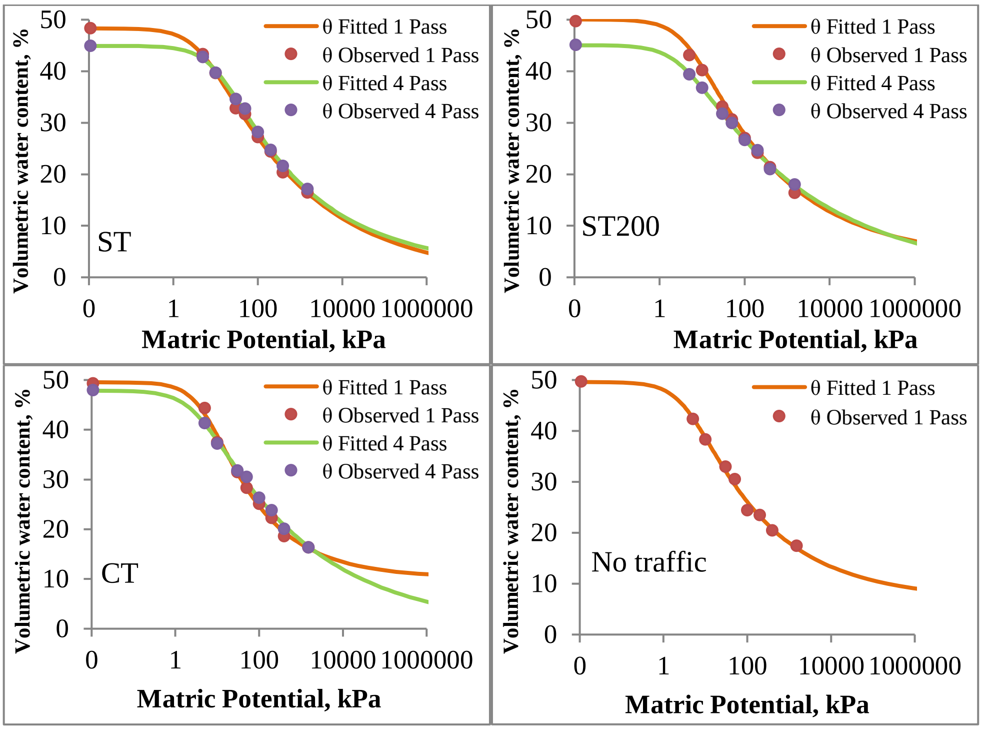
Figure 4.22 Penetration resistance values plotted against soil water content for 10-15 cm depth at Digram 2016. ST= Strip tillage, ST200=Strip tillage with 200 kg load, CT= Conventional tillage.

Soil water retention curve

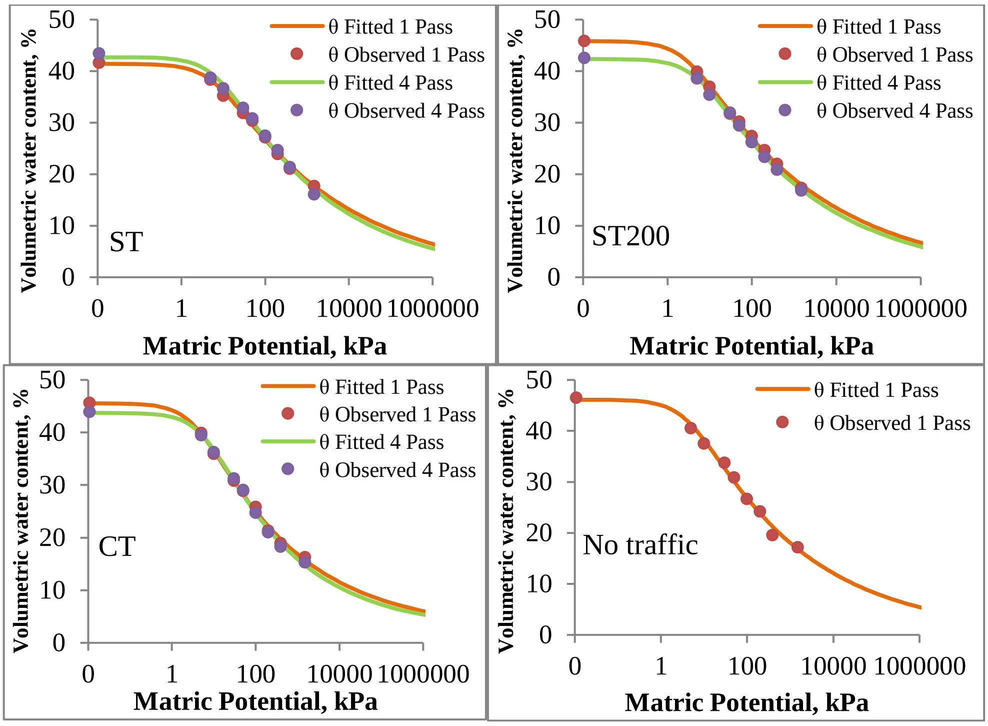
The main effect of number of passes was significant on water content between 0 to -5 kPa matric potential but not at lower (more negative) potential (

Figure 4.23). At –10 kPa, the matric potential water content of ST200-4Pass soil was significantly lower (39.4 %) than the water content of the soil under ST200-1Pass (43.1 %). The results suggest that increased BD by four passes decreased the water content at – 10 kPa. However, despite the significant lower BD, CT-4Pass had lower water content (41.3 %) at – 10 kPa matric potential. There was no significant effect of tillage, loading weight or number of wheel passes on water retention in the 0 to – 1500 kPa tension range in the 5-10 cm or 10-15 cm soil depths.

0-5 cm depth Digram



5-10 cm depth Digram



10-15 cm depth Digram

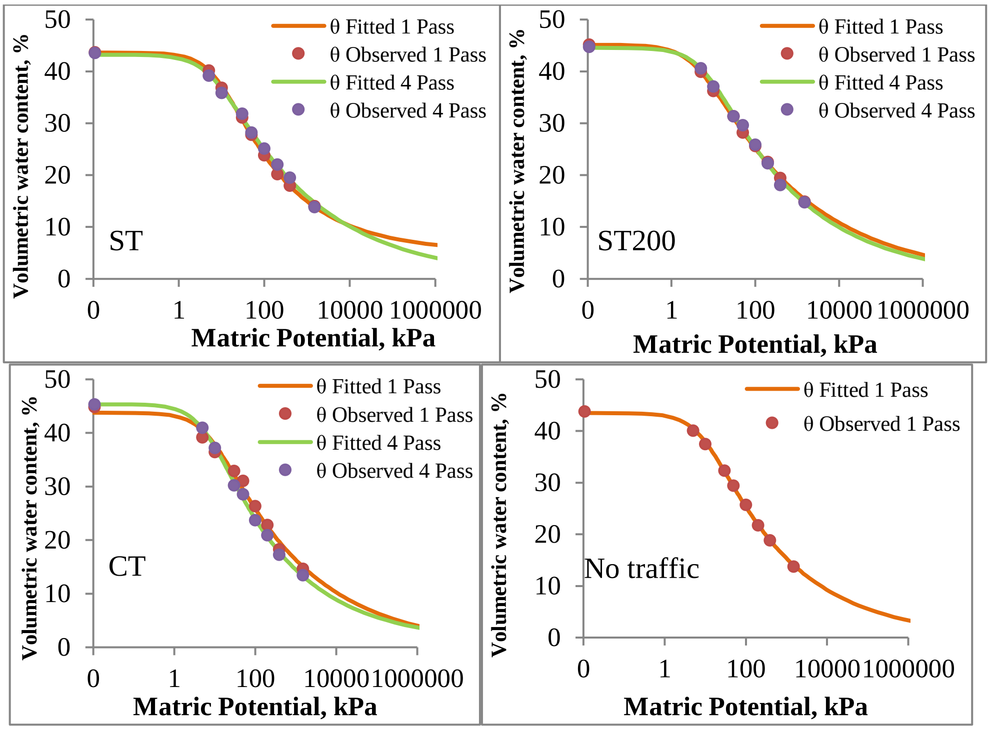


Figure 4.23 Water retention curve under different treatments in three depths at Digram 2017. ST= Strip tillage, ST200=Strip tillage with 200 kg load, CT= Conventional tillage.

Penetration resistance at soil water contents at sowing, field capacity, and permanent wilting point

Comparison of PR values for different tillage, loading weight, and number of wheel passes treatment for three depths for SWC at sowing (θ_{Sow}), field capacity (θ_{FC}) and permanent wilting point (θ_{PWP}) are presented in Table 4.10, Table 4.11, and Table 4.12. For comparison purposes, PR values were adjusted with the help of the corresponding PR vs SWC curves shown in Figure 4.20, Figure 4.21, and Figure 4.22.

Penetration resistance at 0-5 cm depth estimated from the PR vs SWC relationship

Penetration resistance estimated for θ_{Sow}

The ST200-4Pass treatment increased PR by 0.5 MPa over ST200-1Pass (Table 4.10), while ST200-4Pass over ST-4Pass increased PR by 0.6 MPa. The CT-4Pass treatment significantly reduced PR by 0.2 MPa over CT-1Pass.

Penetration resistance estimated for θ_{FC}

The interaction effect of tillage or loading weight × the number of wheel passes was significant on PR at θ_{FC}. Penetration resistance under ST-1Pass was 0.9 MPa which was increased by 0.3 MPa for an extra three passes and increased by 0.5 MPa by adding an extra 200 kg load. With an extra three wheel passes under ST200-4Pass, PR increased by 0.5 MPa compared to ST200-1Pass. However, there was no significant difference in PR values between CT-1Pass and CT-4Pass. The differences in PR between ST200-4Pass and ST-4Pass was 0.7 MPa.

Penetration resistance estimated for θ_{PWP}

At θ_{wp}, the interaction effect of tillage or loading weight × the number of wheel passes was significant on PR. The difference in PR values between ST200-4Pass and ST200-1Pass was 0.7

MPa, while the difference between ST200-4Pass and ST-4Pass was 0.6 MPa. The CT-4Pass treatment reduced PR values by 0.9 MPa compared to CT-1Pass.

Penetration resistance at 5-10 cm depth estimated from the PR vs SWC relationship

Penetration resistance estimated for θ_{Sow}

At θ_{sow}, PR increased by 0.6 MPa under ST200-4Pass compared to ST200-1Pass, and PR increased by 0.4 MPa under ST-4Pass compared to ST-1Pass. The CT-4Pass treatment also increased PR by 0.2 MPa compared to CT-1Pass at this depth. The CT-4Pass treatment increased PR at this depth by 0.4 MPa compared to undisturbed soil at this depth under No traffic treatment.

Penetration resistance estimated for θ_{FC}

The CT-4Pass treatment increased PR significantly by 0.3 MPa compared to CT-1Pass. Penetration resistance increased by 0.5 MPa under ST200-4Pass compared to ST200-1Pass and PR increased by 0.4 MPa under ST-4Pass compared to ST-1Pass. At this depth, CT-4Pass increased PR values by 0.6 MPa compared to undisturbed soil at this depth under No traffic treatment.

Penetration resistance estimated for θ_{PWP}

There was no significant effect of tillage, loading weight, and number of wheel passes treatment on the PR in the 5-10 cm soil depth at $\theta_{PWP.}$

Penetration resistance at 10-15 cm depth estimated from the PR vs SWC relationship

There was no significant effect of tillage, loading weight, and number of wheel passes in the 10-15 cm soil depth. The highest PR values in 10-15 cm soil depth compared to the top two soil depths under the No traffic treatment suggest the presence of a plough pan at this depth.

Table 4.10 Penetration resistance for different tillage, loading weight, and number of wheel passes treatment at different soil water content in the 0-5 cm soil, Digram 2016.

Depth 0-5 cm, θ_{Sow} = 26.4 % vol

Treatments	**PR_{sow}, MPa**	**θ_{FC}, %**	**PR_{FC}, MPa**	**θ_{PWP}, %**	**PR_{PWP}, MPa**
ST-1 Pass	1.6	39.62	0.9	16.44	4.4
ST-4 Pass	2.1	39.68	1.2	17.14	4.2
ST200-1Pass	2.2	40.2	1.4	16.39	4.1
ST200-4Pass	2.7	36.76	1.9	17.98	4.8
CT-1Pass	1.1	37.45	0.6	16.33	3.6
CT-4Pass	0.9	37.21	0.6	16.35	2.7
No traffic	1.5	38.28	0.8	17.42	3.7
P_{load}	<0.001		<0.001		<0.001
P_{Pass}	<0.001		0.001		ns
$P_{load \times Pass}$	<0.001		0.006		0.04
$LSD_{0.05}$ Average	0.1		0.1		0.41

$LSD_{0.05}$=Average least significant difference for Residual Maximum Likelihood (REML) for all main and interaction effect (see the section for statistical method). ST= Strip tillage, ST200=Strip tillage with 200 kg load, CT= Conventional tillage. θ_{FC}= Soil water content at field capacity, PR_{FC}=Penetration resistance at θ_{FC}, θ_{PWP}= Soil water content at permanent wilting point, PR_{PWP}= Penetration resistance at θ_{PWP}, PR_{sow}= Penetration resistance for soil water content at sowing.

Table 4.11 Penetration resistance for different tillage, loading weight, and number of wheel passes treatment at different soil water content in the 5-10 cm soil, Digram 2016.

Depth 5-10 cm, θ_{Sow} = 27.1 % vol

Treatments	PR_{sow}, MPa	θ_{FC}, %	PR_{FC}, MPa	θ_{PWP}, %	PR_{PWP}, MPa
ST-1 Pass	1.4	35.22	0.8	17.68	4.5
ST-4 Pass	1.8	36.65	1.2	16.08	3.8
ST200-1Pass	1.4	36.95	0.9	17.31	4.0
ST200-4Pass	2.0	35.41	1.4	16.82	4.5
CT-1Pass	1.4	35.92	0.9	16.28	4.9
CT-4Pass	1.6	36.25	1.2	15.29	4.6
No traffic	1.2	37.51	0.6	17.19	4.4
P_{load}	ns		ns		ns
P_{Pass}	0.006		0.002		ns
$P_{load\times Pass}$	ns		ns		ns
$LSD_{0.05}$ Average	0.2		0.2		ns

$LSD_{0.05}$=Average least significant difference for Residual Maximum Likelihood (REML) for all main and interaction effect (see the section for statistical method). ST= Strip tillage, ST200=Strip tillage with 200 kg load, CT= Conventional tillage. θ_{FC}= Soil water content at field capacity, PR_{FC}=Penetration resistance at θ_{FC}, θ_{PWP}= Soil water content at permanent wilting point, PR_{PWP}= Penetration resistance at θ_{PWP}, PR_{sow}= Penetration resistance for soil water content at sowing.

Table 4.12 Penetration resistance for different tillage, loading weight, and number of wheel passes treatment at different soil water content in the 10-15 cm soil, Digram 2016.

Depth 10-15 cm, θ_{Sow} = 27.5 % vol

Treatments	**PR_{sow}, MPa**	**θ_{FC}, %**	**PR_{FC}, MPa**	**θ_{PWP}, %**	**PR_{PWP}, MPa**
ST-1 Pass	1.4	36.86	1	14.03	7.4
ST-4 Pass	1.2	35.86	0.7	13.86	7.9
ST200-1Pass	1.3	36.20	0.9	14.91	5.5
ST200-4Pass	1.4	37.06	0.9	14.78	6.8
CT-1Pass	1.6	36.44	1	14.67	5.5
CT-4Pass	1.4	37.21	1	13.45	7.3
No traffic	1.4	37.45	0.8	13.74	6.8
P_{load}	ns		ns		ns
P_{Pass}	ns		ns		ns
$P_{load\times Pass}$	ns		ns		ns
$LSD_{0.05}$ Average	ns		ns		ns

$LSD_{0.05}$=Average least significant difference for Residual Maximum Likelihood (REML) for all main and interaction effect (see the section for statistical method). ST= Strip tillage, ST200=Strip tillage with 200 kg load, CT= Conventional tillage. θ_{FC}= Soil water content at field capacity, PR_{FC}=Penetration resistance at θ_{FC}, θ_{PWP}= Soil water content at permanent wilting point, PR_{PWP}= Penetration resistance at θ_{PWP}, PR_{sow}= Penetration resistance for soil water content at sowing.

Least limiting water range and plant available water content for mean bulk density values

Table 4.13 presents LLWR of Digram soil under seven treatments at three soil depths. The limits of θ_{FC}, θ_{AFP}, θ_{PWP} and θ_{PR} used to calculate the LLWR, PAW and the percentage reduction in PAW with the LLWR are also presented. As shown in the table with the bold type text, the θ_{FC} was the upper limit of the LLWR under CT treatment either with one pass or four passes at the 0-5 cm depth. But unlike Alipur soil, the lower limit of the LLWR under CT-1Pass or CT-4Pass treatments was θ_{PR}. For all other treatments and depths, the upper and lower limits of the LLWR was respectively the θ_{AFP} and θ_{PR}.

Averaged across the number of passes, LLWR decreased in the order: CT>No traffic>ST>ST200 in the 0-5 cm soil depth. Considering loading weight treatments, four passes gave smaller LLWR than one pass at 0-5 cm and 5-10 cm soil depth. Considering CT treatments, four passes gave wider LLWR than one pass at 0-5 cm, but at 5-10 cm depth, four passes gave smaller LLWR than one pass. In the 0-5 cm depth, the magnitude of LLWR for the Digram soil varied between 6 % and 17 %, with the highest value in the CT-4Pass treatments, but there was a sharp decline in LLWR in the 5-10 cm soil depth (3 to 8%) and 10-15 cm soil depth (4 to 6%). The percentage reduction in PAW ranged from 3 to 69 % considering all seven treatments at 0-5 cm depth.

Table 4.13 The least limiting water range (LLWR) and the limits of volumetric water content used in the calculation of the LLWR at Digram in 2016

Treatments	**Depth**	**θ_{FC}, %**	**θ_{AFP}, %**	**θ_{PWP}, %**	**θ_{PR}, %**	**LLWR, %**	**PAW, %**	**Reduction to PAW %**
ST-1 Pass	1	39.62	**37.15**	16.44	**22.22**	14.94	23.18	35.57
	2	35.22	**28.35**	17.68	**21.82**	6.53	17.54	62.77
	3	36.86	**26.89**	14.03	**21.97**	4.92	22.83	78.46
ST-4 Passes	1	39.68	**34.06**	17.14	**24.17**	9.89	22.54	56.12
	2	36.65	**26.20**	16.08	**22.12**	4.08	20.57	80.15
	3	35.86	**27.16**	13.86	**21.91**	5.24	22.00	76.16
ST200-1Pass	1	40.20	**35.69**	16.39	**24.09**	11.59	23.82	51.32
	2	36.95	**27.74**	17.31	**20.88**	6.86	19.64	65.09
	3	36.20	**26.49**	14.91	**21.70**	4.79	21.29	77.48
ST200-4Pass	1	36.76	**33.11**	17.98	**27.32**	5.79	18.78	69.18
	2	35.41	**26.17**	16.82	**23.74**	2.42	18.59	86.95
	3	37.06	**26.64**	14.78	**21.74**	4.90	22.29	78.01
CT-1Pass	1	**37.45**	39.12	16.33	**19.39**	18.06	18.06	0.00
	2	35.92	**27.19**	16.28	**21.73**	5.46	19.64	72.18
	3	36.44	**27.74**	14.67	**22.29**	5.45	21.77	74.97
CT-4Pass	1	**37.21**	40.32	16.35	**17.01**	20.20	20.20	0.00
	2	36.25	**26.08**	15.29	**22.14**	3.94	20.96	81.19
	3	37.21	**27.71**	13.45	**22.08**	5.63	23.77	76.32
No traffic	1	38.28	**38.09**	17.42	**21.01**	17.08	20.86	18.14
	2	37.51	**29.51**	17.19	**20.65**	8.86	20.33	56.41
	3	37.45	**27.10**	13.74	**22.24**	4.86	23.72	79.50

θ_{FC}= Soil water content at field capacity, determined from the water retention curve, θ_{AFP}=Soil water content at 10 % air-filled porosity, θ_{PWP}= soil water content at permanent wilting point, determined from the water retention curve, θ_{PR}= Soil water content at PR value of 2.5 MPa, calculated from the SWC vs PR relationship. LLWR= Least limiting water range, PAW= Plant available water content.

The LLWR was negatively related to BD values for all treatments at all depths (Figure 4.24). The negative slope of the trend lines shows the line for 0-5 cm depth was steeper than the other two lines. The LLWR was the highest (20.21 %) at BD of 1.32 g cm^{-3} under CT treatment in 0-5 cm depth.

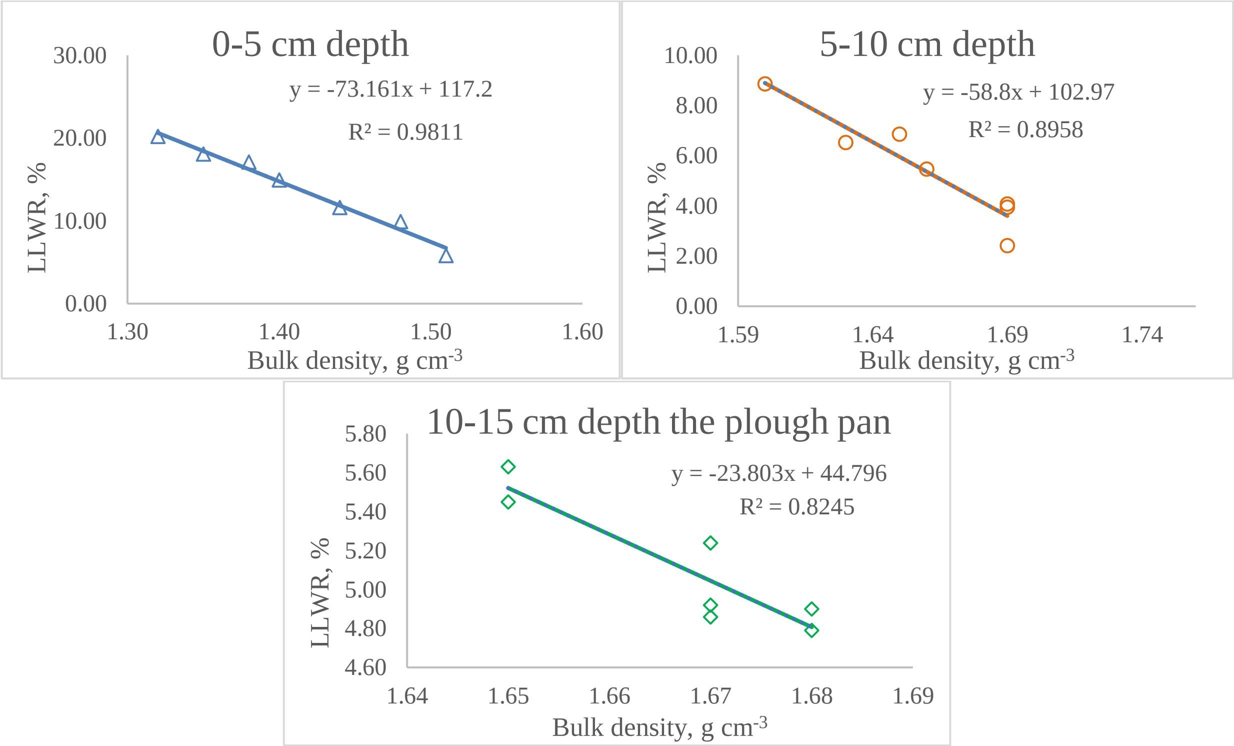


Figure 4.24 Relationship of least limiting water range (LLWR) to BD for 0-5 cm, 5-10 cm and 10-15 cm soil depths for different tillage, loading weight, and number of wheel passes treatments in Digram.

Saturated hydraulic conductivity

The main effect of tillage or loading weight treatment and the main effect of number of wheel passes was significant ($P<0.05$) on the saturated hydraulic conductivity, K_{sat} (Figure 4.25). Taking the average across the number of wheel passes, K_{sat} under ST and ST200 was 0.63 cm h^{-1} and 0.75 cm h^{-1}, respectively, and both were significantly lower than under CT (1.66 cm h^{-1}) (Figure 4.25). However, K_{sat} under ST and ST200 was not different, and both were similar to No traffic treatment

(1.01 cm h^{-1}). This finding suggests that putting additional load on the vehicle resulted in no significant differences in the K$_{sat}$ values of ST treatments.

The K$_{sat}$ values under ST and ST200 with single wheel pass were 0.96 cm h$^{-1,}$ and 1.03 cm h^{-1}, respectively, which was reduced by four wheel passes to 0.29 cm h^{-1} and 0.47 cm h^{-1} respectively. The ST and ST200 treatment with four wheel passes gave significantly lower K$_{sat}$ compared to No traffic. However, CT-4Pass (1.74 cm h^{-1}) did not increase K$_{sat}$ compared to CT-1Pass (1.58 cm h^{-1}). The K$_{sat}$ values were 58 % and 74 % higher under CT-1 Pass and CT- 4 Pass, respectively, compared to that under No traffic treatment. There were no significant differences in K$_{sat}$ values under different treatments at the plough pan (10-15 cm).

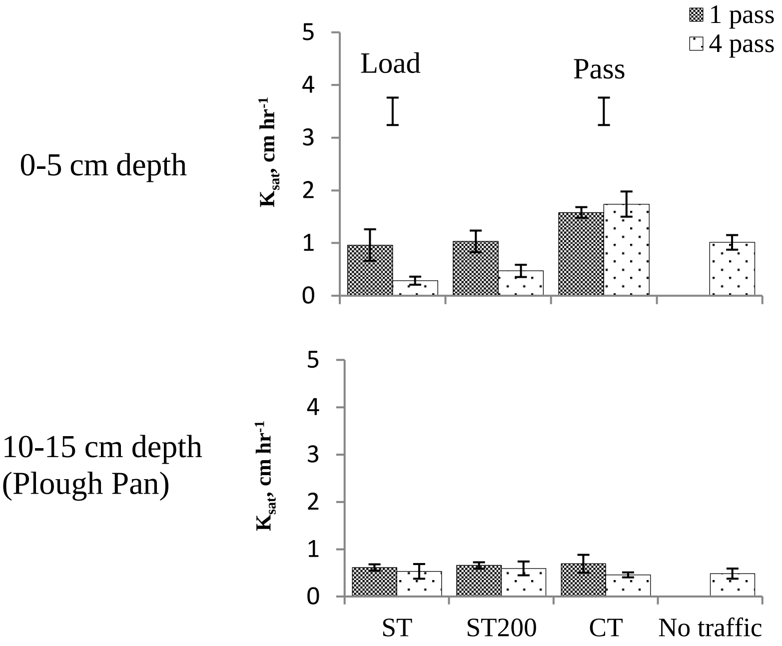


Figure 4.25 Wheel traffic effects on saturated hydraulic conductivity (K$_{sat}$) at Digram in 2016. ST= Strip Tillage, ST200= Strip tillage with 200 kg load, CT= Conventional tillage, No traffic= Undisturbed soil (control). The floating bar indicates the average least significant difference at 5 % level of significance.

Infiltration rate and cumulative infiltration

CT-1Pass showed the highest mean initial infiltration rate after 10 minutes (0.34 cm min^{-1}), whereas the lowest was obtained in the ST200-4Pass treatment (0.05 cm min^{-1}). After 10 min, there was a reduction in infiltration rates in all treatments, but the reduction was sharp under the loading weight treatments compared to that under tillage treatments (Figure 4.26). In the loading weight treatments (ST and ST200), the initial infiltration rates under four pass started approaching a steady value sooner (approximately 20 min after the start of the run) than the single pass (about 60-70 min). In the case of CT and the No traffic plot, the infiltration rates started approaching the steady-state after approximately 100 min.

Under loading weight treatments (ST and ST200), the steady-state infiltration rate in single wheel pass treatment was five times higher than that in four wheel pass treatment. The mean steady-state infiltration rate was significantly higher under CT plots than under ST and ST200 plots (Table 4.14). However, there were no significant differences in infiltration rates between CT-1Pass and CT-4Pass.

The mean cumulative infiltration at the end of 240 min was also higher in the CT plots than under the ST and ST200 plots. Cumulative infiltration decreased significantly with ST-4Pass and ST200-4Pass by 83 % and 88 %, respectively, over No traffic treatment.

Table 4.14 Effect of tillage, loading weight, and number of wheel passes on soil infiltration characteristics taken in 2017 at Digram, Rajshahi.

Tillage or loading weight treatments	Infiltration characteristics					
	Initial (i_i) (cm min^{-1})		Steady-state (i_s) (cm min^{-1})		Cumulative (I) (cm min^{-1})	
	1 Pass	4 Pass	1 Pass	4 Pass	1 Pass	4 Pass
ST	0.26	0.06	0.06	0.01	22.5	4.4
ST200	0.26	0.05	0.05	0.01	15.6	3.2
CT	0.34	0.40	0.11	0.12	37.9	42.5
No traffic	0.31		0.08		26.2	
$LSD_{0.05}$ Average	0.11		0.04		9.0	

i_i = initial infiltration after 10 min, i_s = Steady-state infiltration, mean of last 60 minutes infiltration rate, I= Cumulative infiltration after 240 minutes. All data are mean of four replicates. $LSD_{0.05}$=Average least significant difference for Residual Maximum Likelihood (REML) for all main and interaction effect (see section 4.2.10). ST= Strip tillage, ST200=Strip tillage with 200 kg load, CT= Conventional tillage.

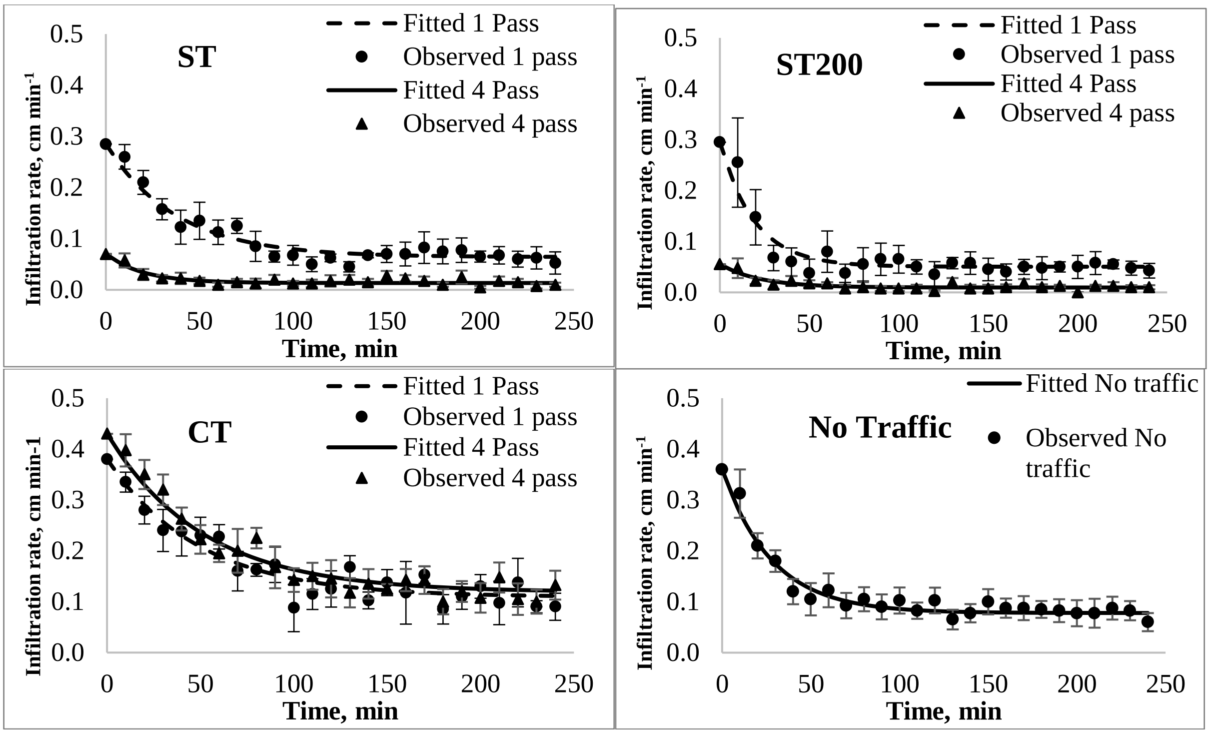


Figure 4.26 Infiltration curves for different tillage, loading weight, and number of wheel passes. ST=strip tillage, ST200=strip tillage with 200 kg load, CT=conventional tillage, No traffic- undisturbed soil. The infiltration data were fitted to the Horton model.

Chickpea emergence

Percent chickpea emergence for all tillage, loading wight, and number of wheel passes compared to No traffic plot at Digram in 2016 is presented in Figure 4.27. Per cent plant emergence was significantly (P<0.05) affected by the main effect of both tillage or loading weight treatment and the main effect of number of wheel passes. Taking the average across the number of wheel passes, percent plant emergence was significantly higher under CT (81 %) than under ST (62 %). Plant emergence was also higher under CT than that under ST200 (58 %). Plant emergence under No traffic (68 %) was intermediate between CT and ST200. There were no significant differences between the plant emergence under ST-1Pass and No traffic treatment. However, ST-4Pass gave significantly lower plant emergence than the No traffic plot. Similarly, ST200-4Pass gave lower plant emergence than that under No traffic treatment.

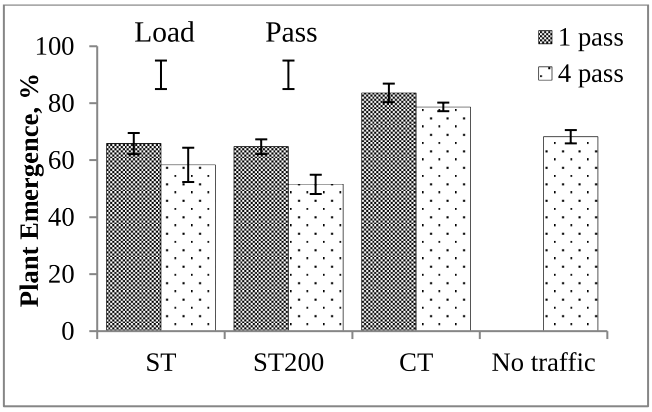


Figure 4.27 Wheel traffic effects on chickpea plant emergence (%) at Digram in 2016. ST= Strip Tillage, ST200= Strip tillage with 200 kg load, CT= Conventional tillage, No traffic= Undisturbed soil (control). (percentage plant emergence was calculated from 710 seeds sown on each plot). Floating bars indicates the least significant difference at 5 % level of significance.

Experiment 4

4.3.4 Thakurgaon 2017

BD and Chickpea emergence in Thakurgaon under different tillage, loading weight, and number of wheel passes treatments and three soil water contents

Effects of tillage or loading weight treatment were significant on the BD (Table 4.15) at all three SWC. The difference in BD values was observed between the compacted soil and the tilled soil with significantly lower BD values under CT. There was no significant effect of tillage or loading weight treatment, or number of wheel passes on the plant emergence in Thakurgaon soil. However, a significant effect of water content ($P<0.001$, LSD=2.46) on chickpea plant emergence was observed. Under 29 % SWC, 81 % of chickpea emerged, which was significantly higher than the plant emergence under 26 % water content (71 %). Averaged across all tillage or loading weight treatments, 21 % SWC gave 62 % chickpea emergence.

Table 4.15 Effect of different tillage, loading weight, and number of wheel passes treatment on Thakurgaon soil bulk density and chickpea emergence under three soil water content.

(A)

Treatment	Vol Water content, %		Bulk density, g cm^{-3}		% Chickpea Emergence
	Before Treatment	After Treatment	Before Treatment	After Treatment	
ST-1 Pass	29.8	29.2	1.30	1.40	80.8
ST-4 Passes		29.6		1.40	77.5
ST200-1Pass		29.3		1.36	83.9
ST200-4Pass		29.4		1.43	75.0
CT-1Pass		29.5		1.28	83.4
CT-4Pass		29.0		1.23	84.0
P_{Load}		ns		0.003	ns
P_{Pass}		ns		ns	Ns
$P_{Load \times Pass}$		ns		ns	Ns
$LSD_{0.05}$ Average		ns		0.07	Ns

(B)

Treatment	Vol Water content, %		Bulk density, g cm^{-3}		% Chickpea Emergence
	Before Treatment	After Treatment	Before Treatment	After Treatment	
ST-1 Pass	26.3	26.1	1.34	1.42	73.7
ST-4 Passes		25.1		1.42	72.9
ST200-1Pass		25.4		1.38	70.5
ST200-4Pass		25.8		1.45	69.2
CT-1Pass		25.4		1.30	73.4
CT-4Pass		25.6		1.22	67.3
P_{Load}		ns		0.003	ns
P_{Pass}		ns		ns	ns
$P_{Load \times Pass}$		ns		ns	ns
$LSD_{0.05}$ Average		ns		0.08	ns

(C)

Treatment	**Vol Water content, %**		**Bulk density, g cm^{-3}**		**% Chickpea Emergence**
	Before Treatment	**After Treatment**	**Before Treatment**	**After Treatment**	
ST-1 Pass	21.9	21.8	1.32	1.32	62.0
ST-4 Passes		20.6		1.39	65.3
ST200-1Pass		21.8		1.39	60.4
ST200-4Pass		21.9		1.41	58.6
CT-1Pass		21.4		1.30	64.8
CT-4Pass		21.7		1.28	62.2
P_{Load}		ns		0.015	ns
P_{Pass}		ns		ns	ns
$P_{Load \times Pass}$		ns		ns	ns
$LSD_{0.05}$ Average		ns		0.06	ns

$LSD_{0.05}$=Average least significant difference for Residual Maximum Likelihood (REML) for all main and interaction effect (see the section for statistical method). ST= Strip tillage, ST200=Strip tillage with 200 kg load, CT= Conventional tillage.

Bulk density vs Penetration resistance determined in experiment 2 and 3 for Alipur and Digram soil

A positive relationship was found between BD and PR at the 0-5 cm depth for both Alipur and Digram soil (Figure 4.28). The Relationship is (correlation coefficient) significant at the 0-5 cm depth. At the 5-10 cm depth, the relationship was significant at Digram soil only. At 10-15 cm depth, the relationship is not significant at either of the locations. The regression showed that the trend line for Digram soil was steeper than that for Alipur soil. These results showed that Digram soil is more responsive to wheel compaction than Alipur soil.

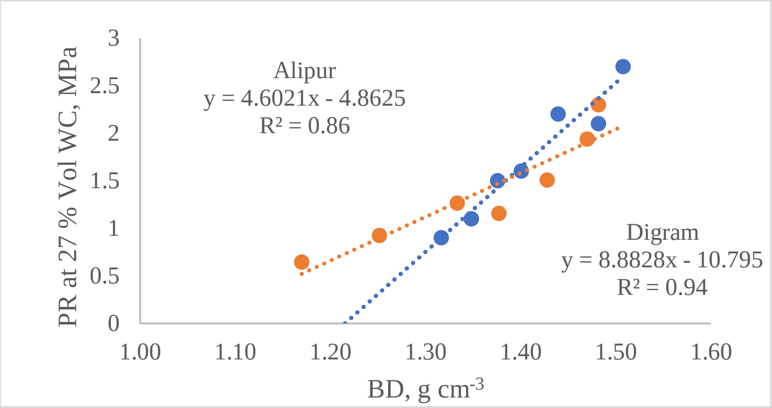


Figure 4.28 Relationship between BD and PR for Alipur and Digram Soil as found from experiment 2 and 3. The orange dots represent the values for Alipur soil, and the blue dots represent the values for Digram soil. The equation represents the regression for the BD and the PR values.

Bulk density vs steady-state infiltration rate as determined from experiment 2 and 3 for Alipur and Digram soil

Steady-state infiltration rate was negatively and significantly correlated to the BD values for both soils (Figure 4.29). The relationship shows that the trendline is steeper in the case of Digram soil compared to the Alipur soil.

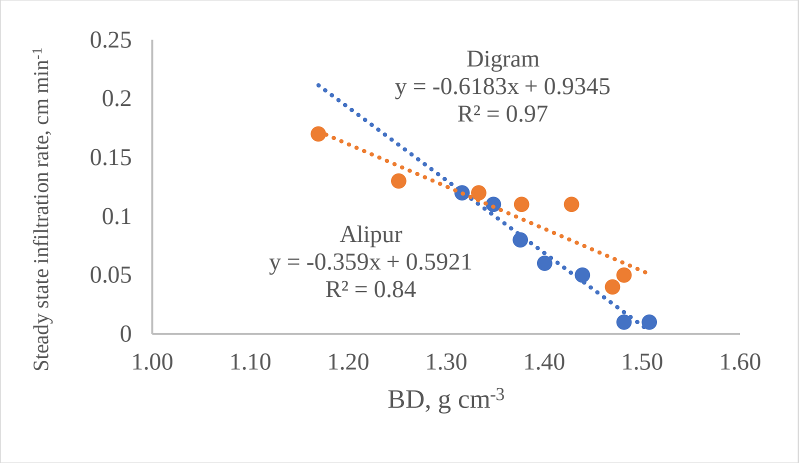


Figure 4.29 Relationship between BD and steady-state infiltration rate for Alipur and Digram Soil 0-5 cm depth. The orange dots represent the values for Alipur soil, and the blue dots represent the values for Digram soil. The equation represents the regression for the BD and the infiltration values.

4.4 Discussion

Larger values of the BD and higher PR compared to the No traffic treatment soil and reduced saturated hydraulic conductivity demonstrated soil compaction by a light tractor, especially with four wheel traffic passes in both soils. Soil compaction was observed in wheel tracks of the investigated Alipur and Digram soils, only above the depth of most frequent tillage (generally 0-10 cm), in what is defined as the topsoil. The soil below the tillage depth, where there is evidence of a plough pan, which also represents the subsoil, was not disturbed by the wheels even with four wheel traffic passes.

4.4.1 Effect of tillage, loading weight, and number of wheel passes on soil physical properties

Bulk density

Bulk density of 0-5 cm depth under single pass CT treatment in silty clay loam soil was 1.35 g cm^{-3} which was 1.40 g cm^{-3} under single wheel pass with ST (Figure 4.19). Higher values of BD under single wheel pass treatment compared to single pass CT treatment indicated even single wheel pass with a light 2-WT of 4.02 kN could reverse the effect of soil tillage by increasing PR from 1.1 kPa to 1.6 kPa (Table 4.1). Topsoil compaction as a result of a single wheel pass of the light tractor is reported by Daveiga *et al.* (2007), who found that even one traffic pass with a light tractor (28 kN) after the chiselling reduced the beneficial effect of previous tillage drastically.

Soil BD of silty loam soil at Alipur with single wheel pass was 1.37 g cm^{-3}, which increased to 1.40 g cm^{-3} at two passes, and further increased to 1.47 g cm^{-3} with four passes indicating BD increased linearly with the increase in number of passes (Figure 4.10). The linear relationship between BD and number of passes is in accordance with those found by Botta *et al.* (2009). Increases in soil BD and PR as the evidence of soil compaction due to repetitive trafficking has also been found in various studies, as reviewed by Håkansson and Reeder (1994a). Several other authors also have found that BD increased exponentially with the increase in vehicle passing intensity (Horn *et al.*, 1995; Moraes *et al.*, 2013). Bergamin *et al.* (2010) showed that two passes increased BD and continued increasing BD up to six passes in the topsoil due to a tractor weighing 50 kN. However, these results disagree with the result found by Moraes *et al.* (2013), who observed that greater changes in the soil compaction level were caused by the first traffic by a harvester equipped with grain header and grain tank total weighing of 70 kN in the front axle. Their findings of higher increments in the soil compaction level in the first traffic might be attributed to the fact that in the first traffic of a heavy tractor increases the internal strength of the topsoil that exerts resistance to the external stress by the vehicle load during the following traffic events. By contrast, Schäffer *et al.* (2007) suggest that the initial pass by a combine harvester weighing 95 kN created some deformation of the restored topsoil, from which the soil did not recover until the next pass. They also found that the cumulative effect of 10 passes produced significant soil compaction. In the present study, as the ground pressure of the 2-WT was small (2.6 kN without extra loading to 6.0 kN with extra loading) compared to a heavy vehicle (5.3 kN to 78.5 kN) Khepar *et al.* (2000); (Schäfer-Landefeld *et al.*, 2004; Zhang *et al.*, 2007b), the first pass could create only a little internal strength of the topsoil which is accumulated in the following passes and produced compacted topsoil by the fourth pass. Land preparation for the establishment of each crop in Bangladesh typically involves 3 or more passes, with the 2-WT suggesting that in fields growing 2-3 crops per year, there is a substantial effect on soil compaction. Shifting to CA, which would reduce the number of passes to 3 per year, could therefore reverse soil compaction, especially as it is accompanied by a 65 % increase in soil organic matter in the 0-15 cm layer (Alam *et al.*, 2018b).

Bulk density in the 0-5 cm depth at Alipur under ST-1Pass was 1.38 g cm^{-3} which was increased to 1.47 g cm^{-3} under ST-4Pass and increased to 1.43 g cm^{-3} under ST200-1Pass treatment. Similarly, at Digram, BD under ST-1Pass was 1.40 g cm^{-3} which was increased to 1.48 g cm^{-3} under ST-4Pass, and increased to 1.44 g cm^{-3} under ST200-1Pass treatment. These results demonstrated that both the increased number of wheel passes and the applied 200 kg loading significantly compacted 0-5 cm soil depth. However, the greater level of compaction in 0-5 cm soil was achieved by increasing the number of passes rather than increasing the loading. At Digram, in the 5-10 cm soil depth, BD increased from 1.63 g cm^{-3} under ST-1Pass to 1.69 g cm^{-3} under ST-4Pass, suggesting the increase in the number of passes also resulted in the stress transmission to the 5-10 cm depth in silty clay loam soil. The increasing depth of soil compaction with the increase in the tractor passes was also reported by Becerra *et al.* (2010), even using a tractor with a low axle load. In that study comparing a heavy (50 kN) and a light tractor (15 kN) with up to 8 passes, they observed that with the three passes, the light tractor caused higher BD values in 20 cm depth than the heavy tractor.

The 8-13 cm depth at Alipur and the 10-15 cm depth at Digram were identified as the plough pan due to their higher initial BD and PR values. At these depths, there were no significant differences in BD or PR values between weight loading treatments or the number of wheel passes (Figure 4.9 and Table 4.6 for Alipur and Figure 4.19, Table 4.12 for Digram). The vertical stress distribution beneath wheels depends on the axle load and the ground pressure (Lamandé and Schjønning, 2011a), soil characteristics such as the water content (Lamandé and Schjønning, 2011b) and soil structure (Hamza and Anderson, 2005). Ground pressure determines the initial level of stress at the surface, but total axle load influences the subsoil (30 -40 cm) compaction independent of the pressure on the soil at the surface (Jorajuria *et al.*, 1997; Chamen *et al.*, 2003). The direct relationship between axle load and subsoil compaction, independent of the ground pressure, is well documented by Botta *et al.* (2002) and Becerra *et al.* (2010). In the current study, applying an additional 200 kg load on the VMP mounted on the 2-WT increased the axle load up to 48 % compared to the vehicle without loading. The additional loading was not probably sufficient to transmit the vertical stress to the subsurface soil layer. In addition, the initial soil strength of the plough pan was high enough to withstand the applied stress of the loaded vehicle. The precompression stress, sometimes called as the internal soil strength, is greatest in the plough pan (Horn *et al.*, 1995), and thus the plough pan is very resistant to further compaction (Schäfer-Landefeld *et al.*, 2004).

Penetration resistance

Strong positive relationships between the BD and the PR were found for both soils in the topsoil layer, where the tillage, loading weight, and number of wheel passes treatments significantly increased both PR and BD and compacted the soil. Bulk density and PR increased with number of passes at both locations. However, the BD changes due to tractor traffic tended to be less responsive than the PR. For example, BD at 0-5 cm depth increased by ≤ 10 % under four passes compared to No traffic (Figure 4.9 and Figure 4.19), while the corresponding increase in PR was 80 % with the same SWC, even though for both parameters, the differences between the No traffic and the four passes were significant (Table 4.5 and Table 4.10). These relative responses of PR and the BD to the compaction are in accord with those of Botta *et al.* (2006) and Becerra *et al.* (2010). Penetration resistance depends not only on BD but also on SWC or matric potential (Mirreh and Ketcheson, 1972) and particle size distribution (Cassel *et al.*, 1978). For the No traffic treatment, PR values at sowing increased with increasing depth and a peak of PR is observed at the plough pan at both Alipur (8-13 cm) and Digram (10-15 cm) (Table 4.5 to Table 4.6 for Alipur Table 4.10 to Table 4.12 for Digram). This can be ascribed to the repeated impact of ploughing at the same depth through the years preceding the present study-especially the process of puddling during rice cultivation (Sharma and De Datta, 1985). For all loading weight and the number of wheel passes treatments, PR values at the topsoil were lower than that at the plough pan of Alipur. In contrast, at Digram, four wheel passes produced PR as high in topsoil as the plough pan. Greater compaction in the 0-5 cm depth compared to plough pan by four wheel passes at Digram might be attributed to the higher clay content at Digram (32 %) than Alipur (21 %) (Becerra *et al.*, 2010). These results suggest that a 2-WT with an increased number of wheel passes can produce as much compaction in the surface soil as in the plough pan. Furthermore, despite having similar BD values at the 5-10 cm and 10-15 cm soil in Digram soil, the PR value is lower at the 10-15 cm depth than 5-10 cm soil since the water content at the 10-15 cm was higher than the 5-10 cm soil (Table 4.11 and Table 4.12).

4.4.2 The implication of soil water content, number of wheel passes and formation of a plough pan

At Alipur, the average volumetric water content during a tractor wheel traffic operation was 26 % at 0-5 cm, 26.7 % at 8-13 cm and 27 % at 10-15 cm depth (Table 4.5 to Table 4.7). In this area, dry season tillage is commonly carried out when the soil is drier than field capacity in comparison to wet season cultivation for rice production when the SWC is close to saturation (48 %). This study was completed to measure the effect of tillage, loads, and traffic on compaction in the field environment during the dry season. It is well established that soil wetness is an important factor affecting the compaction and compressibility of soil (Proctor, 1933; Terzaghi *et al.*, 1996). In these fields in the previous season, during puddling of rice soil, the saturated plastic condition under which tillage and puddling take place probably created conditions optimal for the soil's structural collapse and compaction just under the soft puddled surface layer (Moormann and Breeman, 1978).

At Digram in 0-5 cm depth, the increased BD (1.40 g cm^{-3}) and PR values (1.6 MPa) compared to the No traffic plot (BD=1.38 g cm^{-3} and PR=1.5 MPa) (Figure 4.19 and Table 4.10) suggest that under single wheel pass, surface soil experienced compaction and the compaction was much higher under an increased number of wheel passes even though SWC was much lower than the field capacity (volumetric water content 33 % vs ~ 39 %). This is also true for the compaction at the 5-10 cm depth during CT operations. Under CT single pass and four passes, the tines of the tiller only reached and loosened the soil of the top 5 cm and decrease BD and PR values. However, wheel traffic during CT operation increased significant soil BD of 5-10 cm soil depth compared to No traffic (Figure 4.19). The subsoil compaction under CT is attributed to the tractor wheels that run in the open-wheel ways during the second and subsequent traffic event and tillage operation because wheels then run directly on the 5-10 cm soil. This finding is in accord with that found by Weisskopf *et al.* (2000), who suggested that one rear wheel of the tractor runs in the open furrow, directly affecting the subsoil.

4.4.3 Least Limiting Water Range and Plant Available Water

Soil water content availability is generally described by the concept of plant available water (PAW), which is defined as the difference between volumetric water content at field capacity and permanent wilting point (Veihmeyer and Hendrickson, 1931, 1949, 1950). By contrast, the LLWR is the range in soil water content within which limitations to plant growth associated with water potential, aeration, and mechanical resistance to root penetration are minimal (Da Silva *et al.*, 1994) and provides a better characterization of the effects of compaction on soil physical properties. Based on the concept introduced by Letey (1985), the LLWR approach not only takes into account the limits of field capacity and permanent wilting point but also the limitations from aeration and soil penetration resistance. Thus, the LLWR integrates the effects of aeration, soil strength and water potential into one index on the basis of soil water content (Da Silva *et al.*, 1994). The usefulness of LLWR as an index of soil physical quality in a wide variety of soils, crops, and management practices is reported by numerous researchers (Da Silva *et al.*, 1994; Betz *et al.*, 1998; Tormena *et al.*, 1999; Zou *et al.*, 2000; Benjamin *et al.*, 2003; Da Silva *et al.*, 2004; Lapen *et al.*, 2004; Leao *et al.*, 2005; Neményi *et al.*, 2006).

The impact of changes in soil bulk density on plant growth is linked to water availability and factors such as aeration or restrictions to root development and growth (Da Silva and Kay, 1997). Soils with a wider LLWR are more resilient to environmental stresses, and plants growing in the soil are less likely to suffer from poor aeration, matric potential, and/or penetration resistance, and the soil is more productive compared to soil with a narrower LLWR (da Silva and Kay, 2004).

In the 0-5 cm depth of CT for both single and four passes, the magnitude of LLWR varied between 18.06 and 22.55 % at both sites, which was also equal to the PAW. Analysis of the upper and lower limits of the LLWR suggested that the θ_{FC} and the θ_{PWP} became the factors that limit plant root growth and water uptake in the wet end and dry end of the water gradient for the tilled soil by CT-1Pass and CT-4Pass at 0-5 cm depth at both sites (Table 4.8 and Table 4.13). Conventional tillage decreased soil BD and increased the magnitude of the LLWR by lowering the θ_{PR}. The LLWR was thus defined by the $\theta_{PR,}$ not the θ_{PWP}, and θ_{FC} was the upper limit. Similar observations under CT with low BD values were also recorded by Mishra *et al.* (2015). Kadžienė *et al.* (2011) also found higher values of LLWR for ploughed and harrowed systems than for no tillage without residue. Similar observations were also recorded (Calonego and Rosolem, 2011; Kahlon and Chawla, 2017).

In the surface layer of all loading weight and number of wheel passes treatments, the magnitude of LLWR for both sites varied between 5.79 and 19.93 % (Table 4.8 and Table 4.13). Reduction in LLWR for compacted soil compared to tilled soil indicates that for compacted soil, the θ_{AF}, not the θ_{FC}, was the upper limit of LLWR and the limiting factor for plant root growth and water uptake in the wet end of the water gradient. Similarly, for compacted soil, the θ_{PR}, not the θ_{PWP}, was the lower limit of the LLWR and the limiting factor for plant root growth and water uptake in the dry end of the water gradient. These results indicated that θ_{AF} or θ_{PR} being the upper or lower limit, the range in SWC where root growth was not limited was decreased. Thus LLWR was less than PAW, and water available to plants was reduced. Guedes Filho *et al.* (2013) suggested the relationship between the BD and the LLWR. They suggested that the increase in BD increases the cohesion of the soil particles, decreases macroporosity and increases microporosity, reduces soil aeration, which leads to decreased water content at AFP and increased PR within the LLWR. Reduction in LLWR by compaction was also reported by several researchers (Beutler *et al.*, 2008; Choudhary *et al.*, 2008; Chen *et al.*, 2014).

In the surface layer for both sites irrespective of loading weight, LLWR under four wheel pass treatment ranged between 5.79 and 10.88 %, while LLWR under single wheel pass ranged between 11.59 and 19.34 %. These results thus indicate that shifting from the increased number of wheel passes with tillage to single wheel pass with tillage will reduce the risk of compaction and provide an improved soil structure and better soil environment for achieving a wider LLWR.

It is also evident from the BD vs LLWR results that the magnitude of LLWR rapidly declined with the increase in BD values (Figure 4.24). Similar results were observed by Da Silva *et al.* (1994) in silty loam soil, by Mishra *et al.* (2015) in the IGP alluvium group with sandy clay loam texture, and by (Safadoust *et al.*, 2014) in clay loam and sandy loam soils. A sharp decline in LLWR in the plough pan irrespective of tillage, loading weight, and number of wheel passes treatments were noted for both locations, indicating poor soil structural condition and limited water availability. Similar results in the Indian Agricultural Research Institute with IGP alluvial sandy clay loam soil comparing different tillage systems were reported by Mishra *et al.* (2015), who found 12 % LLWR under CT in 0-15 cm, which was declined to 7 % in 30-45 cm soil depth.

In the 0-5 cm depth, LLWR under ST200-4Pass at Digram (5.79 %) were smaller compared to LLWR under the same treatment at Alipur (8.78 %) (Table 4.8 and Table 4.13). The smaller LLWR at Digram could be attributed to more clay content at Digram (31.4 %) compared to clay content at Alipur (23.8 %), which resulted in greater θ_{PR} at Digram (27.32 %) compared to θ_{PR} at Alipur (25.30 %). A greater reduction in LLWR for soil with greater clay content was also observed by Chen *et al.* (2014).

4.4.4 Effect of loading weight and number of wheel passes treatments on Infiltration and hydraulic conductivity

Many studies have found that compaction modifies the pore size distribution of soils mainly by reducing the macroporosity (Eriksson, 1975; Ehlers, 1982; Blackwell *et al.*, 1986; Alakukku, 1996, 1997). Besides the volume and number of macropores, compaction may also affect their connectivity. Modifications in soil macroporosity are very important since they also affect other soil properties such as infiltration and hydraulic conductivity, which have been discussed below.

In the topsoil of the two locations investigated, the steady-state infiltration under CT was 3-10 times higher than that under wheel traffic passes. Bulk density of the 0-5 cm soil depth under CT ranged between 1.17 and 1.25 g cm^3 at Alipur and between 1.32 and 1.35 g cm^3 at Digram. Whereas BD of the same depth under loading weight and increased number of wheel passes ranged between 1.38 and 1.48 g cm^3 at Alipur and that ranged between 1.40 g cm^3 to 1.51 g cm^3. The differences in initial infiltration and reduction of infiltration rate with time among the treatments suggest the higher capability of the CT pore system to increase the amount of water infiltrating before filling macro-pores and reaching steady-state (Lipiec *et al.*, 2006). As the BD under CT was reduced, the TP was increased, which might have also increased the macro porosity. The presence of large pores and flow active porosity in the topsoil of CT might have contributed to a higher water infiltrating pore system. By contrast, soil compactness induced by extra loading and four wheel passes, as evidenced by higher BD, might have reduced the volume of macropores that reduced the flow of water through the compacted soil. Meek *et al.* (1992) reported infiltration rate decreased by 53 % when BD of a sandy loam soil increased from 1.6 to 1.8 g cm^3. The shear stress by the wheel traffic distorts the vertical pores (Horn, 2003), which negatively influence the water flow through the soil. Reduction in infiltration rate by 30 % due to tractor traffic compared to No traffic areas in a loamy soil of France was also reported by Van Dijck and Van Asch (2002). Lipiec *et al.* (2009) reported in a loam soil of Poland, the infiltration rate under no compaction treatment was higher than a compaction treatment with five wheel traffic.

There was a strong negative correlation between BD and infiltration rate for both soils. For example, BD of the most compacted soil under ST200-4Pass was higher (1.48 g cm^3) than the most tilled soil under CT-4Pass (1.17 g cm^3), but K_{sat} under ST200-4Pass was lower (0.30 cm h^{-1}) than the K_{sat} under CT-4Pass (2.52 cm h^{-1}). However, in spite of having lower BD under CT four pass than CT single pass, there was no significant difference between K_{sat} values under these two treatments. Since the plough pan was highly compacted, the low hydraulic conductivity of the plough pan eventually controlled the steady-state infiltration of the topsoil for all treatments. Li *et al.* (2001) indicated the infiltration of the topsoil is a function of the degraded subsurface layer that has the lowest infiltration capacity.

Saturated hydraulic conductivity (K_{sat}) has been used to characterise the effect of soil compaction on water flow since K_{sat} values are predominantly governed by the abundance of relatively large pores and their continuity (Lipiec and Hatano, 2003; Pagliai *et al.*, 2003). In the present study, the average K_{sat} under CT was 3-4 times higher than that under single pass wheel traffic and 3-6 times higher than that under four pass wheel traffic. A reduction in the K_{sat} values due to compaction was also found by Chyba *et al.* (2014).

The reduction in K_{sat} might be the consequences of the shear deformation of the pore continuity (Horn, 2003). A drastic reduction of K_{sat} with increasing compaction has been reported in many studies (Dawidowski and Koolen, 1987; Debicki *et al.*, 1993; Håkansson and Medvedev, 1995). The ratio of K_{sat} or steady infiltration rate of tilled and compacted soil range from several (Young and Voorhees, 1982) to several hundred (Horton *et al.*, 1994; Arvidsson, 1997; Guérif *et al.*, 2001). Burt and Slattery (1996) found infiltration capacities less than 0.5 cm h^{-1} in wheel tracks, compared to 6.4 cm h^{-1} on cultivated slopes.

4.4.5 Effect of loading weight and number of wheel passes treatments on chickpea emergence

Increased loading weight and number of wheel passes significantly reduced chickpea emergence, while the tilled soil under CT gave the highest success in plant emergence compared to the No traffic plot. The soil physical properties produced by the CT created a favourable environment for the penetration and elongation of the root and shoot. The laboratory measurements of the PR and correcting the water content to the SWC at the time of sowing (26 to 27 % volumetric) suggest that the PR of the conventionally tilled loose soil was 0.6 to 1.1 MPa at 0-5 cm depth regardless of the location. In the low resistant soil, seedling roots were able to elongate without hindrance, which resulted in higher success in emergence. In a pot trial with the same soil of HBT of Bangladesh, Vance (2013) suggest that root elongation of the chickpea seedlings was inhibited and depressed by 50 % at the PR > 1 MPa with the gravimetric SWC of 12 %. Root growth is prevented at the PR between 2 to 3.7 MPa depending on the plant species (Kirkegaard *et al.*, 1992). In the present study, the most compacted soil by the ST200-4Pass, which produced PR of 2.3 to 2.7 MPa at the top layer with sowing SWC of 26 % to 26.4 %, gave the lowest plant emergence. Plant emergence is limited when penetration and elongation of both shoots and roots are restricted due to the strong soil (Nasr and Selles, 1995). In compacted soil, plants use their energy to support root penetration into the strong soil layer and leaving little energy to support shoot growth (Nasr and Selles, 1995). However, in the current study, the plant emergence in the highly compacted plot was not completely stopped. During chickpea seeding, a small hole was made, the seed was placed, and the hole was covered with loose soil. The roots of the seedlings easily penetrated the loose fine aggregates of the soil seedbed, and shoot elongation did occur. In the field condition, the shoot penetrated through the voids between aggregates of soil having PR <0.6 MPa (Vance, 2013). Where initial seedling growth is unimpeded, roots are able to penetrate deeper into the profile to access water and nutrients (Johansen *et al.*, 1997), which helps post-emergence shoot growth. In the current study, it was observed that after 30 days of sowing, the roots were around 15 cm long for all treatments which suggest that the roots penetrated into the ploughpan. However, the results were not presented since there were no treatment differences in root length and there was no evidence collected on whether the roots were diverted to lateral growth to avoid the strong soil of the plough pan. However, Musa *et al.* (2001) suggested that root penetration into the plough pan was not be limited as long as this layer does not dry out.

The mean SWC of the 0-5 cm soil at the time of sowing (θ_{Sow}) was 26-27 %. Graphical presentation of LLWR indicates that this value of θ_{Sow} for the CT, single pass compaction treatment and the No traffic plot was safely above the water content at critical PR (θ_{PR}). However, for four pass compaction treatments, θ_{Sow} was close to θ_{PR} (27 % volumetric) for the same treatment. This result suggests that among the four limiting water contents used to define the LLWR (θ_{FC}, θ_{AF}, θ_{PWP}, θ_{PR}), θ_{PR} was responsible for low plant emergence in the four pass wheel traffic treatments. The plant population was counted 14 days after sowing. At Alipur, seeds were sown on the 1st of February when the temperature was 15-18^{0}C. However, at Digram, seeds were sown on the 25th of March when the temperature ranged between 20-25^{0} C. The two seasons of sowing suggest that 0-5 cm soil of Digram was more likely to dry out due to high temperature during the first couple of weeks after seedling emergence. This might be one of the reasons for less seedling emergence at Digram. Another reason might be the textural class. The LLWR of the subsoil (5-15 cm) for both locations was ranged from 2-8 %, although the water content of the plough pan was less likely to dry out during the observation period.

For Thakurgaon, soil compaction did not significantly affect the BD of the topsoil. The wettest SWC had the highest, and the driest SWC had the lowest emergence percentage of chickpea seedlings among three water content treatments. However, the water content was within the range of water content that limits or delay the chickpea emergence. Vance *et al.* (2015) suggested the gravimetric SWC of a heavy textured soil for optimal chickpea emergence is 17 %, and chickpea emergence is delayed when water content goes below 12 % and above 23 %. They also suggested that emergence was possible at lower soil water potentials in the finer-textured soil, while in coarser textured soil, emergence was still possible at higher soil water potentials. The results in the present study suggest that for coarse-textured soil like sandy loam in Thakurgaon, lightweight 2-WT did not create compaction that can hamper the chickpea emergence when chickpea is sown at a suitable SWC for germination.

4.5 Conclusion

A single pass wheeling by a 0.4-tonne 2-WT caused differences in BD and PR at 0-5 cm depth, but the magnitude of the change was small. However, after four passes with a 2-WT, the effect of compaction became highly significant not only at 0-5 cm depth but also in situations where there was no shallow plough pan at 5-10 cm. Cumulative compaction effect in this case transmitted from surface to the 5-10 cm depth. For both 0-5 cm and 5-10 cm depths, the greatest differences in BD and PR was achieved by increasing the number of passes rather than increasing the tractor loads. Frequent traffic events in combination with CT also induced compaction at 5-10 cm depth. Compaction by CT-4Pass at 5-10 cm depth indicated that a 2-WT, when frequently trafficked at this depth for many years, as is the conventional practice on farms in Bangladesh (De Datta *et al.*, 1978), created a dense soil layer which is reasonably related to the formation of the plough pan. While ground pressure or axle load of a 2-WT is way below the 4-WT that is used worldwide, adding 50 % (200 kg) extra load to the 2-WT produced no considerable increase in compaction, unlike the effect of increasing the number of wheel passes. The soil in the plough pan did not respond to the increased number of wheel passes or extra loading due to its high pre-compression strength that prevented additional compaction or breakage.

This study showed an interrelationship among the BD, soil PR, available water and infiltration. Under four wheel pass treatments, soil PR of the 0-5 cm depth reached the critical value of PR for root growth (2.5 MPa). The soil PR of the 0-5 cm depth under ST-4Pass or ST200-4Pass was comparable to the soil PR of the plough pan. Increased BD under four wheel pass reduced the macroporosity and water holding capacity, which was reflected in the reduced LLWR. The LLWR concept includes the effects of several growth-limiting factors such as matric potential, aeration and penetration resistance that are integrated into a single parameter, the LLWR range, which could be a good soil quality indicator in soil compaction studies. Measurement of LLWR indicated that CT had a larger LLWR which is also comparable to the LLWR of ST-1Pass. When the soil depths are compared, the surface soils of the two locations had a greater LLWR than that of the subsurface. The LLWR of the plough pan were likely to be negative.

Regardless of loading weight, four wheel passes compared to the single wheel pass drastically decreased the infiltration and the hydraulic conductivity of the compacted soil. This result suggests that single wheel pass traffic can help to reduce the effect of compaction and to increase water infiltration. The reduced BD under single wheel pass traffic also affects the water availability, as evidenced by the LLWR, for the crop, which will also affect the water balance in the root zone soil. Strip planting is a minimum soil disturbance technique where tillage operation, seed and fertiliser placement are done with a single pass wheel traffic. Thus, reduced compaction by SP serves the opportunity to increase infiltration and hydraulic conductivity compared to intensive tillage with increased wheel passes, which also may alter the water balance. The effect of minimum soil disturbance techniques on the water balance is further investigated in Chapter 5 for wheat and Chapter 6 for rice. The controlled traffic farming system is a technique where vehicle wheels are confined to a single line and traffic follow the same track. Bed planting is one of the examples of controlled traffic where wheel traffic is limited to the furrows only and allows the soil of the furrows to be compacted. Water balance under BP is also discussed in the following chapters.

All compaction treatments increased the PR and density of topsoil and generated an unsuitable physical condition for chickpea emergence at Rajshahi in two soils with 24-33 % clay content. A remarkable decrease in chickpea emergence was detected when soil PR was 1.2 MPa, and BD was 1.4 g cm^{-3}. However, at Thakurgaon, in sandy soil (9 % clay), neither a single wheel pass nor four wheel passes limited chickpea emergence.

5 Effect of minimum soil disturbance planting on the water balance of wheat in northwest Bangladesh

5.1 Introduction

Growing wheat after harvesting transplanted monsoon rice (rice-wheat cropping system) is the most popular cropping system in IGP (Kukal and Aggarwal, 2003b). However, these two major cereals have contrasting edaphic requirements. Puddling has been the most commonly used practice for the establishment of transplanted rice (De Datta *et al.*, 1978). In contrast, wheat prefers upland well-drained soil having good tilth. Puddling is favourable for rice as it helps to control weeds and creates a soft medium for easy transplantation of rice seedlings. However, puddling enhances the development of plough pans which increases water retention in the root zone for rice but has detrimental effects on the growth and yield of succeeding non-rice crop such as wheat (Aggarwal *et al.*, 1995). Puddling also causes deterioration in soil physical properties (Aggarwal *et al.*, 1995; Kukal and Aggarwal, 2003a), and as a result, wheat yield following rice declines (Sur *et al.*, 1981; Gill and Aulakh, 1990; Aggarwal *et al.*, 1995). In addition, excessive wetness in puddled rice soil can delay the planting of the following non-rice crop and result in yield reduction. Typically, farmers drain out standing water about 14 days before rice harvest and allow the soil to dry. In conventional agriculture, due to the presence of a plough pan, dry land preparation takes about two to four weeks, and thus sowing of wheat after rice harvest is often delayed. Therefore, the yield of wheat crop in most of the areas is low after monsoon rice (Roy, Meisner, and Haque 2004). Optimum sowing time of wheat in Bangladesh is the second fortnight of November, but the yield of wheat is reduced by 1 to 1.5 per cent per day from delays in sowing (Hobbs and Mehta 2003, Ortiz-Monasterio, Dhillon, and Fischer 1994), which is similar to yield reductions reported for India (35-40 kg ha^{-1} day^{-1}) by a delay in planting after November 20 (Randhawa, Dhillon, and Singh 1981).

Tillage and water are the most costly inputs for wheat crop production. The conventional practice of intensive tillage, involving 6-8 tillage operations for wheat, consumes a high proportion (25-30 %) of the total operational energy in wheat production (Sidhu *et al.*, 2004). As alternatives to intensive tillage, Zero Tillage (ZT) and Bed Planting (BP) combined with plant residue retention have become popular technologies to offset the production costs and other constraints associated with soil degradation during land preparation (Hobbs, 2001). In India and elsewhere, wheat can be planted in a timely manner and at a reduced cost using minimum soil disturbance technologies (Hobbs, 2001; Malik *et al.*, 2004; Yadvinder-Singh and Ladha, 2004). No-tillage wheat also requires less irrigation water than Conventional Tillage (CT) for pre-sowing irrigation in particular (Malik *et al.*, 2004).

Recently a 2-WT operated VMP was developed for crop establishment by minimum soil disturbance techniques using ZT and Strip Planting (SP), which has created for the smallholder farmers' new opportunities to adopt CA in rice-based rotations in South Asia. Minimum soil disturbance planting by VMP (SP) had similar or, in some cases, higher yields than the CT systems for diverse non-rice crops (Bell *et al.*, 2017). Furthermore, water savings are the key benefits for minimum soil disturbance, particularly in non-rice crops, due to slower loss of soil water by evaporation. In addition, soil cover by standing or prostate crop residue slows the rate of soil water evaporation. The cooler soil temperatures under retained residue also contribute to slower evaporation loss of soil water.

While the potentiality of minimum soil disturbance planting for increasing or maintaining wheat yield compared to CT in the northwest of Bangladesh has been reported (Islam, 2016; Bell *et al.*, 2017), limited information is available on the influence of this establishment method for wheat in rice-based rotations in terms of water balance and water productivity. In this chapter, the hypothesis was that altered soil physical properties under long term minimum soil disturbance with crop residue retention would also change the magnitude of components of the water balance in irrigated wheat. Since water is expected to infiltrate deeper in soil profile through unbroken macropores under minimum soil disturbance, evaporation will be decreased. In addition, since plant roots of the wheat crop can uptake more water from deep soil, transpiration may be increased. Eventually, crop evapotranspiration (ET_c) and thus irrigation water use under SP or BP will be less in wheat. The objective of this chapter is, therefore, to determine the effect of SP and BP on the water balance components in wheat under the climatic condition of the northwest of Bangladesh. This chapter also reports, based on evaluation of SP and BP compared to CT in rice-based rotation, the water productivity for the irrigated wheat.

5.2 Materials and Methods

5.2.1 Experimental site

Experiments were conducted from 2015 to 2017 on a silty clay loam soil (High Barind Tract) at Rajshahi, Bangladesh (24^o 31′ N, 88^o 22′ E). The experiments were completed on a long-term experiment site, which was established in 2010 (Islam, 2016).

5.2.2 Experimental design and treatments

The experiment had a split-plot design (plots 7 m × 15 m) with four replicates. The main plots comprised tillage treatments (Strip planting (SP), Bed planting (BP) or Conventional Tillage (CT)), and the sub-plots received different crop residue treatments (Low and high residue, equivalent to 20 % and 50 % of cereal straw retained, respectively). Details of the treatments are given in Chapter 3.

5.2.3 Irrigation Scheduling

Wheat seeds were sown with residual soil water 4-5 weeks after the monsoon rice harvest. After wheat sowing, irrigations were scheduled based on the growth stages of wheat. Irrigation water was applied once at each of the four critical growth stages, i.e. crown root initiation (CRI), booting, flowering, and grain filling. In 2014-15, the amounts of irrigation water applied to the

CT and SP plots were based on the volume required to fully flood them to a depth of about 5 cm. The BP plots were irrigated in the furrows, and the amount they received was the amount required to fill the furrows without overtopping the beds (bed height 12 cm).

In 2015-16 and 2016-17, I determined the volume of irrigation water based on the soil water depletion for each plot. On the day before the irrigation event at each of the four growth stages, I measured the soil water content of the root zone depth (0-180 cm) and calculated the soil water deficit (SWD). The volume of applied irrigation water was the amount required to replace 100 % of the soil water deficit in the specified soil depth. Irrigation water depths indicated by the SWD in each treatment were calculated using Eq (6.1) (Michael, 2008):

$SWD = (\theta_{FC} - \theta_i) \times D_{RZ}$ ……………………………………………………………………6.1

where SWD = soil water deficit (cm), θ_{FC} = volumetric soil water content at field capacity (%), θ_i = soil water content before irrigation (%), D_{RZ}: root zone depth (cm).

Irrigation water in different treatments was applied to raise the water content to the FC at all the critical growth stages so that crops did not suffer due to water stress to remove limitations in the water supply as an effect on yields.

5.2.4 Components of water balance

Water balance components were determined using the Eq (6.2) (Choudhury *et al.*, 2007):

$I + R = ET_c + DD + \Delta SWC$……………………………………………………………..6.2

where I = irrigation (cm), R =rainfall, ET_c = Crop evapotranspiration (cm), DD = Deep drainage below the root zone (cm), and ΔSWC = change in soil water storage in the root zone.

In our wheat experiments, I assumed surface runoff from the plots were negligible as irrigation water was contained by 20-cm-high bunds. The capillary contribution from groundwater to the crop root zone was assumed to be negligible because the groundwater table was more than 5 m below the soil surface.

Irrigation and rainfall

All treatment plots were irrigated on the same day from groundwater. Volumetric irrigation water (m^3) was measured using a flow meter, which was installed at the hydrant of a low-pressure tube water transportation system. Daily rainfall data were collected from a rain gauge located 10 m from the experimental plots. The plots received 1.5 cm, 0.6 cm, and 1.2 cm of effective rainfall between the sowing and harvest of the wheat season in 2014-15, 2015-16, and 2016-17, respectively.

Measurement of soil water content and calculation of changes in soil water storage

Measurement of SWC of the soil profile up to a depth of 180 cm was done for depth increments of 0-10,10-20, 20-30, 30-60, 60-90, 90-120, and 120-180 cm. Measurements were done before sowing and after harvest, and the day before irrigation at CRI, Booting, Anthesis, Grain filling growing stages of the wheat. Two consecutive measurements of SWC were used to calculate ΔSWC and ET_c for different growth stages. The total ΔSWC as in the water balance equation was calculated from the difference in measured soil water contents just before sowing and right after harvest using a capacitance moisture meter (ICT international model MP406) up to 180 cm depth by auguring.

Details of the measurement of soil water content with the moisture meter and its calibration is described in Chapter 3.

Calculation of crop evapotranspiration from changes in soil water content data

I was unable to separate the components of ET_c, i.e. evaporation and transpiration, due to limited laboratory facilities and time. Hence, the current study deals with ET_c as a combined output in the water balance. The ET_c was calculated from the changes in measured soil water content. The ET_c

for the period from sowing to CRI was calculated from the changes in soil water content measured at sowing and before the 1st irrigation at CRI. The ET_c for the period from CRI to booting was calculated from the changes in soil water content measured after the 1st irrigation at CRI and before the 2nd irrigation at booting. Similarly, the ET_c for the period from booting to anthesis was calculated from the changes in soil water content measured after the 2nd irrigation at booting and before the 3rd irrigation at anthesis. The ET_c for the period from anthesis to grain filling was calculated from the changes in soil water content measured after the 3rd irrigation at anthesis and before the 4th irrigation at grain filling. The ET_c for the period from grain filling to harvest was calculated from the changes in soil water content measured after the 4th irrigation at grain filling and at harvest. Seasonal ET_c was calculated from the summation of all ET_c. As the effective rainfall was 1.5 cm in 2015, 0.6 cm in 2016 and 1.2 cm in 2017 in the three wheat seasons, I assumed that changes in SWC due to a rainfall event were negligible. On the days of each irrigation event, ET_c was determined to be 80 % of the pan evaporation of that day (Choudhury *et al.*, 2007).

Estimation of crop evapotranspiration using model simulation

Crop evapotranspiration during the period from wheat sowing to the harvest and for each growth stages was also estimated using the DSSAT-CSM-CERES-Wheat model v. 4.7 (Hoogenboom *et al.*, 2017) using the calibrated and computed genetic coefficients for wheat variety BARI Gom-26 (Jahan *et al.*, 2018). Climatic data such as maximum and minimum temperature, relative humidity, and rainfall collected from the experimental site were used. Solar radiation data were collected from the meteorology station at Bangladesh Rice Research Institute substation, Rajshahi, Bangladesh, located 40 km from the experimental site. Soil BD values of the current study, soil organic matter content from previous studies by Islam (2016) and Alam *et al.* (2018b) were used for the model simulation. Parameters used in the simulation of evapotranspiration using DSSAT-CSM-CERES-Wheat model are presented in the Appendix 5.1 and Appendix 5.2.

Deep drainage

Net deep drainage (DD, cm) beyond the root zone (180 cm) of the three wheat seasons were estimated as the residual of Eq. (6.2).

5.2.5 Irrigation water productivity and Crop water use efficiency

Irrigation water productivity (WP_I) was calculated by the formula (Alam *et al.*, 2017):

$$WP_I = \frac{Grain\ yield\ (kg\ ha^{-1})}{Irrigation\ water\ use\ (m^3 ha^{-1})}$$

The water use efficiency (WUE) was calculated by the formula (Parihar *et al.*, 2017):

$$WUE = \frac{Grain\ yield\ (kg\ ha^{-1})}{Evapotranspiration\ (m^3 ha^{-1})}$$

As there was very little rainfall during the wheat season in each of the years, total water use did not take these amounts of rainfall into account.

5.2.6 Wheat crop management

BARI wheat26 was sown on 28th of November 2014 and harvested on 24th March of 2015 in year 1. Sowing dates for year 2 and year 3 were 28th November 2015 and 22nd November 2016, respectively. Harvesting of wheat was done in year 2 and year 3, respectively, on 18 March 2016 and 13 March 2017.

Fertilizer application was made following the recommendation by Wheat Research Centre, Bangladesh. Urea, di-ammonium phosphate (DAP), muriate of potash (MP) and gypsum fertilizer were applied to supply N:P:K:S at the rate of 120:30:55:20 kg ha^{-1}. Two-thirds of urea and all of DAP, MP and gypsum were applied at the time of land preparation. The rest of the urea fertilizer was applied as top dressing after the first irrigation at the CRI stage. At the time of land preparation for SP and BP with VMP, DAP fertilizer was drilled with wheat seed, while other fertilizers were broadcast. For CT, all fertilizers were broadcast during the final land preparation. For weed control, Affinity® herbicide of the Carfentrazone group was applied at a rate of 2.5 g/liter water at the time of sowing.

5.2.7 Statistical Method

Data were analyzed by split-plot analysis of variance (using Genstat 18th edition) to evaluate differences between treatments, and the means were separated using the least significant difference (LSD) at $p < 0.05$.

5.3 Results

5.3.1 Water balance components

Crop Evapotranspiration (ET_c)

Crop evapotranspiration was almost entirely supplied by the irrigation water applied and stored soil water at sowing because there was limited rainfall (1.5 cm during 2014-15, 0.6 cm during 2015-16 and 1.2 cm during 2016-17 wheat season) (Table 5.1). During three wheat seasons, ET_c of different treatments ranged from 25.7 cm to 26.9 cm in 2014-15, 20.5 to 26.6 cm in 2015-16 and 21.0 to 26.7 cm in 2016-17 depending on the irrigation method used. Among the cropping years, the most irrigated treatment (CT-LR in 2014-15) gave the maximum ET_c (26.9 cm), and the least irrigated treatment (ST-HR in 2015-16) had the lowest ET_c (20.5 cm). The ET_c of different tillage and residue treatments at different depths in the soil profile is presented in Figure 6.2. The ET_c in the topsoil depth (0-10 cm) was the highest in the soil profile and was less in the deeper soil depths.

In 2014-15, there was no significant difference in seasonal ET_c due to either the tillage treatments or the residue management. However, in the 0-10 cm soil depth, ET_c of BP and CT (mean 8.6 cm) was significantly higher ($p=0.008$) than that of SP plots (mean 7.1 cm) (Table 5.2). Moreover, in 0-10 cm depth ET_c of LR retention was 8.5 cm, which was significantly ($p=0.003$) reduced to 7.6 cm in the HR treatment. In 10-20 cm soil depth, only tillage treatment had a significant effect on the ET_c (p=0.02), where ET_c of CT, BP and SP were 7.7 cm, 7.5 cm and 6.9 cm, respectively. Therefore, in the 0-20 cm depth, SP plots decreased the average ET_c by 16 % relative to the CT and the BP plots. The ET_c of 20-180 cm depths were not significantly different in different tillage or residue retention treatments.

In 2015-16, the main effect of tillage treatment on seasonal ET_c was significant (p=0.016) because the ET_c of SP plots was lower (21.4 cm) than CT and BP (26.0 cm and 24.4 cm, respectively, which were not significantly different from each other). The 18 % savings in irrigation for SP was reflected by the change in ET_c at the 0-20 cm soil depths. In 0-10 cm depth, ET_c of CT and BP plots were 7.6 cm and 7.5 cm, respectively, which was significantly reduced to 6.3 cm in the SP plots. At 10-20 cm depth, the ET_c of CT was 7.5 cm, which was significantly (p=0.027) higher than that of SP plots (5.7 cm). There were no significant differences of ET_c between BP (6.4 cm) and SP or between BP and CT. In 0-20 cm depths, SP treatment saved about 22 % ET_c compared to CT and BP treatments. The main effect of residue retention was significant only in the 10-20 cm depth (p=0.025): HR saved 7 % of ET_c compared to LR treatment. From 20-180 cm soil depth, ET_c of different tillage treatments was not significant in this year.

In 2016-17, the ET_c of SP was 21.5 cm which was 16 % lower (p=0.024) than ET_c of CT (26.4 cm) and BP (23.6 cm) in the 0-180 cm soil profile. There was no significant difference of ET_c between CT and BP plots. The main effect of residue retention was not significant either in the whole soil profile or the topsoils. However, the main effect of tillage treatment was significant in 0-10 cm, 10-20 cm, and 20-30 cm soil depths. In 0-10 cm depth, ET_c of SP (7.0 cm) was significantly lower (p=0.001) than CT and BP plots (9.2 cm and 8.6 cm, respectively). The ET_c of CT and BP was not significantly different. In 10-20 cm depth, the highest ET_c was occurred in CT compared to BP and SP plots. ET_c of BP and SP plot were not significantly different. A similar trend of ET_c was also observed in 20-30 cm soil depth. In 20-30 cm depth, the ET_c of the CT plot was 3.8 cm but reduced by 46 % in SP plots. In 0-30 cm depth, SP and BP plots saved about 39

% and 32 % of ET_c, respectively, compared to CT plots. In 10-20 cm depth, HR treatment saved about 20 % of ET_c compared to LR treatment.

Table 5.1 Components of soil water balance at different tillage treatment and residue management from 2015 to 2017 at Digram, Rajshahi.

Year 1					
Treatments	**Water Balance Components (cm) ± Standard Error (cm)**				
	Input			**Output**	
	I	**R**	**ΔSMC**	**D**	**ET_c**
SP-LR	25.98 ± 1.63	1.50	7.50 ± 0.57	9.24 ± 1.21	25.74 ± 1.15
SP-HR	25.46 ± 1.64	1.50	5.64 ± 2.08	6.56 ± 2.05	26.03 ± 1.90
BP-LR	29.24 ± 1.60	1.50	6.52 ± 1.56	10.90 ± 2.38	26.36 ± 0.96
BP-HR	26.60 ± 1.64	1.50	3.84 ± 0.88	5.33 ± 1.21	26.61 ± 1.69
CT-LR	36.21 ± 1.57	1.50	4.56 ± 1.64	15.31 ± 2.23	26.96 ± 0.89
CT-HR	34.41 ± 1.30	1.50	1.66 ± 0.37	11.80 ± 1.50	25.77 ± 110
LSD$_{0.05}$, Tillage	3.20	-	Ns	ns	ns
LSD$_{0.05}$, Residue	ns	-	2.48	3.03	ns
LSD$_{0.05}$, Tillage × Residue	ns	-	Ns	ns	ns
Year 2					
Treatments	**Water Balance Components (cm) ± Standard Error (cm)**				
	Input			**Output**	
	I	**R**	**ΔSMC**	**D**	**ET_c**
SP-LR	19.43 ± 1.22	0.70	4.64 ± 0.66	1.67 ± 0.49	22.39 ± 1.37
SP-HR	17.24 ± 0.94	0.70	4.02 ± 1.33	0.75 ± 1.15	20.51 ± 0.81
BP-LR	20.43 ± 1.35	0.70	4.74 ± 0.44	0.49 ± 0.77	24.68 ± 1.29
BP-HR	21.43 ± 1.05	0.70	4.99 ± 0.42	2.28 ± 0.91	24.14 ± 1.00
CT-LR	28.34 ± 0.82	0.70	4.78 ± 1.09	6.45 ± 1.03	26.67 ± 1.02
CT-HR	26.96 ± 0.75	0.70	3.84 ± 0.36	5.40 ± 0.72	25.40 ± 0.41
LSD$_{0.05}$, Tillage	0.98	-	Ns	1.45	2.70
LSD$_{0.05}$, Residue	ns	-	Ns	ns	ns
LSD$_{0.05}$, Tillage × Residue	ns	-	Ns	ns	ns

Year 3					
Treatments	**Water Balance Components (cm) ± Standard Error (cm)**				
	Input			**Output**	
	I	**R**	**ΔSMC**	**D**	**ET_c**
SP-LR	22.73 ± 1.93	1.20	7.94 ± 2.82	8.60 ± 3.16	22.08 ± 1.84
SP-HR	21.56 ± 1.07	1.20	7.28 ± 2.58	7.82 ± 2.97	21.02 ± 0.69
BP-LR	23.89 ± 1.03	1.20	9.02 ± 1.02	8.84 ± 1.04	24.08 ± 1.02
BP-HR	23.26 ± 0.55	1.20	7.44 ± 3.03	7.64 ± 3.04	23.06 ± 0.61
CT-LR	26.47 ± 1.16	1.20	8.91 ± 1.62	8.59 ± 1.89	26.78 ± 1.24
CT-HR	26.24 ± 0.54	1.20	4.37 ± 1.78	4.69 ± 1.92	25.92 ± 0.74
$LSD_{0.05}$, Tillage	3.22	-	Ns	ns	3.08
$LSD_{0.05}$, Residue	ns	-	Ns	ns	ns
$LSD_{0.05}$, Tillage × Residue	ns		Ns	ns	ns

SP= Strip planting, BP=Bed planting, CT=Conventional tillage, LR=Low residue, HR=High residue, I=irrigation, R= Rainfall, ΔSMC=changes in SWC before sowing and after harvest, D= deep drainage (percolation + seepage), ET_c= Crop evapotranspiration.

Table 5.2 Seasonal ET_c (cm) loss at different depths of the soil profile for three tillage and two residue treatments (LR=low residue, HR=high residue) in Year 1 (2014-15), Year 2 (2015-16) and Year 3 (2016-17) for Digram, Rajshahi. Seasonal ET_c for each depth is the summation of all ET_c calculated from the changes in soil water content measured before each irrigation at different growth stages (see section 5.2.4).

Year 1																					
Depths	**0-10 cm**			**10-20 cm**			**20-30 cm**			**30-60 cm**			**60-90 cm**			**90-120 cm**			**120-180 cm**		
Tillage	**LR**	**HR**	**Mean**	**LR**	**HR**	**Mean**	**LR**	**HR**	**Mean**	**LR**	**HR**	**Mean**	**LR**	**HR**	**Mean**	**LR**	**HR**	**Mean**	**LR**	**HR**	**Mean**
Strip	7.4	6.8	7.1	7.0	6.8	6.9	4.9	4.9	4.9	3.2	2.9	3.1	1.4	2.5	2.0	1.1	1.4	1.3	0.7	0.7	0.7
Bed	8.9	7.8	8.4	7.7	7.3	7.5	4.1	4.8	4.5	2.3	2.8	2.6	1.7	2.4	2.1	0.9	0.7	0.8	0.7	0.7	0.7
Conv	9.3	8.3	8.8	7.7	7.6	7.7	4.7	4.2	4.5	1.8	2.0	1.9	1.4	1.9	1.7	1.3	1.1	1.2	0.8	0.7	0.8
Mean	8.5	7.6		7.5	7.2		4.6	4.6		2.4	2.6		1.5	2.3		1.1	1.1		0.7	0.7	
$LSD_{0.05}$																					
Tillage	0.9			0.5			ns			ns			ns			ns			ns		
Residue	0.5			ns			ns			ns			ns			ns			ns		
Till × Res	ns			ns			ns			ns			ns			ns			ns		
Year 2																					
Depths	**0-10 cm**			**10-20 cm**			**20-30 cm**			**30-60 cm**			**60-90 cm**			**90-120 cm**			**120-180 cm**		
Tillage	**LR**	**HR**	**Mean**	**LR**	**HR**	**Mean**	**LR**	**HR**	**Mean**	**LR**	**HR**	**Mean**	**LR**	**HR**	**Mean**	**LR**	**HR**	**Mean**	**LR**	**HR**	**Mean**
Strip	6.5	6.1	6.3	6.1	5.3	5.7	3.3	3.1	3.2	2.7	2.4	2.6	2.2	2.1	2.2	0.8	0.9	0.85	0.8	0.7	0.8
Bed	7.5	7.6	7.6	6.7	6.2	6.5	3.5	3.5	3.5	2.8	2.8	2.8	2.4	2.4	2.4	1.0	0.8	0.9	0.8	0.8	0.8
Conv	7.7	7.5	7.6	7.8	7.2	7.5	3.7	3.4	3.6	3.1	3.0	3.1	2.3	2.4	2.4	1.1	1.0	1.1	1.0	1.0	1.0
Mean	7.2	7.1		6.9	6.2		3.5	3.3		2.9	2.7		2.3	2.3		1.0	0.9		0.9	0.8	
$LSD_{0.05}$																					
Tillage	0.8			1.2			ns			ns			ns			ns			ns		
Residue	ns			0.5			ns			ns			ns			ns			ns		
Till × Res	ns			ns			ns			ns			ns			ns			ns		

Year 3																					
Depths	**0-10 cm**			**10-20 cm**			**20-30 cm**			**30-60 cm**			**60-90 cm**			**90-120 cm**			**120-180 cm**		
Tillage	**LR**	**HR**	**Mean**	**LR**	**HR**	**Mean**	**LR**	**HR**	**Mean**	**LR**	**HR**	**Mean**	**LR**	**HR**	**Mean**	**LR**	**HR**	**Mean**	**LR**	**HR**	**Mean**
Strip	6.9	7.0	7.0	5.4	4.2	4.8	2.7	2.6	2.7	2.7	2.8	2.8	2.2	2.1	2.2	1.3	1.6	1.5	0.8	0.8	0.8
Bed	8.6	8.6	8.6	5.4	4.6	5.0	2.5	2.4	2.5	2.9	2.8	2.9	2.5	2.5	2.5	1.3	1.2	1.3	0.8	1.0	0.9
Conv	9.9	8.6	9.3	7.3	6.3	6.8	3.7	4.0	3.9	2.8	2.9	2.9	1.8	2.3	2.1	0.8	1.1	1.0	0.5	0.7	0.6
Mean	8.5	8.1		6.0	5.0		3.0	3.0		2.8	2.8		2.2	2.3		1.1	1.3		0.7	0.8	
$LSD_{0.05}$																					
Tillage	0.8			1.4			0.7			ns			ns			ns			ns		
Residue	ns			0.7			ns			ns			ns			ns			ns		
Till × Res	ns			ns			ns			ns			ns			ns			ns		

Irrigation water use

The amount of irrigation water applied was significantly affected by the tillage treatments across the three years of experiments ($p < 0.05$) (Table 5.1). In the first year, irrigation was applied based on the amount required to flood the plots fully. Thus, flooded plots in year 1 received the highest amount of irrigation water. The depth of irrigation water applied in year 1 was 36 cm for the CT treatments and was significantly less (26 cm) in the SP and (28 cm) in the BP treatments. In year 2, irrigation water applied to reach field capacity, in SP and BP was 18 cm and 21 cm, respectively, and both were significantly less ($p < 0.05$) than CT treatment (28 cm). In year 3, irrigation water applied was significantly lower ($p < 0.05$) in SP compared to CT and BP; however, the differences in irrigation depth were small. Strip planting treatment saved 15 % and 8 % irrigation water over CT and BP treatment. The main effect of residue retention on the irrigation water application was not significant in any of the three wheat seasons.

Deep drainage

Tillage and residue had an inconsistent effect on deep drainage (deep percolation and seepage) in three years. For example, in year 1, high residue significantly reduced deep drainage over low residue by 33 %, while tillage treatment had no significant effect on deep drainage. In year 2, the effect of tillage treatment on deep drainage was highly significant ($p<0.001$). Strip planting reduced deep drainage by about 4.7 cm over CT, while BP did not reduce deep drainage compared to CT. In year 3, there was no effect of tillage or residue on deep drainage.

There was a positive relationship between irrigation and drainage for three tillage treatments (Figure 5.1).

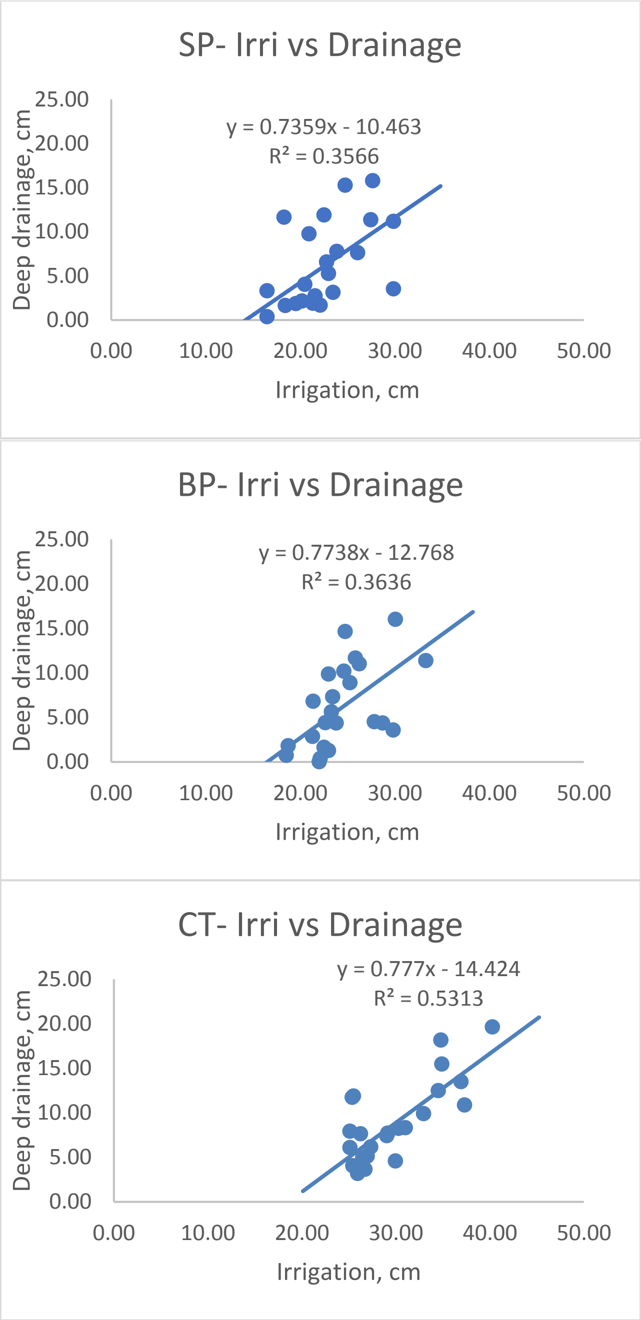


Figure 5.1 Relationship between irrigation and deep drainage for SP= Strip planting, BP= Bed planting, and CT= Conventional tillage. Data points (n=24) are from three years of low residue and high residue treatments and four replications.

Changes in soil water content ΔSWC

Soil water content at the harvest was lower than the SWC at the sowing. This means that the decline of SWC during the wheat season was an input of the water balance. There was no significant effect of tillage on ΔSWC in any of the three years. High residue treatment reduced

ΔSWC by 40 %, suggesting that high residue treatment had to supply a significantly lower amount of soil water to the input of the water balance. However, the effect was significant only in year 1.

5.3.2 Soil Water storage

Tillage treatments had a significant effect on soil water storage during three wheat seasons (Table 5.3). In 2014-15, most of the soil water depletion occurred in the upper two soil depths (0-10 cm and 10-20 cm). Wheat was sown with the residual moisture 4-5 weeks after the monsoon rice harvest. At sowing, soil moisture content was below FC for all tillage treatments at 0-20 cm depth. Pre-sowing soil water storage was 82 %, 67 %, and 66 % of the FC in 0-10 cm depth for SP, BP and CT respectively, while it was 85 %, 73 %, and 72 % of the FC in 10-20 cm depths for SP, BP and CT treatments respectively. For 0-20 cm depth, SP showed significantly ($p<0.05$) higher soil water storage throughout the whole season, except at the booting stage when soil water storage was the same for all tillage treatments. Strip planting stored 20 %, 27 %, 15 %, 36 % and 22 % higher soil water compared to CT plots in the 0-20 cm depth at sowing, CRI, anthesis, grain filling and harvest time, respectively, which resulted in 0.99 cm, 0.93 cm, 0.54 cm, 1.02 cm, and 0.61 cm higher soil water at those growing stages in 0-20 cm depth. At this depth, soil water values for BP and CT treatments were similar, but both were significantly lower than that for the SP treatment. The overall soil water storage in the 0-20 cm depth was 4.08 cm higher in SP and 1.2 cm higher in BP treatment compared to CT treatment. Soil water storage increased with increasing depth from 20 to 180 cm, and at all depths and growth stages, soil water storage was statistically equal for all three-tillage treatments. By contrast, in 20-30 cm depth, SP and BP treatment significantly stored 24 % and 15 % more water compared to CT at the grain filling stage.

In 2015-16, SWC in the 0-10 cm depth at wheat sowing was highest with SP and BP treatments and lowest with CT treatment. Soil water in the 10-20 cm depth followed the same trend. In the 0-20 cm depth, SP treatment had 20 % higher soil water compared to CT at sowing. Soil water storage in this depth for BP was also 20 % greater than CT treatment. At sowing, SWC at 0-20 cm depth was higher than the year 2014-15. Soil water storage at sowing was 85 %, 87 %, and 74 % of FC in 0-10 cm depth for SP, BP and CT respectively, and in 10-20 cm, soil water was 97 %, 95 % and 78 % of FC for SP, BP and CT plots, respectively. In 0-20 cm depth, SP stored 24 %, 20 %, 21 %, and 31 % higher soil water than CT plot, which resulted in 0.9 cm, 0.82 cm, 0.82 cm and 1.10 cm higher water content at CRI, booting, anthesis, and grain filling stage of the wheat season. Bed planting stored 9 %, 10 %, 14 % and 14 % higher soil water than CT plot, which resulted in 0.35 cm, 0.41 cm, 0.55 cm and 0.50 cm more water content in the 0-20 cm depth at CRI, booting, anthesis, and grain filling stage of the wheat season. Similar to the year 2014-15, the difference in soil water storage in 20-30 cm depth was not significant throughout the whole season, except in the grain filling stage when SP stored 17 % more ($p<0.05$) soil water than BP and CT treatment. The overall soil water storage (0-30 cm) in the SP and BP plots was 7 cm and 4 cm higher, respectively, than the CT Plots.

In 2016-17, wheat sowing was done one week earlier than in 2014-15 and 2015-16. At 0-10 cm depth, soil water storage at sowing was 88 %, 90 %, and 78 % of FC in 0-10 cm depth for SP, BP and CT, respectively, and in 10-20 cm depth, soil water was 97 %, 96 % and 83 % of FC for SP, BP and CT plots respectively. Thus, soil moisture at sowing was 4 % (average of three tillage treatment) higher than the 2015-16 sowing period and was the highest among the three wheat seasons. Soil water storage of the surface 0-20 cm soil depth was significantly ($p<0.05$) higher in SP than CT plots throughout the whole season. In 0-10 cm soil depth, there was no significant difference in soil water storage between ST and BP treatments at the commencement of the season. The difference, however, started to appear as the season advanced. Averaging water storages across the growing stages, SP and BP treatment stored 19 % and 10 %, respectively, more water than CT treatment in 0-10 cm soil depth. In 10-20 cm depth, considering overall water storages across the growing stages, SP and BP treatment stored 30 % and 26 %, respectively, more water than CT. In 20-30 cm depth, there was no significant difference regarding soil water storage among the tillage treatments until the middle of the season. From anthesis to harvest, SP and BP stored significantly (22 % and 20 %, respectively), higher soil water than CT treatment in the 20-30 cm depth. The overall soil water storage (0-30 cm soil profile) in the SP and BP plots was 7.5 cm and 6.35 cm higher, respectively, compared to CT plots.

Table 5.3 Tillage effects on soil water storage (cm) of the soil profile at different growth stages of wheat for Digram, Rajshahi site in 2014-15, 2015-16 and 2016-17.

Year 1							
Depth, cm	**Tillage**	**Growing stages of wheat**					
		Sowing	**CRI**	**Booting**	**Anthesis**	**Grain Filling**	**Harvest**
0-10	SP	2.89	2.11	2.44	2.08	1.79	1.85
	BP	2.39	1.53	2.4	2	1.66	1.41
	CT	2.35	1.6	2.52	1.74	1.56	1.37
	$LSD_{0.05}$	0.24	0.2	ns	0.21	ns	0.25
10-20	SP	3.03	2.27	2.39	2.03	2.15	1.74
	BP	2.63	1.86	2.43	2.1	1.78	1.59
	CT	2.58	1.85	2.54	1.83	1.36	1.61
	$LSD_{0.05}$	0.32	0.34	ns	0.16	0.17	ns
20-30	SP	3.51	2.97	2.81	2.53	2.73	2.27
	BP	3.23	2.75	2.93	2.75	2.53	2.43
	CT	2.83	2.45	3	2.54	2.19	2.52
	$LSD_{0.05}$	ns	ns	ns	ns	0.27	ns
30-60	SP	9.83	8.9	9.79	9.35	9.73	9.22
	BP	10.55	9.69	8.91	9.78	9.95	9.4
	CT	9.14	8.38	8.89	9.16	9.62	9.75
	$LSD_{0.05}$	ns	ns	ns	ns	ns	ns
60-90	SP	10.61	9.8	10.25	9.88	9.05	9.99
	BP	9.73	8.92	10.01	9.54	9.37	9.63
	CT	9.63	8.9	9.71	9.65	9.22	9.72
	$LSD_{0.05}$	ns	ns	ns	ns	ns	ns
90-120	SP	10.09	9.5	10.42	10.04	9.62	10.12
	BP	10.47	9.93	10.16	10.06	9.46	10.48
	CT	10.69	10.14	9.71	10	9.49	10.18
	$LSD_{0.05}$	ns	ns	0.25	ns	ns	ns
120-180	SP	20.75	19.77	20.65	20.85	19.95	19.83
	BP	21.18	20.21	20.13	20.41	19.76	20.05
	CT	20.26	20.3	20	19.6	19.53	20.23
	$LSD_{0.05}$	ns	ns	ns	ns	ns	ns

Year 2							
Depth, cm	**Tillage**	**Growing stages of wheat**					
		Sowing	**CRI**	**Booting**	**Anthesis**	**Grain Filling**	**Harvest**
0-10	SP	3.04	2.34	2.38	2.27	1.98	1.99
	BP	3.08	2.2	2.16	2.03	1.79	1.83
	CT	2.63	1.87	1.97	1.9	1.67	1.78
	LSD$_{0.05}$	0.36	0.33	0.16	0.23	0.2	ns
10-20	SP	3.45	2.27	2.52	2.41	2.59	2.26
	BP	3.39	1.86	2.33	2.38	2.18	1.96
	CT	2.78	1.84	2.11	1.96	1.8	1.6
	LSD$_{0.05}$	0.49	0.34	0.18	0.27	0.23	0.46
20-30	SP	3.4	3.04	2.87	2.6	2.86	2.73
	BP	3.37	2.96	2.87	2.61	2.46	2.58
	CT	3.26	2.91	2.79	2.53	2.44	2.5
	LSD$_{0.05}$	ns	ns	ns	ns	0.2	ns
30-60	SP	10.68	9.64	9.56	9.88	9.98	10.13
	BP	10.51	9.44	9.62	9.94	9.94	9.99
	CT	10.57	9.52	9.66	9.93	9.88	10.06
	LSD$_{0.05}$	ns	ns	ns	ns	ns	ns
60-90	SP	10.53	9.7	10.05	10.16	9.36	10.08
	BP	10.64	9.76	10.12	9.74	9.56	10.09
	CT	10.65	9.82	9.87	9.78	9.44	10.01
	LSD$_{0.05}$	ns	ns	ns	ns	ns	ns
90-120	SP	10.73	10.03	10.12	10.29	9.95	10.33
	BP	10.8	10.09	10.08	10.16	9.78	10.47
	CT	10.79	10.08	10.03	10.17	9.74	10.48
	LSD$_{0.05}$	ns	ns	ns	ns	ns	ns
120-180	SP	21.55	20.27	21.3	19.77	20.06	21.39
	BP	21.48	20.19	21	20.02	20.02	20.95
	CT	21.36	20.07	20.9	19.02	19.85	21.2
	LSD$_{0.05}$	ns	ns	ns	ns	ns	ns

Year3							
Depth	**Tillage**	**Growing stages of wheat**					
		Sowing	**CRI**	**Booting**	**Anthesis**	**Grain Filling**	**Harvest**
0-10	SP	3.14	2.38	2.1	1.93	1.71	1.48
	BP	3.22	2.35	1.97	1.78	1.51	1.17
	CT	2.78	1.98	1.95	1.43	1.37	1.28
	$LSD_{0.05}$	0.29	0.25	0.12	0.14	0.18	0.23
10-20	SP	3.46	2.27	2.45	2.31	2.41	2.33
	BP	3.4	1.86	2.54	2.45	2.29	2.25
	CT	2.95	1.84	2.25	1.84	1.5	1.6
	$LSD_{0.05}$	0.36	0.34	0.2	0.3	0.38	0.34
20-30	SP	3.57	3.29	2.88	2.85	3.03	3.01
	BP	3.53	3.27	2.99	2.97	3.03	2.76
	CT	3.26	2.93	2.86	2.5	2.42	2.36
	$LSD_{0.05}$	ns	ns	ns	0.15	0.18	0.27
30-60	SP	10.87	9.82	10.01	10.27	10.16	9.82
	BP	11.04	9.99	9.89	10.18	10.09	9.77
	CT	10.2	9.21	9.43	9.89	10.17	9.59
	$LSD_{0.05}$	ns	ns	ns	ns	ns	ns
60-90	SP	11.03	10.04	9.69	9.59	8.86	9.87
	BP	10.91	9.89	9.53	9.39	9.05	10.03
	CT	10.33	9.41	9.14	9.4	9.01	10.06
	$LSD_{0.05}$	ns	ns	ns	ns	ns	ns
90-120	SP	11.18	10.27	9.96	9.7	8.95	10.04
	BP	11.06	10.18	9.81	9.49	8.72	9.86
	CT	10.71	9.89	10.01	9.57	9.02	10.02
	$LSD_{0.05}$	ns	ns	ns	ns	ns	ns
120-180	SP	21.9	20.31	19.92	19.72	18.96	20.98
	BP	21.76	20.17	19.93	19.58	18.48	20.83
	CT	21.89	20.33	20.01	19.77	19.16	20.82
	$LSD_{0.05}$	ns	ns	ns	ns	ns	ns

5.3.3 Effect of tillage on the yield of Wheat

In the SP treatment, wheat yield averaged across the residue levels was 18 %, 25 % and 21 % higher than in the CT treatment, respectively, in year 1, year 2 and year 3 (In year 1, the wheat yield was highest (5.28 t ha^{-1}) in the SP-HR treatment and lowest (4.15 t ha^{-1}) in the CT-LR treatment. Similarly, the highest wheat yield was obtained under SP-HR in the last two years (4.48 and 5.04 t ha^{-1} for year 2 and year 3, respectively). The lowest wheat yield in year 2 was found under BP-LR (3.02 t ha^{-1}), while in year 3, it was found under CT-LR treatment (3.71 t ha^{-1}). Bed planting produced higher wheat yield than CT practice though the effect was only significant in year 1. In year 1, wheat grain yield was 16 % higher in BP than in CT. Rice residue retention treatment had a significant effect on wheat yield in three years. Averaged across the tillage treatments, high residue retention treatment increased wheat yield by 7 — 18 % in three years.

There was no significant tillage × year interaction on wheat yield. In the first year, the wheat yield was significantly higher than that in the other two years. Yield declined from 5.10 t ha^{-1} in the first year to 4.28—4.78 t ha^{-1} in subsequent years for SP, and from 5.03 t ha^{-1} in the first year to 3.41—4.03 t ha^{-1} in subsequent years for BP. In the second year, the reduction in yield under BP (1.62 t ha^{-1}) was double that the reduction in yield under SP (0.82 t ha^{-1}). In year 3, the difference in yield compared to year 1 under SP was 0.32 t ha^{-1}. In contrast, the yield difference under BP in year 3 compared to year 1 was double that under SP (0.62 t ha^{-1}). It is also interesting to note that the mean yield advantage of SP over CT in the last 2 years (0.86 t ha^{-1}) was higher than that in the first year (0.76 t ha^{-1}).

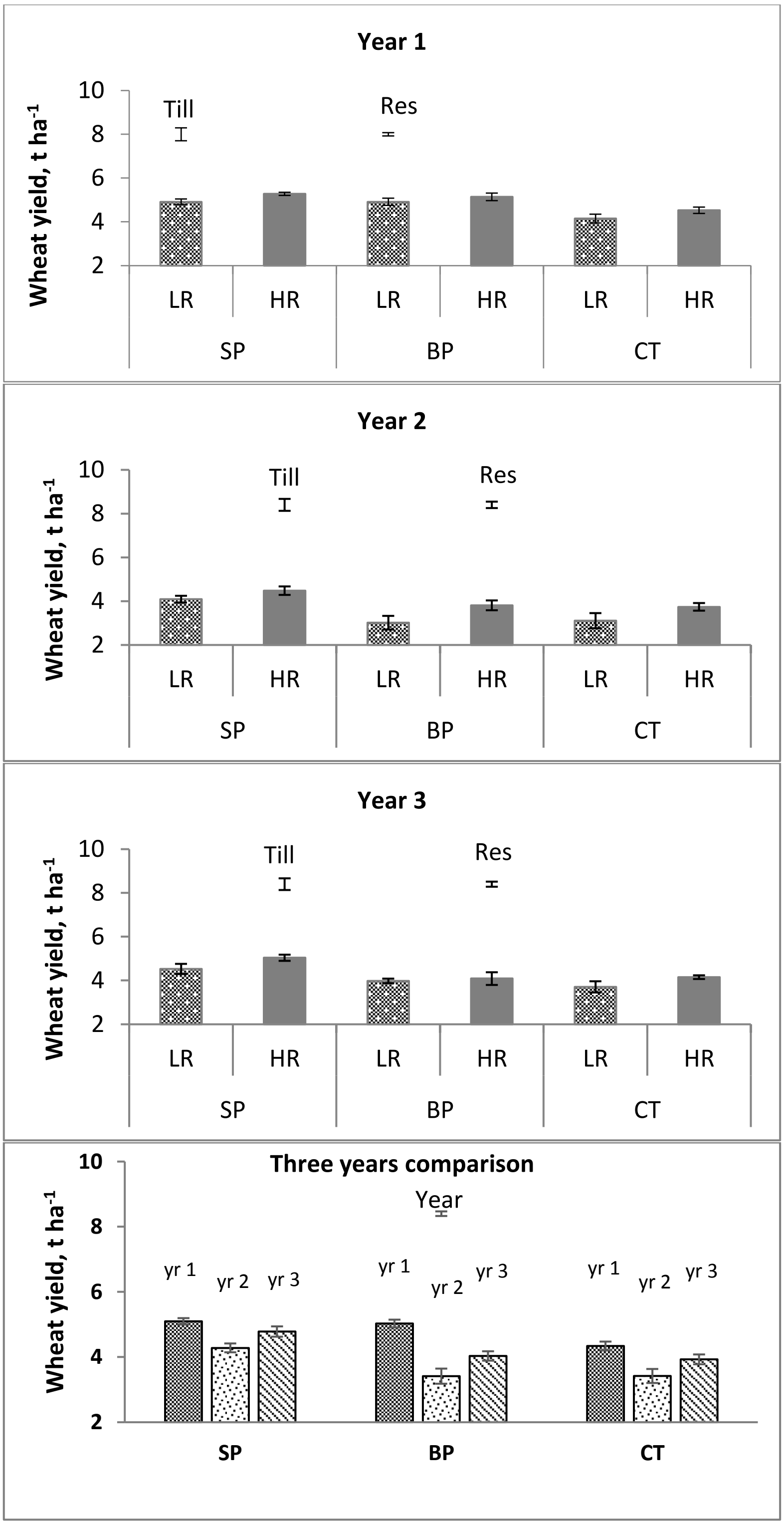


Figure 5.2 Tillage and residue effects on Wheat yield for Digram, Rajshahi site in 2014-15, 2015-16 and 2016-17 and for the average of residue levels over the three years. SP= Strip planting, BP= Bed Planting, CT= Conventional tillage. Note, the tillage × residue interaction was not significant for any of the 3 years.

5.3.4 Yield components of wheat

Plant population at 30 days after sowing (DAS)

Plant population at 30 DAS under LR management was 6.4 %, 5.3 % and 6.0 % higher than that under HR management in respectively Year 1, Year 2 and Year 3 (Table 5.4). In Year 1, plant population under SP and BP was respectively 7.1 % and 3.5 % higher than that under CT, while SP gave 3.4 % higher plant population than BP. In Year 2, SP and BP gave 8.3 % and 2.3 % higher plant population than CT, respectively, and plant population under SP was 5.9 % higher than that under BP. In Year 3, SP resulted in a 9.3 % higher plant population than BP and CT with no significant differences between BP and CT. Taking an average across all treatments, Year 1 gave significantly 6.6 % and 5.0 % higher plant population than Year 2 and Year 3, respectively, with no significant difference in Year 2 and Year 3. Year and tillage interaction did not affect significantly plant population.

Plant population at harvest

Plant population at harvest according to different treatments followed the same trend of plant population at 30 DAS. Plant population at harvest under LR management was 7.0 %, 6.0 % and 6.5 % higher than that under HR management in Year 1, 2 and 3, respectively (Table 5.4). In Year 1, SP and BP resulted in respectively 9.6 % and 6.7 % higher plant population than CT with 2.7 % higher plant population under SP than BP. In Year 2, SP gave 6.6 % and 8.2 % higher plant population compared to BP and CT, with no significant difference between BP and CT. Similarly, in Year 3, SP resulted in 7.6 % and 9.5 % higher plant population compared to BP and CT, and there was no significant difference in plant population between BP and CT. Year 1 resulted in significantly 6.4 % and 3.8 % higher plant population than Year 2 and Year 3, respectively, with no significant difference between Year 2 and Year 3.

Total tillers/plant and effective tillers/plant

In Year 1, total tillers per plant under SP (7.1) and under BP (6.8) were significantly higher than CT (5.9), with no significant difference between SP and BP (Table 5.5). Similarly, in Year 3, SP (6.4) and BP (6.1) resulted in significantly higher total tillers per plant than CT (5.1).

Similar trends were observed for effective tillers per plant. In Year 1, SP (5.9) and BP (5.6) gave higher effective tillers per plant than CT (4.8). In year 3, effective tillers under BP (5.4) was higher than that under CT (4.9).

Spikes/m^2

In Year 1, HR management under SP significantly increased spikes/m^2 by 4.8 % compared to LR (Table 5.6). By contrast, HR under BP and CT reduced spikes/m^2 by 7.0 % and 5.5 %, respectively, compared to LR. In Year 2 and Year 3, averaged across the tillage treatments, HR management increased spikes/m^2 by 4.9 % and 4.7 % over LR management. In Year 2, SP increased 15 % and 17 % spikes/m^2 than BP and CT, respectively. Similarly, in Year 3, SP obtained 15.5 % and 18 % more spikes/m^2 compared to BP and CT, respectively. The highest spikes/m^2 was obtained in Year 1, which is 10 % higher than Year 2 and 5.7 % higher than Year 3.

Grains/Spike and 1000 grain weight

There was no significant effect of tillage or residue or their interactions on grains/spike or on 1000 grain weight. The highest number of grains/spike was found in Year 1 with no significant difference from that in Year 3 (Table 5.6). There was a significant difference between grains/spike of Year 1 and Year 2 and between Year 2 and Year 3.

Table 5.4 Effects of tillage and residue management on yield components of wheat in three years.

Tillage treatments	Year 1			Year 2			Year 3		
	LR	**HR**	**Mean**	**LR**	**HR**	**Mean**	**LR**	**HR**	**Mean**
Plant population/m² at 30 DAS									
SP	157	144	150	147	138	143	150	142	146
BP	151	140	145	138	132	135	139	128	133
CT	141	139	140	135	129	132	137	131	134
Mean	150	141		140	133		142	134	
$LSD_{0.05}$									
Tillage				3.0					
Residue				2.4					
Tillage × Residue				ns					
Year				3.0					
Year × Tillage				ns					
Plant population/m² at harvest									
SP	152	139	146	143	133	138	147	138	142
BP	148	135	142	133	126	130	134	123	128
CT	134	132	133	131	125	128	130	124	127
Mean	145	135		136	128		137	128	
$LSD_{0.05}$									
Tillage				3.1					
Residue				2.6					
Tillage × Residue				ns					
Year				3.1					
Year × Tillage				ns					

Table 5.5 Effects of tillage and residue management on tillers/plant of wheat in three years.

Tillage treatments	Year 1			Year 2			Year 3		
	LR	**HR**	**Mean**	**LR**	**HR**	**Mean**	**LR**	**HR**	**Mean**
Tillers/plant									
SP	6.8	7.5	7.1	6.3	6.3	6.3	6.0	6.8	6.4
BP	6.5	7.0	6.8	6.0	6.3	6.1	6.0	6.3	6.1
CT	5.8	6.0	5.9	6.0	6.3	6.1	4.8	5.5	5.1
Mean	6.3	6.8		6.1	6.3		5.6	6.2	
$LSD_{0.05}$									
Tillage				0.6					
Residue				ns					
Tillage × Residue				ns					
Year				ns					
Year × Tillage				ns					
Effective tillers/plant									
SP	5.5	6.3	5.9	5.5	5.3	5.4	5.0	5.5	5.3
BP	5.5	5.8	5.6	5.3	5.8	5.5	5.3	5.5	5.4
CT	4.3	5.3	4.8	5.0	5.3	5.1	4.8	5.0	4.9
Mean	5.1	5.8		5.3	5.4		5.0	5.3	
$LSD_{0.05}$									
Tillage				0.5					
Residue				ns					
Tillage × Residue				ns					
Year				ns					
Year × Tillage				ns					

Table 5.6 Effects of tillage and residue management on spikes/m², grains/spike of wheat in three years.

Tillage treatments	Year 1			Year 2			Year 3		
	LR	HR	Mean	LR	HR	Mean	LR	HR	Mean
Spikes/m²									
SP	312	327	320	293	312	303	309	324	316
BP	318	297	308	258	268	263	265	283	274
CT	288	273	280	253	263	258	265	271	268
Mean	306	299		268	281		280	293	
$LSD_{0.05}$									
Tillage				4.4					
Residue				3.6					
Tillage × Residue				6.3					
Year				5.4					
Year × Tillage				ns					
Grains/spike									
SP	51.0	52.4	51.7	47.4	47.6	47.5	50.3	51.1	50.7
BP	50.4	51.5	50.9	48.0	47.7	47.9	50.6	50.9	50.7
CT	50.0	50.1	50.0	48.1	48.2	48.1	50.2	49.9	50.1
Mean	50.5	51.3		47.8	47.8		50.4	50.6	
$LSD_{0.05}$									
Tillage				ns					
Residue				ns					
Tillage × Residue				ns					
Year				0.7					
Year × Tillage				ns					

Table 5.7 Effects of tillage and residue management on the 1000-grain weight of wheat in three years.

Tillage treatments	Year 1			Year 2			Year 3		
	LR	HR	Mean	LR	HR	Mean	LR	HR	Mean
1000-grain weight									
SP	50.5	50.8	50.7	50.4	49.7	50.0	50.0	50.3	50.2
BP	50.5	50.1	50.3	49.9	49.8	49.8	50.5	50.1	50.3
CT	50.4	50.1	50.3	49.8	49.9	49.8	50.0	50.1	50.1
Mean	50.5	50.3		50.0	49.8		50.2	50.2	
$LSD_{0.05}$									
Tillage				ns					
Residue				ns					
Tillage × Residue				ns					
Year				ns					
Year × Tillage				ns					

5.3.5 Irrigation water productivity

Significantly higher irrigation water productivity (WP_I) of wheat was recorded with SP compared to CT treatment (Figure 5.3). For the wheat crop, WP_I was 2.01-2.39 kg m^{-3}, 1.67-1.84 kg m^{-3}, and 1.24-1.50 kg m^{-3} in SP, BP and CT, respectively, across three years of experimentation. The WP_I of wheat (three years mean) was increased significantly by about 67 % with SP compared to CT, irrespective of residue retention. Wheat on BP improved WP_I by 35 % (three years mean) compared to CT. In year 2 and 3, WP_I in wheat under SP was significantly higher by 35 % (two years average) compared to wheat on BP. Averaged across the tillage treatments, WP_I with high rice residue retention was significantly higher by 13-22 % than the low residue only in year 1 and year 2. There was no significant difference in wheat grain WP_I between years.

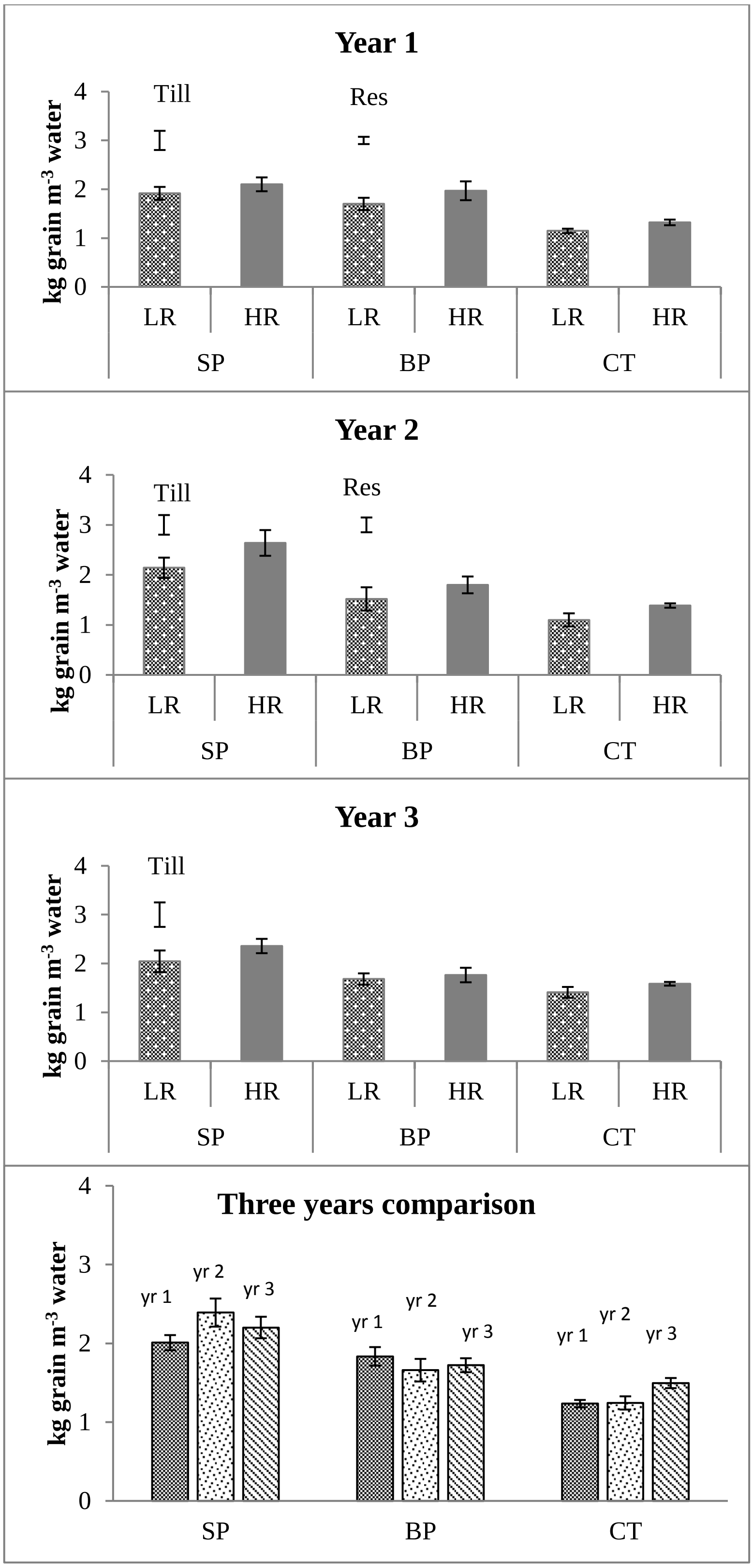


Figure 5.3 Tillage and residue effects on irrigation water productivity of wheat for Digram, Rajshahi site in 2014-15, 2015-16 and 2016-17 and comparison of yield of three years. SP= Strip planting, BP= Bed Planting, CT= Conventional tillage.

5.3.6 Crop water use efficiency

Both SP and HR retention treatment increased crop water use efficiency (WUE), although the effect was significant only in year 2 and year 3 (Figure 5.4). Like irrigation water productivity, the highest WUE was achieved (2.41 kg m^{-3}) under SP-HR treatment in year 3, while the lowest value of WUE (1.18 kg m^{-3}) was found under CT-LR treatment in year 2. The WUE recorded in wheat under SP was 20-54 % more (averaged across the residue treatment) than that under CT. Bed planting had no significant effect on WUE relative to CT in any of the three years. Averaged across the tillage treatments, high residue retention treatment had a mean 18 % higher WUE compared to low residue treatment. Averaged across the tillage and residue treatments, the highest (1.86 kg m^{-3}) WUE was achieved in year 1.

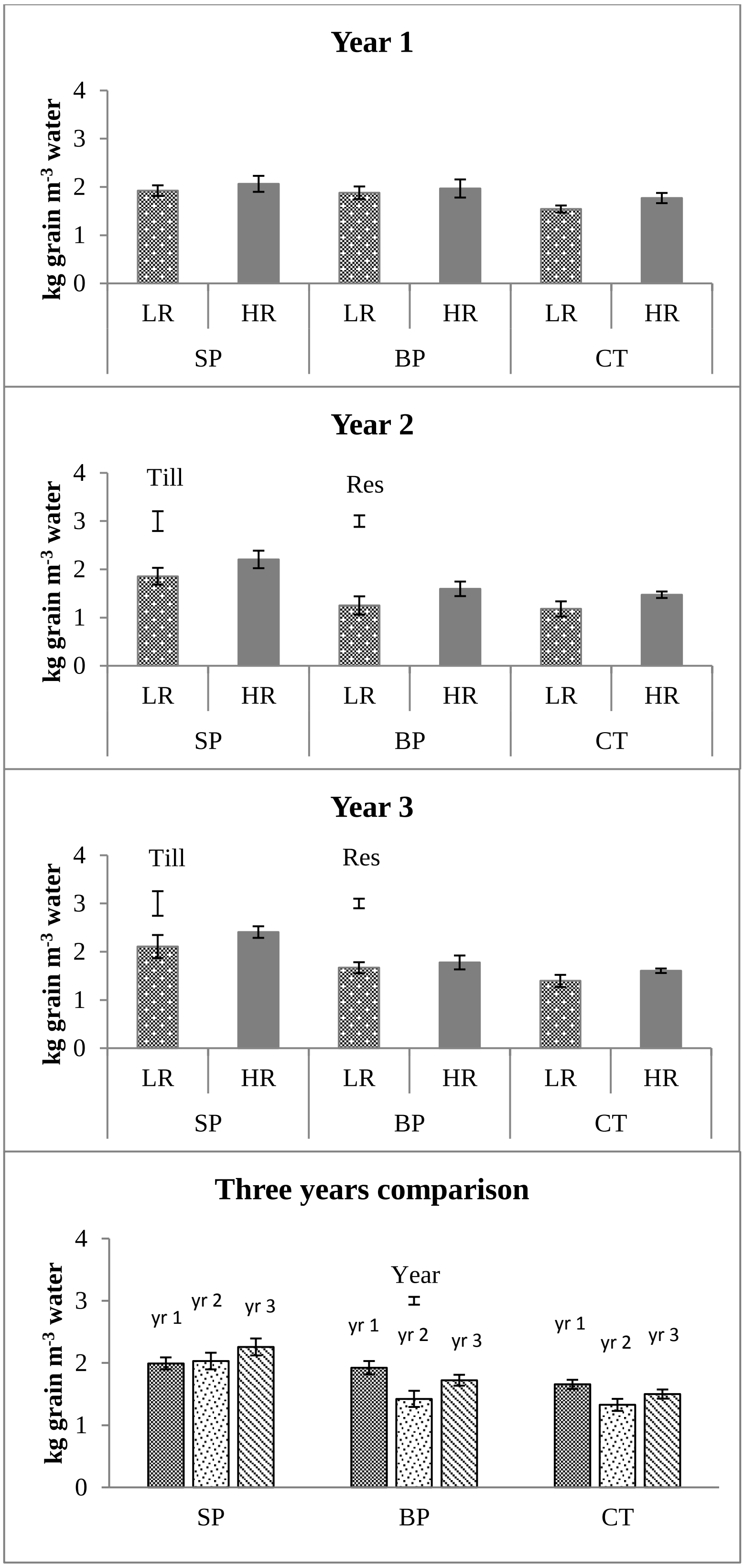


Figure 5.4 Tillage and residue effects on crop water use efficiency of wheat for Digram, Rajshahi site in 2014-15, 2015-16 and 2016-17 and comparison averaged over residue level for of three years. SP= Strip planting, BP= Bed Planting, CT= Conventional tillage.

5.3.7 Measured crop evapotranspiration vs simulated crop evapotranspiration at different growing stages of wheat

Table 5.1 shows side by side comparison between measured and simulated crop evapotranspiration of wheat at different growth stages. The results demonstrate that in year 1, measured ET_c was affected significantly by tillage treatments only at the CRI stage. At this stage, SP significantly increased measured ET_c compared to CT. In contrast, simulated ET_c was affected by tillage treatments at all growing stages except the CRI stage. However, the effect of SP on reducing simulated ET_c compared to CT was inconsistent among different growing stages. At the booting stage, simulated ET_c in SP was significantly similar to that in CT. At anthesis, simulated ET_c in SP was lower than that in CT. However, as the crop approached the grain filling stage, SP showed similar simulated ET_c to CT. At harvest, simulated ET_c in SP was higher than that in CT. Simulated ET_c under BP was higher than CT at booting stage, while that was reduced compared to CT at anthesis and grain filling stage, again simulated ET_c was increasing compared to CT in the harvest. In year 1, there was no significant effect of high residue retention treatment on reducing either measured or simulated ET_c compared to CT.

In year 2, there was no significant effect of tillage treatments on simulated ET_c in either of the growing stages. While SP reduced measured ET_c compared to CT, the effect was significant only at the stages after booting. Reduction in measured ET_c under SP compared to CT was 23 %, 20 % and 19 %, respectively, in anthesis, grain filling, and harvest. Measured ET_c under BP was intermediate between SP and CT at all growing stages except CRI. High residue retention treatment significantly reduced measured ET_c by 6 % and 5 % over low residue treatment at the booting and grain filling stage.

Similar to year 2, SP significantly reduced measured ET_c compared to CT at all stages except CRI in year 3. However, in contrast to year 2, the reduction in measured ET_c was less in the earlier stages than the later stages. Reduction in measured ET_c by SP was 20 %, 24 %, 24 %, and 28 % compared to CT in booting, anthesis, grain filling and harvest, respectively. At these growing stages, similar to SP, BP reduced measured ET_c compared to CT. Reduction in measured ET_c by BP compared to CT was 19 %, 18 %, and 20 %, respectively, in anthesis, grain filling and harvest. High residue retention treatment reduced measured ET_c compared to low residue treatment, but the effect was significant only at the harvest stage by 11 %. Simulated ET_c was not affected either by tillage or residue treatment at either of the growing stages.

Table 5.8 Measured and simulated crop evapotranspiration ET_c (cm) at different growth stages of wheat as affected by tillage and residue retention treatments for Digram, Rajshahi site in 2014-15, 2015-16 and 2016-17. Crop evapotranspiration for different growth stages was calculated from the changes in soil water content measured before each irrigation at each growing stages. Simulated ET_c was estimated using the DSSAT-CSM-CERES-Wheat model (see section 5.2.4).

Wheat crop evapotranspiration (ET_c)													
Depth, cm	**Tillage**	**Growing stages of wheat**											
		CRI		**Booting**		**Anthesis**		**Grain Filling**		**Harvest**		**Total**	
		Meas	**Simu**	**Meas**	**Simu**	**Meas**	**Simu**	**Meas**	**Simu**	**Meas**	**Simu**	**Meas**	**Simu**
Year 1	SP-LR	2.85	2.72	4.16	3.97	5.48	5.24	6.40	6.12	6.86	6.56	25.74	24.62
	SP-HR	2.82	2.68	4.16	3.93	5.55	5.25	6.48	6.12	7.03	6.64	26.03	24.61
	BP -LR	2.78	2.64	4.46	4.24	5.50	5.21	6.44	6.10	7.18	6.81	26.36	24.99
	BP-HR	2.62	2.46	4.44	4.12	5.68	5.23	6.58	6.05	7.28	6.73	26.61	24.60
	CT-LR	2.44	2.55	4.34	3.75	6.12	5.31	7.04	6.13	7.01	6.12	26.96	23.85
	CT-HR	2.04	2.47	4.19	3.80	5.84	5.29	6.81	6.16	6.89	6.28	25.77	24.00
	$LSD_{0.05\ Till}$	0.43	ns	Ns	0.27	ns	0.05	ns	0.04	ns	0.43	ns	ns
	$LSD_{0.05\ Res}$	ns	ns	Ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

Wheat crop evapotranspiration (ET_c)													
Depth, cm	**Tillage**	**Growing stages of wheat**											
		CRI		**Booting**		**Anthesis**		**Grain Filling**		**Harvest**		**Total**	
		Meas	**Simu**	**Meas**	**Simu**	**Meas**	**Simu**	**Meas**	**Simu**	**Meas**	**Simu**	**Meas**	**Simu**
Year 2	SP-LR	2.44	2.59	3.80	4.02	4.86	5.12	5.71	6.03	5.58	5.88	22.39	23.63
	SP-HR	2.33	2.77	3.25	3.87	4.64	5.54	5.14	6.13	5.15	6.15	20.51	24.47
	BP -LR	3.02	3.05	3.92	3.96	5.55	5.57	6.11	6.15	6.07	6.12	24.68	24.85
	BP-HR	2.66	2.70	3.87	3.95	5.48	5.57	6.04	6.14	6.09	6.20	24.14	24.56
	CT-LR	2.83	2.54	4.08	3.68	6.27	5.66	6.85	6.18	6.65	6.01	26.67	24.07
	CT-HR	2.35	2.20	3.88	3.62	6.05	5.65	6.61	6.17	6.52	6.08	25.40	23.71
	$LSD_{0.05\ Till}$	ns	ns	Ns	ns	0.66	ns	0.65	ns	0.76	ns	2.70	ns
	$LSD_{0.05\ Res}$	ns	ns	0.15	ns	ns	ns	0.29	ns	ns	ns	ns	ns

Wheat crop evapotranspiration (ET_c)													
Depth, cm	**Tillage**	**Growing stages of wheat**											
		CRI		**Booting**		**Anthesis**		**Grain Filling**		**Harvest**		**Total**	
		Meas	**Simu**	**Meas**	**Simu**	**Meas**	**Simu**	**Meas**	**Simu**	**Meas**	**Simu**	**Meas**	**Simu**
Year 3	SP-LR	2.36	2.50	3.43	4.22	4.54	5.14	5.30	6.16	4.29	6.20	22.08	24.21
	SP-HR	2.21	2.34	3.24	4.11	4.32	5.13	5.03	6.10	3.86	6.13	21.02	23.81
	BP -LR	2.46	2.61	3.95	4.16	4.85	5.16	5.69	6.15	4.87	6.17	24.08	24.25
	BP-HR	2.21	2.61	3.70	4.17	4.69	5.15	5.43	6.16	4.16	6.22	23.06	24.31
	CT-LR	2.36	2.43	4.24	4.14	5.99	5.16	6.88	6.16	5.89	6.34	26.78	24.24
	CT-HR	2.01	2.52	4.09	4.05	5.71	5.19	6.65	6.15	5.41	6.51	25.92	24.42
	$LSD_{0.05\ Till}$	ns	ns	0.54	ns	0.69	ns	0.77	ns	0.67	ns	3.08	ns
	$LSD_{0.05\ Res}$	ns	ns	Ns	ns	ns	ns	ns	ns	0.27	ns	ns	ns

5.3.8 Simulated cumulative crop evapotranspiration, transpiration, and soil evaporation.

There were no significant differences in simulated cumulative ET_c under different tillage treatments and year. However, SP increased transpiration from wheat plant compared to CT, although the increment was significant only in year 1 when water was applied irrespective of evaporation demand and thus wheat plot was over irrigated (Table 5.9). Alternatively, SP significantly reduced simulated soil evaporation by about 1 cm over CT in year 1. Like SP, BP also increased transpiration by 2.4 cm and reduced soil evaporation by 1.6 cm over CT in year 1. In year 2 and year 3, there were no significant differences in simulated soil evaporation under three tillage treatments. Both transpiration and soil evaporation were significantly different according to years. In year 3, transpiration under SP and BP was less than those in year 1 and 2, while in year 3, soil evaporation was higher in SP and BP compared to year 1 and year 2.

Table 5.9 Separation of Crop evapotranspiration into transpiration and soil evaporation using the DSSAT model for three years and three tillage treatments.

Treatments	**Transpiration**			**Soil evaporation**		
	Year 1	**Year 2**	**Year 3**	**Year 1**	**Year 2**	**Year 3**
SP	14.4	14.7	12.9	10.2	9.3	11.1
BP	15.1	14.8	12.9	9.6	9.9	11.4
CT	12.7	13.2	12.6	11.2	10.7	11.7
$LSD_{0.05}$ Till	1.47	ns	ns	0.81	ns	ns
$LSD_{0.05}$ Year	0.64			0.42		

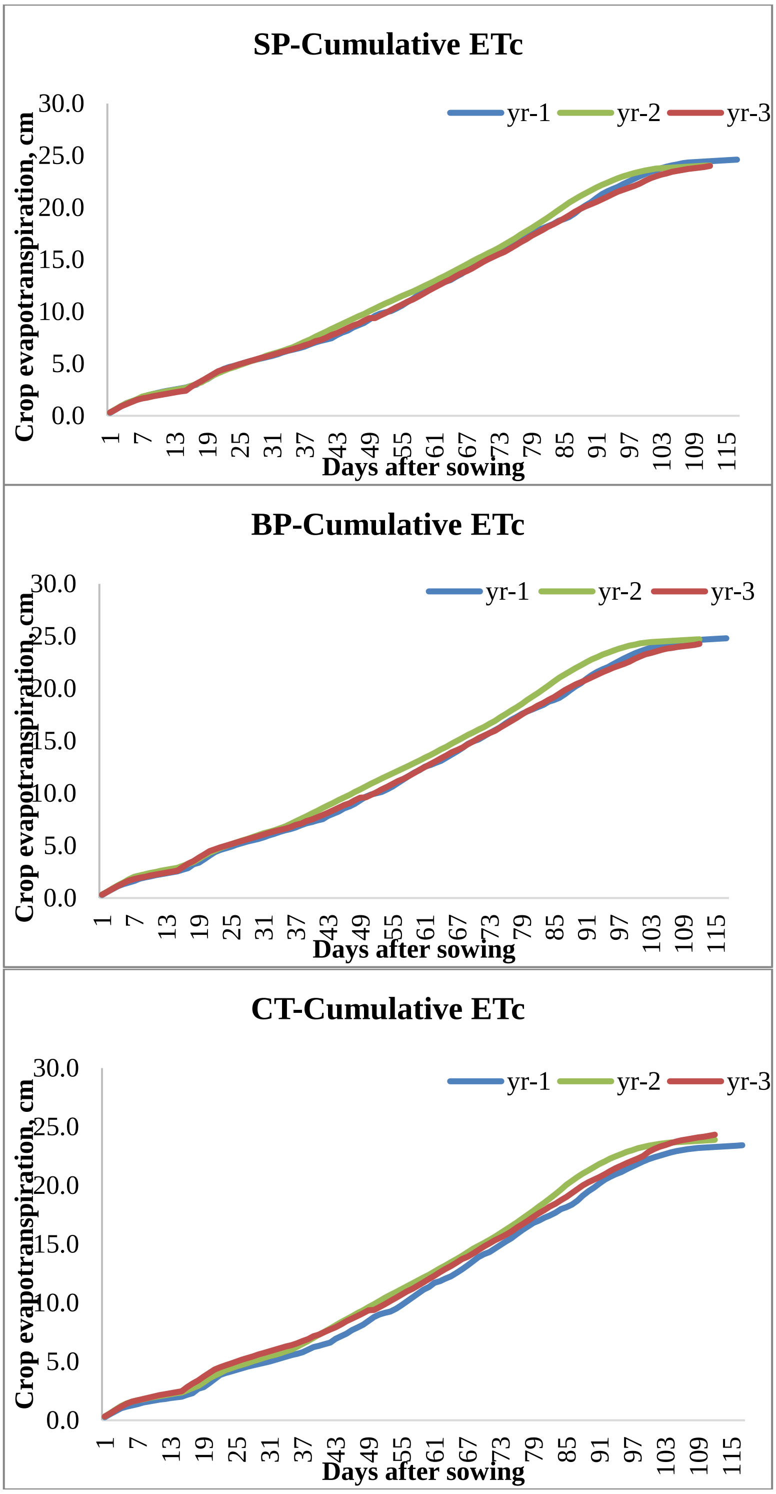


Figure 5.5 Cumulative ET_c simulated using the DSSAT-CSM-CERES-Wheat model for SP-Strip planting, BP-Bed Planting and CT-Conventional tillage for wheat in three years.

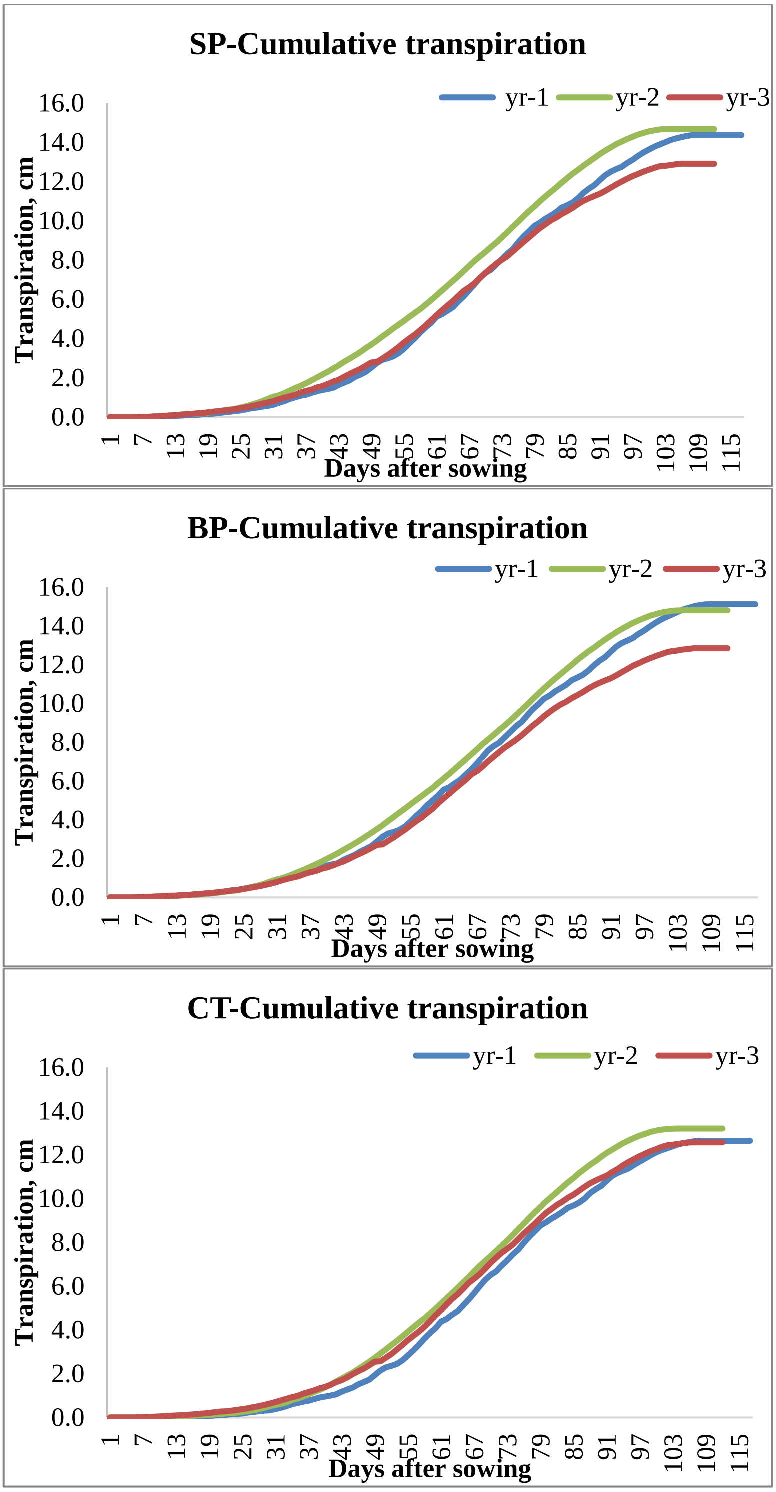


Figure 5.6 Cumulative plant transpiration simulated using the DSSAT-CSM-CERES-Wheat model for SP-Strip planting, BP-Bed Planting and CT-Conventional tillage for wheat in three years.

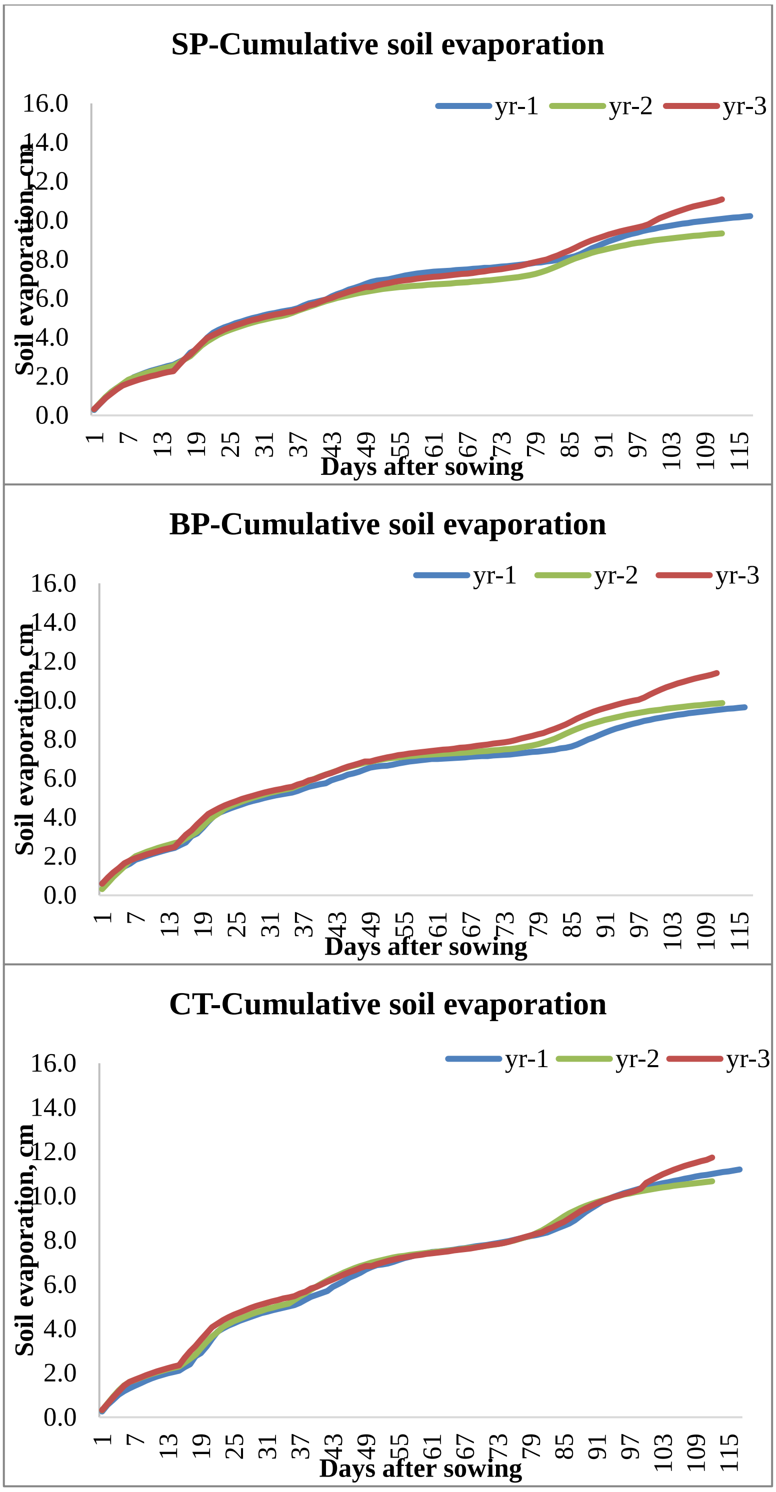


Figure 5.7 Cumulative soil evaporation simulated using the DSSAT-CSM-CERES-Wheat model for SP-Strip planting, BP-Bed Planting and CT-Conventional tillage for wheat in three years.

5.4 Discussion

Increased wheat yield under SP and BP in all three wheat seasons than in CT can be attributed to favourable changes in the soil water environment for wheat growth. Improved soil physical properties in terms of infiltration and water holding capacity likely reduced soil evaporation and supplied more water to the plant roots from deeper in the profile even in the latter part of the season. The SP and BP treatments also saved irrigation water. Consequently, greater yield under SP and BP and reduced irrigation water increased irrigation water productivity and water use efficiency.

5.4.1 Yield advantages by minimum soil disturbance and residue retention

High residue retention increased wheat yield by 7 to 18 % in three years over the low level currently retained by farmers. The increased SOC over seven years might have contributed to yield advantages in HR treatments (Alam *et al.*, 2018b). However, high residue retention in SP and BP treatment gave consistently 5 to 6 % lower plant population at 30 DAS and at harvest. The highest (6 to 9 %) reduction in plant population at 30 DAS was observed in SP, while the reduction in plant population in BP was 5 to 8 %. The lower plant population in SP and BP was attributed to poor seed-soil contact as a result of seeding on residues (Islam, 2016). Despite the lower plant population in the HR treatment, the increased SOC and soil water availability compensated to produce an increased yield in the HR treatment compared to LR treatment.

Considering all three years, wheat yield in SP increased by 17-22 % over CT because of the 8-10 % higher crop establishment in SP. A similar result was also found by Islam (2016), who reported an 8-10 % higher yield in SP compared to CT, which was attributed to the higher plant establishment in SP. Over the three years, wheat grain yield in BP was intermediate. The positive effect of SP on yield occurred despite year to year variations in yield. Strip planting gave a 19 % higher yield in year 1 compared to year 2, which was due to the effect of higher plant population, spikes/m^2 and grains/spikes in year 1 compared to year 2. Higher yield in BP in year 1 compared to year 2 was also attributed to the plant population and spikes per unit area in year 1 compared to year 2. Averaged across all treatments, 30 % higher yield in year 1 compared to year 2 was mainly due to 6 % higher plant population and 10 % higher number of spikes/m^2. Similarly, 13 % lower yield in year 3 compared to year 1 was due to the collective effect of 4 % lower plant population and 6 % lower number of spikes/m^2. The maximum yield of 5.1 t ha^{-1} in SP in Year 1 was higher than the current estimated potential yield of wheat, 3.5-5.1 t ha^{-1} (Mondal *et al.*, 2014). Wheat sowing under the current study was done on 28 November in year 1 and year 2 and on 22 November in year 3. The average (4.25 t ha^{-1}) yield of the current study was consistent with the result of Hossain *et al.* (2011), who found that sowing on 22 November and 29 November BARI Gom-26 wheat variety yielded 3.6 and 4.1 t ha^{-1}, respectively.

5.4.2 Effect of SP on Irrigation water savings

Strip planting in the current study decreased irrigation water supplied by 15—36 % for wheat crops compared to CT. Under SP treatment, planting involved minimal disturbance of the soil, which maintained a level surface in the field which facilitated the faster spread of water across the field in the SP plots than CT, whereby irrigation could be stopped once the wetting of the entire length of the field was complete (Erenstein *et al.*, 2008): this is most likely the reason for reduced irrigation water use. In addition, SP improved soil structure and facilitated SOC build-up (Islam, 2016; Alam *et al.*, 2018b), which has been linked to increased soil water retention capacity, faster infiltration and reduced water use (Erenstein and Laxmi, 2008). Strip planting also involved minimum soil disturbance which has been shown to slow down the loss of water through evaporation (Table 5.2) due to the lesser soil surface area for evaporation (He *et al.*, 2011). Soil cover by undisturbed standing or prostrate rice residue retained in SP plots may also contribute to a reduction in water requirement by conserving soil moisture through a reduction in evaporation loss (Singh *et al.*, 2011; Gathala *et al.*, 2013). Minimum soil disturbance under SP also improved water infiltration (see Chapter 3); hence water that infiltrated deep in the soil was less likely to evaporate quickly. As a result, the water stored deep in the soil is used by the crops in the late wheat season. Strip planting reduced water use for every irrigation event compared to CT. Thus, the lower water use under SP than CT coincided with a lesser amount of irrigation water used in each irrigation as the number of irrigations applied was similar for both tillage systems.

Further savings with SP are also possible because it was possible to sow wheat earlier with the one-pass SP operation than CT to enable wheat to make greater use of residual soil water for germination, potentially saving pre-sowing irrigation. In the present study, CT and SP were planted on the same day, so this advantage of SP was not examined. Delayed sowing of wheat after mid-November also decreased yield potential under CT, so the potential for early sowing may realise greater water use efficiency on farmer's fields using SP.

Few studies on water savings by SP are reported for the EGP. However, there are several studies with ZT wheat that report comparable water savings to that in SP. For example, Jat *et al.* (2009) reported ZT wheat, under double ZT, i.e. zero-till direct drill-seeded rice and wheat after no-tillage (ZTDSR-ZTW), received 24 % less irrigation water compared to CT wheat. Choudhary *et al.* (2018a) reported that the amount of irrigation water applied to ZT wheat with precision irrigation using soil matric potential based approach was 28-41 % less compared to CT wheat with conventional irrigation approach. Jat *et al.* (2013) reported NT wheat under double ZT maize-wheat system received 17 % (across 2 years) less irrigation water compared to CT wheat. Saharawat *et al.* (2010) reported NT wheat had 10 % less water application than that in CT wheat.

5.4.3 Effect of BP on Irrigation water savings

An 8-25 % lower irrigation water use for wheat under BP compared with CT over three cropping years, as observed in the present study, was consistent with earlier reports which showed irrigation water saving ranging from 18-50 % under BP compared with CT treatments (Aggarwal and Goswami, 2003; Hobbs and Gupta, 2003; Hossain *et al.*, 2003; Meisner *et al.*, 2005; Ram *et al.*, 2005; Lauren *et al.*, 2006; Talukder *et al.*, 2006; Jat *et al.*, 2008; Ram *et al.*, 2012; Choudhury *et al.*, 2013). In year 1, water was applied by flood irrigation, and irrigation was stopped when the water level in the furrows reached the top of the bed. The lower irrigation water use in wheat under BP over CT in the first year of our study might be attributed to the volumetric limitation of furrows and faster flow of irrigation water across the field (Humphreys *et al.*, 2008; Jat *et al.*, 2009). The BP technique confines the tractor wheel pass in the furrows only (Limon-Ortega *et al.*, 2006) and thus slows the infiltration of water in the furrow due to its compaction (Kukal *et al.*, 2008; Jat *et al.*, 2009). Wheat was sown with the residual SWC after rice harvest every year. Bed planting potentially increased SOC content in the topsoil (Islam, 2016; Alam *et al.*, 2018b), which beneficially increased water retention. In year 2 and 3, irrigation water was applied according to the evaporation demand. Bed planting and soil cover by rice residue beneficially hindered the loss of water through evaporation and reduced irrigation water use by 5 cm compared to CT.

5.4.4 Effect of BP and SP on crop evapotranspiration and soil water storage

In the present study, the ET_c was met by irrigation water applied as there was very limited rainfall in each of the three wheat seasons. The seasonal ET_c increased with an increase in irrigation amount during the three seasons. Irrespective of tillage treatments, ET_c was highest in year 1 when all tillage treatments were over-irrigated. This may be attributed to the relatively high soil evaporation resulting from prolonged wetting of the soil surface with higher SWC (Liu *et al.*, 2013b). In year 2 and year 3, irrigation amount was governed by the soil water storage, which varied among tillage treatments. Generally, SP treatment had a significantly higher effect than BP and CT on soil water storage in the top 0-20 cm depth and consequently also on irrigation water use. Strip planting received 15-36 % less irrigation than CT plots.

Lower irrigation applied to the SP plot could be attributed to the reduced soil evaporation. Earlier findings from the same experiment showed that SP could reduce soil bulk density, improve soil structure and facilitate soil organic carbon (SOC) build-up, which is related to increased water storage (Islam, 2016). Our findings of significant difference in soil water storage between SP and CT could be attributed to differences in bulk density (BD) in 0-20 cm depth: 1.39 g/cc under SP and 1.47 g/cc under CT treatments (see Chapter 4). Furthermore, findings after 7 consecutive crops show that SOC concentration under SP was 0.81 % and under CT was 0.68 % (Islam, 2016). Under BP treatment, due to better soil structural condition (BD 1.42 g/cc) and improved SOC (86 %) in comparison to CT, it was expected that more soil water storage compared to CT existed in the 0-10 cm depth. However, at sowing in year 1, soil water storage in 0-10 cm in the BP was not significantly different from CT treatment. The lower soil water storage in BP treatment might be due to pre-planting water losses during bed-forming (He *et al.*, 2008). Furthermore, beds may increase soil evaporation because of the increased soil surface area (Humphreys *et al.*, 2004; Kukal and Sidhu, 2004; Choudhury *et al.*, 2007). However, in year 2 and 3 at sowing, soil water storage under BP was significantly higher in comparison to CT.

In year 1, in the 20-30 cm soil depth, there was no significant effect of tillage treatments soil water storage during the whole season apart from the grain filling stage when SP and BP had significantly higher soil water storage compared to CT treatment. This might be attributed to over-irrigation in year 1 so that wheat roots had access to sufficient water from the top two layers. For earlier wheat crops at this site, 80 % of the root length and mass was reported in 0-10 cm depth (Islam, 2016), and this amount of roots are likely to extract most of the water from 0-20 cm depths. Hence, as the season approached the grain filling stage, the remaining 20 % of root length probably extracted water from 20-30 cm depths. At this depth, greater soil water storage in SP and BP treatment might be attributed to the increased infiltration rate in the minimum tillage plots (see results in Chapter 4). Consistent with our results, Dwivedi *et al.* (2012) reported higher infiltration in ZT plots compared to CT plots due to the continuity of water transporting pores under ZT. An increase in soil aggregation under reduced tillage plots might be due to the higher levels of SOC (Jat *et al.*, 2013). A similar trend of soil water storage according to the depth and growing stages was observed in the year 2 and 3 when irrigation was applied to the amount required to replenish the water deficit, and thus wheat was forced to extract water from the deeper soil layer. In year 3, at 20-30 cm depth, there were no significant differences in soil water storage in different tillage treatments from the sowing to booting stage. However, in the later growth stages, which can be attributed to improved infiltration, SP treatment compared to CT increased water storage replenishment of 20-30 cm depth. Soil water storage in the deeper layer 30-180 cm was not significantly different among tillage treatments. However, the ET_c data reveals that there was a little water lost from these depths. There were no wheat roots extracted below 60 cm depth in earlier years of the present experiment (Islam, 2016). This suggests that the drying at this depth was due to deep drainage rather than water extraction by roots (Humphreys *et al.*, 2008).

Irrigation was applied to all tillage treatments at the critical growth stages of wheat viz. CRI, booting, anthesis and grain filling stage. The ET_c during a particular growth period was computed by measurement of SWC changes in the soil profile between two successive critical stages. The maximum water extraction occurred between the anthesis and grain filling stages as this is the most active period of the crop growth, which requires a high amount of energy and for the formation of different yield contributes (Rai, 2015). During this period, adequate soil water is required to fulfil the high ET_c requirement. Water storage results of the soil profile at different growth stages (Table 5.3) suggests that SP compared to CT, supplied 19 % more water at anthesis and 32 % more water at grain filling stages for ET_c demand.

5.4.5 Effect of SP on Irrigation water productivity and crop water use efficiency

In three years, there was very limited rainfall during the wheat season. Therefore, only irrigation water productivity was calculated rather than total (irrigation + rainfall) water productivity. Higher irrigation water productivity (WP_I) under SP wheat in the current study was due to better grain yields and lesser use of water. For example, averaged across three years, SP received 26 % less irrigation and gained 21 % more wheat yield compared to CT; thus, the resultant increase in WP_I in SP wheat was 67 % compared to CT. Consistent with the results from the current study, higher WP_I of wheat under ZT compared to CT was observed by other researchers in the region (Jat *et al.*, 2009; Gathala *et al.*, 2013; Jat *et al.*, 2013; Jat *et al.*, 2014; Choudhary *et al.*, 2018a; Islam *et al.*, 2019; Jat *et al.*, 2019). Gathala *et al.* (2011a) reported a 16 % increase in WP_I of wheat under ZT transplanted rice and ZT drill seeded wheat treatment compared to wheat under CT puddled transplanted rice and CT wheat. Laik *et al.* (2014) reported an increase in WP_I of wheat of 39-138 %.

Crop water use efficiency (WUE) in wheat generally followed the same trend as for irrigation water productivity (WP_I). Furthermore, since nearly all crop evapotranspiration was met by irrigation, and losses by deep percolation were small due to all treatments being kept around field capacity, especially in Years 2 and 3, values for WUE and WP_I were to some extent comparable for respective tillage or residue treatment (Choudhury *et al.*, 2007). For example, the maximum values of WP_I in year 2 and year 3 were 2.64 kg m^{-3} and 2.36 kg $m^{-3,}$ respectively, while the maximum value of WUE in year 2 and year 3 were 2.21 kg m^{-3} and 2.41 kg m^{-3} respectively in SP-HR treatment. Similarly, minimum values of WP_I in the last two years were in CT-LR, and the values were 1.10 kg m^{-3} and 1.41 kg m^{-3}. The values for WUE for the respective years in CT-LR were 1.18 kg/m^{-3} and 1.39 kg m^{-3}.

5.4.6 Effect of BP on Irrigation water productivity and crop water use efficiency

Higher WP_I of wheat recorded with BP using ET_c-based irrigation approach compared to CT treatment was mainly due to less amount of irrigation applied coupled with a higher yield. Irrigation WP under BP was significantly higher than that under CT only in year 1 and year 2, despite the fact that BP received significantly less irrigation than CT in all three years. In year 1, WP_I under BP was 49 % higher than that under CT due to higher grain yield and reduced irrigation input. However, despite similar grain yield under BP and CT in year 2, WP_I under BP was 33 % higher than that under CT due to reduced irrigation input. Irrigation WP was higher (1.42 kg m^{-3}) in wheat on permanent raised beds compared to conventional tillage drill seeded wheat (1.15 kg m^{-3})(Gathala *et al.*, 2011a). Higher WP_I of wheat (1.30 vs 1.16 kg m^{-3}) was reported by (Jat *et al.*, 2015) in PRB compared to no-tillage on flat land. Irrigation WP was 43 % and 34 % higher in PRB compared to CT wheat in the first two years, but in the third year, WP_I water was similar in PRB and CT wheat (Jat *et al.*, 2013), while Kukal *et al.* (2010) reported four years average WP_I was similar in CT wheat and PRB wheat. Water use efficiency was higher with PRB plots of wheat (1.64-2.05 kg m^{-3}) in three years compared to CT (1.19-1.46 kg m^{-3}) (Parihar *et al.*, 2017). Many other studies across the IGP have also reported a 14-23 % increase in WUE of wheat under the BP system compared to the CT system (Ram *et al.*, 2010; Singh *et al.*, 2010; Ram *et al.*, 2012).

5.4.7 Effect of residue retention on irrigation water productivity

There was no significant effect of residue retention on irrigation water savings in either of the three years. However, since HR retention significantly increased wheat yield compared to the LR, WP_I in year 1 and year 2 were higher in HR than LR. Similarly, Sayre and Hobbs (2004) and Gupta *et al.* (2009) reported higher grain yield and WP_I in the irrigated maize-wheat system on permanent beds with residue mulch compared to no residue or flat land planting.

5.5 Conclusion

This study tested the hypothesis that altered soil physical and hydrologic properties under long-term minimum soil disturbance together with increased residue retention would improve crop productivity, reduce water requirements and increase the WP of wheat in rice-based crop rotations in northwest Bangladesh. In the water-scarce Rajshahi district in northwest Bangladesh, the wheat crop performance and its water use under SP and BP were evaluated and compared to CT. The SP gave 21 % greater crop productivity than CT, while SP saved 26 % water use compared to CT. As a result, SP led to a 67 % greater irrigation water productivity compared to CT. The higher crop productivity by SP was mainly attributed to more water uptake by wheat roots from deep soil.

In contrast to SP, water use in BP was only 19 % less than CT due to more evaporation from the greater surface area of the bed. Bed planting produced 16 % greater wheat yield compared to CT only in the first year. The three years average WP_I under BP was 31 % higher than CT. Performance of BP in terms of wheat yield and water use showed inconsistent results over three years. By contrast, SP technologies had consistently higher yield and lower water use than those achieved under CT. Thus SP performed better than BP in terms of crop productivity and crop water use efficiency. The current study demonstrates that SP technologies in the rice-based cropping system can provide a feasible option for many smallholder farmers to produce more food with less irrigation water and thus to more sustainably meet future food needs within the EGP. However, the present results are for wheat only in the dry season. The water balance of the rice crop in the cropping systems also needs to be assessed (see Chapter 6).

6 Effect of minimum soil disturbance planting on the water balance of rice in northwest Bangladesh

6.1 Introduction

Minimum soil disturbance and residue retention are expected to ameliorate the compacted soil layer in a rice-based cropping system caused by puddling and intensive tillage, which would be reflected in the increased hydraulic conductivity of the soil profile. The increased hydraulic conductivity will allow the water in the dryland crops to infiltrate deeper in the soil, and thus slow the rate of evaporation and reduce irrigation water for dryland crops. Hence, a hypothesis for the present study is that minimum tillage over time will weaken the plough pan and, in turn, alter water balance in the rice-based systems. Alternatively, the absence of puddling with minimum soil disturbance in SP and BP could result in higher percolation losses and increase irrigation water use. This change of water balance was beneficial for dryland wheat (Chapter 5) but may be detrimental for rice. However, since water lost by seepage and percolation returns to the groundwater and is potentially available for reuse, non-puddled rice can beneficially increase groundwater recharge.

Under this study, long term minimum tillage is evaluated compared to conventional tillage in terms of water balance for wetland rice production. The objective was also to quantify the components of water balance to determine the source of water losses in different water management treatments, i.e., whether intermittent irrigation such as AWD can reduce seepage-percolation or evaporation losses in minimum soil disturbance planting.

6.2 Material and Method

6.2.1 Experimental site

Experiments were conducted from 2015 to 2017 on a silty loam soil (Alluvial soil) at Alipur, Rajshahi, Bangladesh (24°29 N, 88°46 E). The experiments were completed on a long-term experiment site, which was established in 2010 (Islam, 2016). Details of the experimental site are given in Chapter 3.

6.2.2 Experimental design and treatments

The experiment had a split-plot design (plots 7 m × 15 m) with four replicates. The main plot was tillage treatment (Strip planting (SP), Bed planting (BP) or Conventional tillage (CT)), and the sub-plot was residue treatment (Low and high residue, 20 % and 50 % of cereal straw retained, respectively). Details of the treatments are given in Chapter 3. In 2015, all plots were irrigated by continuous flooding (CF). For the 2016 and 2017 experiments, the whole field was divided into two blocks, each consisting of two replications. Two replicate blocks were devoted to CF irrigation and the other two to Alternate Wetting and Drying (AWD) irrigation. In 2015, plastic sheets were installed in the centre of the bunds down to 15 cm. In 2016, no plastic sheets were installed. In 2017, the plastic sheets were placed around each bund to a depth of 60 cm.

6.2.3 Water balance model

Water balance calculation was performed considering three different phases, namely, ponding phase, saturation phase and depletion phase (Bhadra *et al.*, 2013).

Water balance equation for rice in ponding phase:

$$\mathrm{HP_i = HP_{i-1} + ER_i + IR_i - ET_{c,i} - DP_i} \ldots\ldots(5.1)$$

Water balance equation for rice in saturation phase:

$$\mathrm{D_{s,i} = D_{s,i-1} + ET_{c,i} + DP_i - ER_i - IR_i} \ldots\ldots(5.2)$$

Water balance equation for rice in depletion phase:

$$\mathrm{D_{r,i} = D_{r,i-1} + ET_{c,i} + DP_i - ER_i - IR_i} \ldots\ldots(5.3)$$

Where,

HP_i is the depth of ponding, cm;

ER is the effective rainfall, cm;

IR_i is the depth of irrigation water applied, cm;

$ET_{c,i}$ crop evapotranspiration, cm;

DP_i deep percolation, cm (=0, when the moisture content of the soil is assumed to be less than or equal to field capacity moisture content, i.e., in depletion phase);

D_s is the depth of water required to reach saturation, cm;

D_r is the depth of water required to reach field capacity in the root zone, cm; and i is the day index.

A $HP_{i-1}>0$, indicates the ponding phase, while $HP_{i-1}\leq 0$, indicates either the saturation phase or depletion phase depending on the condition described below:

$D_{s,i-1}=-(HP_{i-1})$.

If $0\leq D_{s,i-1}<SAW_{i-1}$, it is in the saturation phase, but if $D_{s,i-1}\geq SAW_{i-1}$, it is in the depletion phase and

$D_{r,i-1}=D_{s,i-1}-SAW_{i-1}$.

As long as $D_{r,i-1}\geq 0$ it enters in the depletion phase, but when $D_{r,i-1}< 0$ it enters in the saturation phase or ponding phase depending on the following condition :

$D_{s,i-1}=SAW_{i-1}+D_{r,i-1}$.

If $D_{s,i-1}\geq 0$, it remains in the saturation phase but if $D_{s,i-1}< 0$, it goes back to the ponding phase and, $HP_{i-1}=-D_{s,i-1}$

Here,

$SAW_{i-1}= (\theta_{Sv}- \theta_{FCv}) \times Z_{r,i-1}$ or

$= (\theta_{SD}-\theta_{FCD}) \times BD \times Z_{r,i-1}$

Where,

SAW is the depth of water required to reach saturation from field capacity, cm;

θ_{Sv} is the saturation moisture content on vol. basis, fraction;

θ_{FCv} is the field capacity moisture content on vol. basis, fraction;

θ_{SD} is the saturation moisture content on a dry basis, fraction;

θ_{FCD} is the field capacity moisture content on a dry basis, fraction;

BD is the apparent bulk density, fraction; and

Z_r= root zone depth, cm.

The required depth of ponding at the different growth stage of rice is essential for calculating the deficit in different phases. In the ponding phase, the deficit can be calculated using the following relationship:

$DF_{i-1}=Dp_{i-1}-HP_{i-1}$ (If $DF_{i-1}\leq 0$, $DF_{i-1}= 0$).

In the saturation phase, the deficit can be obtained as:

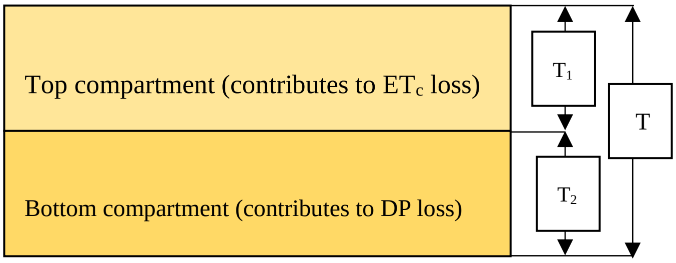
$DF_{i-1}= Dp_{i-1}+ D_{s,i-1}$.

In the depletion phase, the deficit is calculated using the following equation:

$DF_{i-1}=Dp_{i-1}+SAW_{i-1}+D_{r,i-1}$,

Where Dp is the required ponding depth.

For calculating deep percolation in the saturation phase using the modified Khepar *et al.* (2000) method, the top *T* cm of the soil was considered as the hydraulic functional horizon. The top layer was divided into two compartments, T_1 and T_2. Suffix 1 indicates the top compartment, whereas, bottom compartment is denoted by suffix 2.



Layer stratification as required in the Khepar *et al.* (2000)

Deep percolation is calculated as below:

$$DP = \frac{(\varphi_1 - \varphi_2).K_{avg}(\theta)}{T}$$

Where φ_1 and $K_{avg}(\theta)$ are given as:

$$\varphi_1 = \psi_1 + Z_1$$

$$K_{avg}(\theta) = \frac{K_1(\theta) + K_2(\theta)}{2}$$

ψ_1 for T_1 compartment can be calculated as below:

$$\psi_1 = \frac{1}{\alpha_1}.\left[\left(\frac{\theta_1 - \theta_{r1}}{\theta_{s1} - \theta_{r1}}\right)^{-\frac{1}{m_{e1}}} - 1\right]^{\frac{1}{n_{p1}}}$$

Where, $m_{e1} = \left(1 - \frac{1}{n_{p1}}\right)$

θ_1 and θ_2 of T_1 and T_2 compartments for *i*th day are given by:

$$\theta_{1,i} = \frac{(\theta_{1,i-1}.T_1 - ET_{c,i-1})}{T_1} \text{ and}$$

$$\theta_{2,i} = \frac{(\theta_{2,i-1}.T_2 - DP_{i-1})}{T_2}$$

On the first day, $\theta_{1,i-1} = \theta_{2,i-1} = \theta_{s1}$

$K_1(\theta) = K_1.K_{r1}$

with,

$$K_{r1} = \left(\frac{\theta_1-\theta_{r1}}{\theta_{s1}-\theta_{r1}}\right)^{\lambda_{p1}} . \left[1-\left\{1-\left(\frac{\theta_1-\theta_{r1}}{\theta_{s1}-\theta_{r1}}\right)^{\frac{1}{m_{e1}}}\right\}^{m_{e1}}\right]^2$$

(in case of compartment T_2, φ_1, and $K_1(\theta)$ are calculated using similar equations as described above for T_1) where φ_1 is the hydraulic head or total head for T_1, cm; $K_{avg}(\theta)$ is the average of unsaturated hydraulic conductivity for T_1 and T_2, cm day^{-1}; *T is the total depth, cm;* $\psi_1$is the negative pressure head in T_1, cm; Z_1 is the elevation head for T_1, cm; $K_1(\theta), K_2(\theta)$ is the unsaturated hydraulic conductivity for T_1 and T_2, respectively, cm day^{-1}; $\alpha_1$is the inverse of air entry value (bubbling pressure), cm^{-1}; $\theta_1$is the water content (volumetric basis), fraction; $\theta_{s1}$is the saturated water (volumetric basis), fraction; $\theta_{r1}$is the residual water content (volumetric basis), fraction; $m_{e1}$is the empirical parameter; $n_{p1}$is the pore-size distribution index; T_1 and T_2 are the depths of top and bottom compartments, respectively, cm; $K_1$is the saturated hydraulic conductivity of T_1, cm day^{-1}; K_{r1} is the relative unsaturated hydraulic conductivity function and $\lambda_{p1}$is the pore connectivity empirical parameter (default value = 0.5).

From the above equations, the water balance components, crop evapotranspiration, deep percolation and seepage, were calculated from the field measurements taken on a daily basis. In this study, deep percolation and seepage losses were measured as two different components. Because percolation and seepage are the vertical and horizontal movement of water, respectively, the rates vary with differences in ponding depth. Furthermore, with no ponding water, seepage loss is negligible, while there is still percolation losses until the soil comes to field capacity.

6.2.4 Water balance components measurements in the field

In each plot, two mini lysimeters (No1-open bottom and closed top, No2-open bottom and open top) made of PVC pipes with 25 cm internal diameter and 60 cm high were installed and embedded into the plough pan to a depth of 30 cm, and an inclined gauge (30^{o} angle sloping ruler to precisely measure changes in water depth) were placed at the surface (Figure 6.1). During transplanting, rice seedlings were planted in the No2 lysimeter, but No1 had no seedlings. In the ponding phase, daily water level decline in each plot was measured by the inclined gauge, which represented total loss through deep percolation, seepage, and crop evapotranspiration. Daily water declines in the No2 lysimeter presented the deep percolation and crop evapotranspiration. Therefore, the difference in the water level readings from the inclined gauge and the No2 lysimeter was the amount of seepage from the corresponding plot in terms of depth. The top of each No1 lysimeter was covered with a thick plastic sheet and sealed so that the water level declined in the No1 lysimeter represented the vertical water flow, i.e., the deep percolation only. Evapotranspiration in the ponding phase was calculated as the residual term in the water balance equation 5.1.

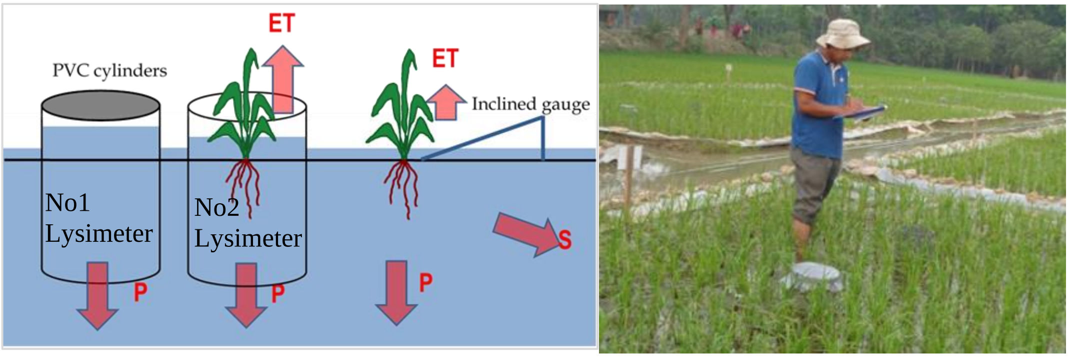


Figure 6.1 Schematic diagram of mini lysimeter used and field measurements of water balance components at Alipur, Rajshahi. P=percolation, S=seepage, ET_c= crop evapotranspiration.

In the AWD plots, the field was subjected to both wet and dry conditions. In addition, when the standing water disappeared, the plot observed a saturated or depletion phase. Hence, equations 5.2 and 5.3 were used to calculate crop evapotranspiration and percolation from SWC measurements made with a moisture probe (MP406, ICT international, Australia). Change in soil water storage (ΔSWC) was calculated by measuring SWC to a depth of 30 cm before initial irrigation and at harvest of each season of the Boro rice crops.

The volume of irrigation water applied to each plot was measured with a flowmeter fitted at the tube well outlet. We measured daily rain using a rain gauge installed at the experimental site. Actual evaporation was taken from a class A evaporation pan installed within the field

6.2.5 Crop management practices

BRRI dhan28 rice variety was grown during the Boro rice season (dry season) in the Alipur long-term CA experimental site. Nitrogen, P, K and S fertilizers were applied in the form of urea, diammonium phosphate (DAP), muriate of potash (MP) and gypsum, respectively at the rate of 130-20-60-20 kg ha^{-1} as per BRRI recommendations (BRRI, 2013). All fertilizers except urea were broadcast just before final land preparation. Urea fertilizer was broadcast in three equal splits at 15, 30 and 45 days after transplanting (DAT). Affinity® herbicide (Carfentrazone) @ 2.5 g/litre water was applied at 15 DAT, and two hand weeding operations were done at 35 DAT and 55 DAT to control weeds. There was no insect infestation during Boro season; still, Virtako® 40 WG @ 75 g ha^{-1} (Chlorantraniliprole 20 % + Thiamethoxam 20 %) pesticide was applied to prevent the crop from suffering Stem Borer infestation.

6.2.6 Statistical analysis

The data were analysed by analysis of variance (ANOVA) with split-plot design using GenStat version 18.0 (VSN international Ltd. United Kingdom). The least significant difference (LSD) at $P < 0.05$ has been used to compare the treatment means. Normality test of the parameters was also done with GenStat software, and all were normally distributed.

6.3 Results

6.3.1 Effect of tillage on irrigation water requirement

The volume of irrigation water applied to three different tillage treatments was not statistically different in 2015. The number of irrigations applied to SP and BP plots and to CT was 11 and 10, respectively (Table 6.1). In 2016, SP and BP plots received higher volumes of irrigation water compared to CT plots in both CF and AWD water management treatments with no significant differences between SP and BP. Under CF irrigation, CT received 11 irrigations, while SP received 4 more irrigations than CT, which resulted in a 34 % higher amount of irrigation water received by SP compared to CT. Similarly, BP under CF received three more irrigations and 32 % more water than CT. Alternate wetting and drying irrigation reduced the number of irrigations and volume of water application for three tillage treatments. Strip planting under AWD received five fewer irrigations and 20 % less water input compared to SP-CF treatment. Bed planting under AWD received three fewer irrigations and 16 % less water in amount than BP-CF irrigation. Conventional tillage with AWD irrigation received two fewer irrigations which resulted in 21 % reduced water application compared to CT-CF irrigation.

In 2017, plastic sheets installed 60 cm deep around every plot reduced irrigation water requirement in SP, and thus irrigation water in SP and CT were not significantly different under CF irrigation (Table 6.1). In 2017, under CF water management, BP received the largest volume of irrigation water which was 17 % and 8 % higher than CT and SP, respectively. In 2017, under AWD irrigation, all tillage treatments received the same amount of irrigation water ($P > 0.05$).

6.3.2 Effect of tillage on percolation losses

Under CF irrigation management, the largest source of water loss was deep percolation, which was 32 % of the total water input (irrigation and rainfall) in CT, while the percolation significantly increased to 34 % and 36 % of the input water in SP and BP, respectively in 2015 (Table 6.1). In 2016, deep percolation for SP, BP and CT was 53 cm, 52 cm, and 30 cm, respectively, which was 41 %, 41 %, and 34 % of the total water input, respectively. In 2015 and 2016, there were no significant differences in deep percolation between SP and BP, but in 2017 deep percolation in BP was significantly higher than that in SP and CT with no differences in deep percolation between SP and CT. In 2017, deep percolation in SP, BP and CT was 39 cm, 47 cm, and 37 cm, respectively, which was 45 %, 51 %, and 46 %, respectively, of the total water input in CF irrigation. Three years' deep percolation suggest that the increased percolation losses under SP and BP were reflected in irrigation water requirement in those treatments. The amount of percolation was positively correlated with irrigation requirement for the tillage treatments in each year. Nevertheless, the highest percolation for each tillage treatment was recorded in 2016 when rice plots were irrigated and transplanted 20 days earlier than the surrounding farmers' plots. The results suggest that continuous standing water increased percolation losses, and eventually, irrigation requirement, more in non-puddled plots than puddled plots. Three years' percolation results also suggest that 15 cm deep plastic sheet installed in the bunds in 2015 reduced percent percolation losses compared to that in plots without plastic sheets in 2016. However, percent deep percolation was increased in 2017 when plastic sheets installed 60 cm below the soil surface in the bunds compared to percent percolation loss in 2016.

The AWD irrigation treatment reduced deep percolation for three tillage treatments in both years (2016 and 2017). In 2016, percolation loss under AWD irrigation in SP, BP treatments were 40 cm and 41 cm, respectively. In contrast, percolation loss under AWD irrigation in CT was almost half of the percolation in SP and BP. There were no significant differences in percolation losses under AWD irrigation between SP and BP tillage. Percolation losses in SP, BP and CT were 37 %, 38 %, and 28 %, respectively of the total water input. Alternate wetting and drying irrigation reduced deep percolation compared to CF irrigation by 25 %, 21 %, and 33 %, respectively, in SP, BP, and CT, respectively. The results suggest that AWD irrigation was relatively more effective in CT plot in reducing deep percolation compared to SP and BP. In 2017, under AWD irrigation, there were no significant differences in percolation losses between SP, BP, and CT with hydrologically well-isolated plots.

6.3.3 Effect of tillage on seepage losses

In 2016, the amount of seepage was significantly higher in SP and BP than CT ($p<0.05$) under both CF and AWD water management. Seepage in SP and BP was on average 30 % of the total water use, and that in CT was 23 % under CF (Table 6.1). However, seepage was lower under AWD than that under CF within the same tillage treatments. Seepage under AWD in SP and BP was 32 % and 31 % of the total water use, respectively, and that in CT plots was 26 %. The AWD water management reduced seepage loss by an average of 12 % compared to CF water management. The 15 cm plastic lining in each plot effectively restricted horizontal water flow and thus reduced 48 % seepage losses through bunds and under bund percolations in 2015 compared to 2016. Similarly, in 2017, 60 cm deep plastic sheet reduced 69 % seepage under CF and 67 % under AWD water management compared to 2016. Seepage in 2015 and 2017 under three tillage treatments were statistically similar and contributed about 20 % of the water balance. The average amount of seepage was about 10 cm that contributed 13 % of the water output.

6.3.4 Effect of tillage on crop evapotranspiration (ET_c)

There was no difference in seasonal ET_c between the tillage treatments except in 2016 when seasonal ET_c followed the order CT=SP>BP under CF irrigation treatments. Crop growth duration was the same (85 days) in three years, although the rice was established on three different dates and the total number of sunshine hours was different in three years. Rice was transplanted on 4 March 2015, 21 February 2016 and 20 March 2017 for three consecutive years. Averaged across three tillage treatments ET_c was 33.0 cm, 34.1 cm and 32.1 cm, respectively, in 2015, 2016 and 2017 under CF irrigation. Despite longer average day lengths in the 2017 season, ET_c was less than in the other two years. In contrast, the highest ET_c was observed in 2016 when transplanting was done 30 days earlier than 2017.

Table 6.1 Components of the seasonal water balance (cm) for Boro Rice from 2015 to 2017.

2015						
Treatmentsa	**Water Balance Components (cm) ± Standard Error (cm)**					
Tillage	**I[b]**	**R[c]**	**DP[d]**	**S[e]**	**ET$_c$[f]**	**ΔSMC[g]**
SP	77.7±5.9	5.0	28.2±1.8 a	18.4±5.6	33.4±0.4	2.7±0.3
BP	85.4±6.2	5.0	32.3±1.4 a	21.9±5.7	33.0±0.4	3.2±0.3
CT	65.1±2.2	5.0	22.7±1.4 b	10.8±2.6	32.7±0.5	3.9±0.3
LSD0.05h, Tillage	ns	-	5.1**	ns	ns	ns

[a]Treatments, SP=Strip planting, BP=Bed planting, CT=Conventional Tillage, CF= Continuous Flood irrigation, [b]I is the irrigation, [c]R is the rainfall, [d]DP is the deep percolation below root zone (0.3 m), [e]S is the seepage, [f]ET$_C$ is the crop evapotranspiration, [g]ΔSMC is the change in soil water storage in the root zone.

[h]interaction effect of Tillage × Residue and the main effect of Residue were not significant. [h]LSD= Least Significant Difference (p≤0.05)

*Significant at 5 % level, ** Significant at 1 % level, means with the same letter are not significantly different

2016							
Treatments[a]		**Water Balance Components (cm) ± Standard Error (cm)**					
Irrigation Practice	**Tillage**	**I[b]**	**R[c]**	**DP[d]**	**S[e]**	**ET$_C$[f]**	**ΔSMC[g]**
CF	SP	121.6±2.3 a	8.6	53.3±2.4 a	39.6±1.9 a	34.3±0.4 a	3.0±0.6
	BP	118.6±4.9 a	8.6	51.7±2.9 a	38.6±3.1 a	32.9±0.1 b	4.1±0.4
	CT	80.7±0.8 b	8.6	30.4±1.0 b	20.1±1.4 b	35.2±0.1 a	3.6±0.5
LSD$_{0.05}$[h], Tillage		13.8**	-	9.7*	9.4*	1.0*	ns
Treatments[a]		**Water Balance Components (cm) ± Standard Error (cm)**					
Irrigation Practice	**Tillage**	**I[b]**	**R[c]**	**DP[d]**	**S[e]**	**ET$_C$[f]**	**ΔSMC[g]**
AWD	SP	97.8±1.3 a	8.6	39.5±1.8 a	34.1±1.1 a	30.6±0.1	2.2±0.7
	BP	99.5±1.4 a	8.6	40.9±2.7 a	33.6±2.1 a	29.7±0.4	3.9±0.4
	CT	64.1±1.1 b	8.6	20.5±0.2 b	19.0±1.7 b	31.4±0.4	1.9±0.3
LSD$_{0.05}$[h], Tillage		10.5**	-	10.7**	4.6*	ns	ns

[a] Treatments, SP=Strip planting, BP=Bed planting, CT=Conventional Tillage, CF= Continuous Flood irrigation, AWD= Alternate wetting and drying irrigation. [b] I is the irrigation, [c] R is the rainfall, [d] DP is the deep percolation below root zone (0.3 m), [e] S is the seepage, [f] ET$_c$ is the crop evapotranspiration, [g] ΔSMC is the change in soil water storage in the root zone.

[h] interaction effect of Tillage × Residue and the main effect of Residue were not significant. [h] LSD= Least Significant Difference ($p \leq 0.05$)

*Significant at 5 % level, ** Significant at 1 % level, means with the same letter are not significantly different

2017							
Treatments[a]		**Water Balance Components (cm) ± Standard Error (cm)**					
Irrigation Practice	**Tillage**	**I**[b]	**R**[c]	**DP**[d]	**S**[e]	**ET$_c$**[f]	**ΔSMC**[g]
CF	SP	62.9±2.9 b	23.3	38.5±1.6 b	10.9±1.6	32.5±0.9	3.4±0.2
	BP	68.4±2.3 a	23.3	47.0±1.4 a	9.6±1.4	31.8±0.4	3.2±0.2
	CT	58.5±3.3 b	23.3	37.2±1.3 b	10.2±1.7	32.1±0.9	2.0±0.2
LSD$_{0.05}$[h], Tillage		5.3*	-	3.21**	ns	ns	ns
Treatments[a]		**Water Balance Components (cm) ± Standard Error (cm)**					
Irrigation Practice	**Tillage**	**I**[b]	**R**[c]	**DP**[d]	**S**[e]	**ET$_c$**[f]	**ΔSMC**[g]
AWD	SP	49.6±2.7	23.3	29.9±2.4	8.5±1.0	30.6±0.2	3.9±0.4
	BP	47.3±3.2	23.3	26.6±1.1	10.5±1.9	30.0±0.3	3.4±0.5
	CT	45.3±4.1	23.3	27.2±2.9	9.2±0.9	30.3±1.0	1.8±0.2
LSD$_{0.05}$[h], Tillage		ns	-	ns	ns	ns	ns

[a]Treatments, SP=Strip planting, BP=Bed planting, CT=Conventional Tillage, CF= Continuous Flood irrigation, AWD= Alternate wetting and drying irrigation. [b]I is the irrigation, [c]R is the rainfall, [d]DP is the deep percolation below root zone (0.3 m), [e]S is the seepage, [f]ET$_c$ is the crop evapotranspiration, [g]ΔSMC is the change in soil water storage in the root zone.

[h]interaction effect of Tillage × Residue and the main effect of Residue were not significant. [h]LSD= Least Significant Difference ($p \leq 0.05$)

*Significant at 5 % level, ** Significant at 1 % level, means with the same letter are not significantly different

6.3.5 Effect of tillage on irrigation water requirement according to growing stages

Table 6.2 shows the irrigation water requirement for land preparation to transplanting (LP-T), transplanting to panicle initiation (T-PI), and panicle initiation to harvest (PI-H) for three tillage treatments and two irrigation water management measured in three years. In 2015, the mean water requirement for land preparation was 9.4 cm and not significantly different among the three tillage treatments. In the early rice season (0 to 35 DAT), SP and BP received more (34 % and 56 %, respectively) irrigation water than CT, but in the rest of the season, water requirements were similar (mean 25.9 cm) for all tillage treatments. In 2016, land preparation for SP treatment required 73 % more irrigation water compared to that for CT plots. Land preparation for BP received almost twice as much irrigation water compared to CT. For the first 35 days of the rice season, the irrigation water requirement for minimum tillage plots was significantly higher compared to CT, with no significant difference between SP and BP. At this growing stage, SP received 57 % more irrigation water than CT, while BP received 48 % more irrigation water than CT. Like the first year, the irrigation water requirement for PI-H was similar for three tillage treatments.

In 2017, under CF irrigation practices, BP treatment required 3.7 cm higher irrigation compared to CT treatment at the T-PI stage. However, there was no significant difference between the irrigation water requirement between SP and CT at this stage. At the PI-H stage, SP and BP required respectively 6.2 cm and 3.4 cm higher irrigation compared to CT treatment. Under AWD irrigation practice, all tillage treatment received similar irrigation regardless of growth stages.

6.3.6 Effect of tillage on percolation losses according to growing stages

The peak percolation rate per day was observed on the day of the first irrigation for land preparation for each of the tillage treatments in three years (Figure 6.2). The peak percolation rate for SP and BP were 2.5 cm day^{-1} and 3.2 cm day$^{-1,}$ which were significantly higher than that for CT (2.0 cm day^{-1}). Water balance results according to rice growing stages (Table 6.2) shows that in 2015 average percolation rate for SP (2.2 cm day^{-1}) and BP (2.3 cm day^{-1}) during LP-T (1 day) was significantly higher than that for CT (1.4 cm day^{-1}), with no significant difference between SP and BP. The results also show that more than half of the seasonal deep percolation took place early in the rice season within 35 days after transplanting (Table 6.2). In 2015, deep percolation from transplanting to panicle initiation (T-PI, 35 days) under SP (16 cm) was significantly higher than CT (12 cm), which were 56 % and 51 %, respectively, of the total seasonal deep percolation for SP and CT. Deep percolation during T-PI under BP was 54 % of the seasonal deep percolation for BP, which were not significantly different compared to SP. The average percolation rate per day during T-PI was 8-10-fold lower than the percolation rate during LP-T. Average percolation rates per day during T-PI for SP and BP were 0.45 cm day^{-1} and 0.50 cm day^{-1} which were significantly higher than that for CT (0.33 cm day^{-1}) (Table 6.3). However, daily percolation rates were reduced further from 35 days after transplanting for SP and BP, and in the rest of the season, there were no significant differences in percolation rates among the tillage treatments. Average percolation rates per day during panicle initiation to harvest (PI-H) was 8-15-fold lower than the peak percolation rate and 2-3-fold lower than the percolation rates during T-PI. Average percolation rates during PI-H for SP, BP and CT were 0.16, 0.20 and 0.17 cm day^{-1}.

In 2016 and 2017, deep percolation followed the same decreasing trend with time as in 2015, with some variations in peak percolation rate and average percolation rate according to different growth stages. In 2016, peak deep percolation, at the time of first irrigation for land preparation, was 4.8, 5.4 and 1.7 cm day$^{-1,}$ and average deep percolation for LP-T was 3.4, 3.7 and 1.5 cm day^{-1} for SP, BP and CT, respectively. Percolation during T-PI was 33.3 and 33.8 cm for SP and BP, respectively, which were 26 % and 27 % of the total water input for the respective tillage treatment. In contrast, percolation for the same duration for CT was 17 % of the total water input, which was significantly lower than SP and BP. However, percolation for PI-H (50 days) was not significantly different for three tillage treatment under CF irrigation. Averaged across the tillage treatments, percolation for PI-H was 0.27 cm day^{-1}. In 2017, percolation during LP-T for SP (3.5 cm) and BP (4.0 cm) was significantly higher than that for CT (2.5 cm). During T-PI, percolation for BP (28.1 cm) was significantly higher than SP (23.4 cm) and CT (22.6 cm), with no significant difference between SP and CT. Percolation during T-PI for BP was 31 % of the total water input. In contrast, percolation during T-PI for SP and CT was 27 % and 28 % of the total water input. The daily percolation rate for BP and SP was 3-fold lower in PI-H (0.31 and 0.24 cm day^{-1}, respectively) than in T-PI (0.8 and 0.67 cm day^{-1}, respectively).

The calculated deep percolation rate in the SP plots during the AWD days ranged from 0.24 cm day^{-1} to 0.51 cm day$^{-1,}$ with the SWC from 38.6 % to 40.0 %. The characteristic curves (see Chapter 3) shows that the corresponding water potential for those water contents was -9.56 to 0 kPa. The water potential suggests that the water content during the AWD days were between the saturated water content and the field capacity.

6.3.7 Effect of tillage on seepage losses according to growing stages

In 2015 and 2017, tillage treatment did not influence the seepage losses according to the growing stages. By contrast, in 2016, SP and BP significantly increased seepage losses compared to CT in the LP-T and T-PI growing stages under CF irrigation. The same trend was observed in the AWD irrigation treatment, when the seepage was twice as high in the SP and BP compared to the value of seepage in CT in both LP-T and T-PI growing stages. In 2016 there was no significant difference in seepage losses in SP and BP compared to CT in PI-H growing stages either in the CF or AWD irrigation.

6.3.8 Effect of tillage on ET_c according to growing stages

Tillage treatment did not affect ET_c according to growth stages in any of the three years, except in the T-PI stage of 2016 ET_c under SP and CT was higher than that in BP. At this stage ET_c under SP and CT was respectively 1.6 cm and 1.8 cm higher than ET_c under BP.

Table 6.2 Components of the water balance (cm) according to growing stages for Boro Rice from 2015 to 2017.

2015																
Treatments[a]	**Water Balance Components (cm) according to growth stages**															
Tillage	**I**[b]				**DP**[d]				**S**[e]				**ET$_c$**[f]			
	LP-T	**T-PI**	**PI-H**	**Total**	**LP-T**	**T-PI**	**PI-H**	**Total**	**LP-T**	**T-PI**	**PI-H**	**Total**	**LP-T**	**T-PI**	**PI-H**	**Total**
SP	9.8	42.1	25.7	77.7	4.3	15.9	8.0	28.2a	1.7	10.3	6.5	18.4	0.5	13.8	19.3	33.4
BP	9.8	49.2	26.3	85.4	4.6	17.5	10.2	32.3a	2.1	12.7	7.1	21.9	0.7	13.9	18.6	33.0
CT	8.5	31.5	25.1	65.1	2.7	11.6	8.7	22.7b	1.4	6.1	3.7	10.8	0.6	13.7	18.6	32.7
LSD$_{0.05}$[h], Tillage	ns	10.1	ns	ns	1.14	2.8	ns	5.1**	ns	ns	ns	ns	ns	ns	ns	ns

[a] Treatments, SP=Strip planting, BP=Bed planting, CT=Conventional Tillage, CF= Continuous Flood irrigation, [b] I is the irrigation, [d] DP is the deep percolation below root zone (0.3 m), [e] S is the seepage, [f] ET$_c$ is the crop evapotranspiration.

[h] interaction effect of Tillage × Residue and the main effect of Residue were not significant. [h] LSD= Least Significant Difference ($p \leq 0.05$)

LP-T= Land preparation to transplanting, T-PI= Transplanting to panicle initiation, PI-H= Panicle initiation to harvesting

*Significant at 5 % level, ** Significant at 1 % level, means with the same letter are not significantly different

2016																	
Treatments[a]		**Water Balance Components (cm) according to growth stages**															
Irrigation Practice	**Tillage**	**I**[b]				**DP**[d]				**S**[e]				**ET_c**[f]			
		LP-T	**T-PI**	**PI-H**	**Total**	**LP-T**	**T-PI**	**PI-H**	**Total**	**LP-T**	**T-PI**	**PI-H**	**Total**	**LP-T**	**T-PI**	**PI-H**	**Total**
CF	SP	18.9	72.3	27.6	121.6a	5.0	33.3	14.9	53.3a	3.4	26.3	9.9	39.6a	0.6	13.7	19.9	34.3b
	BP	21.1	67.9	28.9	118.6a	4.4	33.8	13.7	51.7a	3.4	24.5	10.6	38.6a	0.6	12.1	20.1	32.9c
	CT	10.9	46.0	24.0	80.7b	3.0	15.5	12.0	30.4b	1.7	11.5	6.9	20.1b	0.6	13.9	20.7	35.2a
$LSD_{0.05}$[h], Tillage		2.85	6.77	ns	13.8	1.28	5.06	ns	9.7*	0.9	4.18	ns	9.4*	ns	1.45*	ns	1.0*
Treatments[a]		**Water Balance Components (cm) according to growth stages**															
Irrigation Practice	**Tillage**	**I**[b]				**DP**[d]				**S**[e]				**ET_c**[f]			
		LP-T	**T-PI**	**PI-H**	**Total**	**LP-T**	**T-PI**	**PI-H**	**Total**	**LP-T**	**T-PI**	**PI-H**	**Total**	**LP-T**	**T-PI**	**PI-H**	**Total**
AWD	SP	17.2	54.4	26.3	97.8a	4.7	25.6	9.1	39.5a	2.8	22.2	9.4	34.1a	0.6	12.1	18.7	30.6
	BP	18.3	56.8	24.4	99.5a	3.6	26.7	10.6	40.9a	2.8	22.1	8.8	33.6a	0.6	11.5	18.0	29.7
	CT	11.4	27.4	25.4	64.1b	2.1	11.0	7.4	20.5b	1.4	10.9	6.7	19.0b	0.6	12.1	18.5	31.4
$LSD_{0.05}$[h], Tillage		1.68	4.60	ns	10.5	0.5	4.73	ns	10.7**	0.86	4.23	ns	4.6*	ns	ns	ns	ns

[a]Treatments, SP=Strip planting, BP=Bed planting, CT=Conventional Tillage, CF= Continuous Flood irrigation, AWD= Alternate wetting and drying irrigation. [b]I is the irrigation, [d]DP is the deep percolation below root zone (0.3 m), [e]S is the seepage, [f]ET_c is the crop evapotranspiration. [h]interaction effect of Tillage × Residue and the main effect of Residue were not significant. [h]LSD= Least Significant Difference ($p \leq 0.05$)
LP-T= Land preparation to transplanting, T-PI= Transplanting to panicle initiation, PI-H= Panicle initiation to harvesting
*Significant at 5 % level, ** Significant at 1 % level, means with the same letter are not significantly different

2017																	
Treatments[a]		**Water Balance Components (cm) according to growth stages**															
Irrigation Practice	**Tillage**	**I**[b]				**DP**[d]				**S**[e]				**ET_c**[f]			
		LP-T	**T-PI**	**PI-H**	**Total**	**LP-T**	**T-PI**	**PI-H**	**Total**	**LP-T**	**T-PI**	**PI-H**	**Total**	**LP-T**	**T-PI**	**PI-H**	**Total**
CF	SP	10.6	36.3	16.0	62.9b	3.5	23.4	12.1	38.5b	0.8	6.3	3.8	10.9	0.6	13.3	20.1	32.5
	BP	10.5	39.5	18.8	68.4a	4.0	28.1	15.3	47.0a	0.7	5.2	3.8	9.6	0.5	14.0	20.3	31.8
	CT	10.1	35.8	12.6	58.5b	2.5	22.6	12.2	37.2b	0.7	5.3	4.1	10.2	0.6	12.6	20.1	32.1
$LSD_{0.05}$[h], Tillage		ns	3.0	3.0	5.3*	1.05	4.00	ns	3.2**	ns	ns	ns	ns	ns	ns	ns	ns
Treatments[a]		**Water Balance Components (cm) according to growth stages**															
Irrigation Practice	**Tillage**	**I**[b]					**DP**[d]			**S**[e]				**ET_c**[f]			
		LP-T	**T-PI**	**PI-H**	**Total**	**LP-T**	**T-PI**	**PI-H**	**Total**	**LP-T**	**T-PI**	**PI-H**	**Total**	**LP-T**	**T-PI**	**PI-H**	**Total**
AWD	SP	11.5	28.7	9.3	49.6	3.03	16.5	10.1	29.9	1.1	3.9	3.4	8.5	0.5	12.1	18.2	30.6
	BP	10.5	27.0	9.8	47.3	3.38	15.5	7.9	26.6	0.9	5.2	4.5	10.5	0.4	12.0	18.3	30.0
	CT	10.4	25.8	9.1	45.3	2.50	15.9	8.6	27.2	0.7	4.8	3.7	9.2	0.4	11.6	18.5	30.3
$LSD_{0.05}$[h], Tillage		ns	ns	Ns	ns	0.61*	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

[a]Treatments, SP=Strip planting, BP=Bed planting, CT=Conventional Tillage, CF= Continuous Flood irrigation, AWD= Alternate wetting and drying irrigation. [b]I is the irrigation, [d]DP is the deep percolation below root zone (0.3 m), [e]S is the seepage, [f]ET_c is the crop evapotranspiration.
[h]interaction effect of Tillage × Residue and the main effect of Residue were not significant. [h] LSD= Least Significant Difference ($p \leq 0.05$)
LP-T= Land preparation to transplanting, T-PI= Transplanting to panicle initiation, PI-H= Panicle initiation to harvesting
*Significant at 5 % level, ** Significant at 1 % level, means with the same letter are not significantly different

Table 6.3 Percolation rates for different growth stages of rice in 2015, 2016, 2017.

2015			
Treatments^a		**Percolation rates, cm day^{-1}**	
Tillage	**LP-T (1 day)**	**T-PI (35 days)**	**PI-H (50 days)**
SP	4.3	0.45	0.16
BP	4.6	0.50	0.20
CT	2.7	0.33	0.17
LSD$_{0.05}$, Tillage	1.14*	0.08*	ns

^{a}Treatments, SP=Strip planting, BP=Bed planting, CT=Conventional Tillage, CF= Continuous Flood irrigation. LSD= Least Significant Difference. LP-T= Land preparation to transplanting, T-PI= Transplanting to panicle initiation, PI-H= Panicle initiation to harvesting. *Significant at 5 % level, ns=Not significant

2016				
Treatments^a		**Percolation rates, cm day^{-1}**		
Irrigation	**Tillage**	**LP-T (1 day)**	**T-PI (35 days)**	**PI-H (50 days)**
CF	SP	5.00	0.95	0.30
	BP	4.40	0.97	0.27
	CT	3.0	0.44	0.24
LSD$_{0.05}$, Tillage		1.28*	0.14*	ns
Treatments^a		Percolation rates, cm day^{-1}		
Irrigation	Tillage	LP-T (1 day)	T-PI (35 days)	PI-H (50 days)
AWD	SP	4.70	0.73	0.18
	BP	3.60	0.76	0.21
	CT	2.10	0.31	0.15
LSD$_{0.05}$, Tillage		0.50*	0.14*	ns

^{a}Treatments, SP=Strip planting, BP=Bed planting, CT=Conventional Tillage, CF= Continuous Flood irrigation, AWD= Alternate wetting and drying irrigation. LSD= Least Significant Difference. LP-T= Land preparation to transplanting, T-PI= Transplanting to panicle initiation, PI-H= Panicle initiation to harvesting. *Significant at 5 % level, ns=Not significant.

2017				
Treatments[a]		**Percolation rates, cm day^{-1}**		
Irrigation	**Tillage**	**LP-T (1 day)**	**T-PI (35 days)**	**PI-H (50 days)**
CF	SP	3.0	0.67	0.24
	BP	3.70	0.80	0.31
	CT	2.50	0.65	0.24
LSD$_{0.05}$, Tillage		0.86	0.11	ns
Treatments[a]		**Percolation rates, cm day^{-1}**		
Irrigation	**Tillage**	**LP-T (1 day)**	**T-PI (35 days)**	**PI-H (50 days)**
AWD	SP	3.03	0.47	0.20
	BP	3.38	0.44	0.16
	CT	2.50	0.45	0.17
LSD$_{0.05}$, Tillage		0.61	ns	ns

[a]Treatments, SP=Strip planting, BP=Bed planting, CT=Conventional Tillage, CF= Continuous Flood irrigation, AWD= Alternate wetting and drying irrigation. LSD= Least Significant Difference. LP-T= Land preparation to transplanting, T-PI= Transplanting to panicle initiation, PI-H= Panicle initiation to harvesting. *Significant at 5 % level, ns=Not significant.

Table 6.4 Number of ponding and water disappearing days for rice in 2015, 2016, 2017.

2015				
Tillage	**Ponding days**	**AWD days**	**Dry days before harvest**	**Total[a]**
SP	78.0	_	7.0	85
BP	78.4	_	6.6	85
CT	78.4	_	6.6	85
LSD$_{0.05}$, Tillage	ns	_	ns	

[a] Treatments, SP=Strip planting, BP=Bed planting, CT=Conventional Tillage, CF= Continuous Flood irrigation, LSD= Least Significant Difference, [a] total day of rice growing season counting from transplanting to one week before harvesting when water disappeared from the field. *Significant at 5 % level, ns=Not significant.

2016					
Treatments[a]		**Days**			
Irrigation	**Tillage**	**Ponding days**	**AWD days**	**Dry days before harvest**	**Total[a]**
CF	SP	76.3	_	8.7	85
	BP	76.5	_	8.5	85
	CT	79.5	_	5.5	85
LSD$_{0.05}$, Tillage		2.2	_	2.2	_
Treatments[a]		Days			
Irrigation	Tillage	Ponding days	AWD days	Dry days before harvest	Total[a]
AWD	SP	70.3	9.0	5.7	85
	BP	68.3	11.0	5.7	85
	CT	65.3	12.5	7.2	85
LSD$_{0.05}$, Tillage		2.3	0.8	ns	_

[a] Treatments, SP=Strip planting, BP=Bed planting, CT=Conventional Tillage, CT= Continuous Flood irrigation, AWD= Alternate wetting and drying irrigation. LSD= Least Significant Difference, [a] total day of rice growing season counting from transplanting to one week before harvesting when water disappeared from the field. *Significant at 5 % level, ns=Not significant

2017					
Treatments[a]		**Days**			
Irrigation	**Tillage**	**Ponding days**	**AWD days**	**Dry days before harvest**	**Total**
CF	SP	77.8	_	7.2	85
	BP	77.3	_	7.7	85
	CT	77.0	_	8.0	85
LSD$_{0.05}$, Tillage		ns		ns	
Treatments[a]		**Days**			
Irrigation	**Tillage**	**Ponding days**	**AWD days**	**Dry days before harvest**	**Total**
AWD	SP	70.5	6.5	8.0	85
	BP	71.8	7.2	6.0	85
	CT	69.8	8.0	7.2	85
LSD$_{0.05}$, Tillage		ns	ns	ns	

[a] Treatments, SP=Strip planting, BP=Bed planting, CT=Conventional Tillage, CT= Continuous Flood irrigation, AWD= Alternate wetting and drying irrigation. LSD= Least Significant Difference, [a] total day of rice growing season counting from transplanting to one week before harvesting when water disappeared from the field. *Significant at 5 % level, ns=Not significant

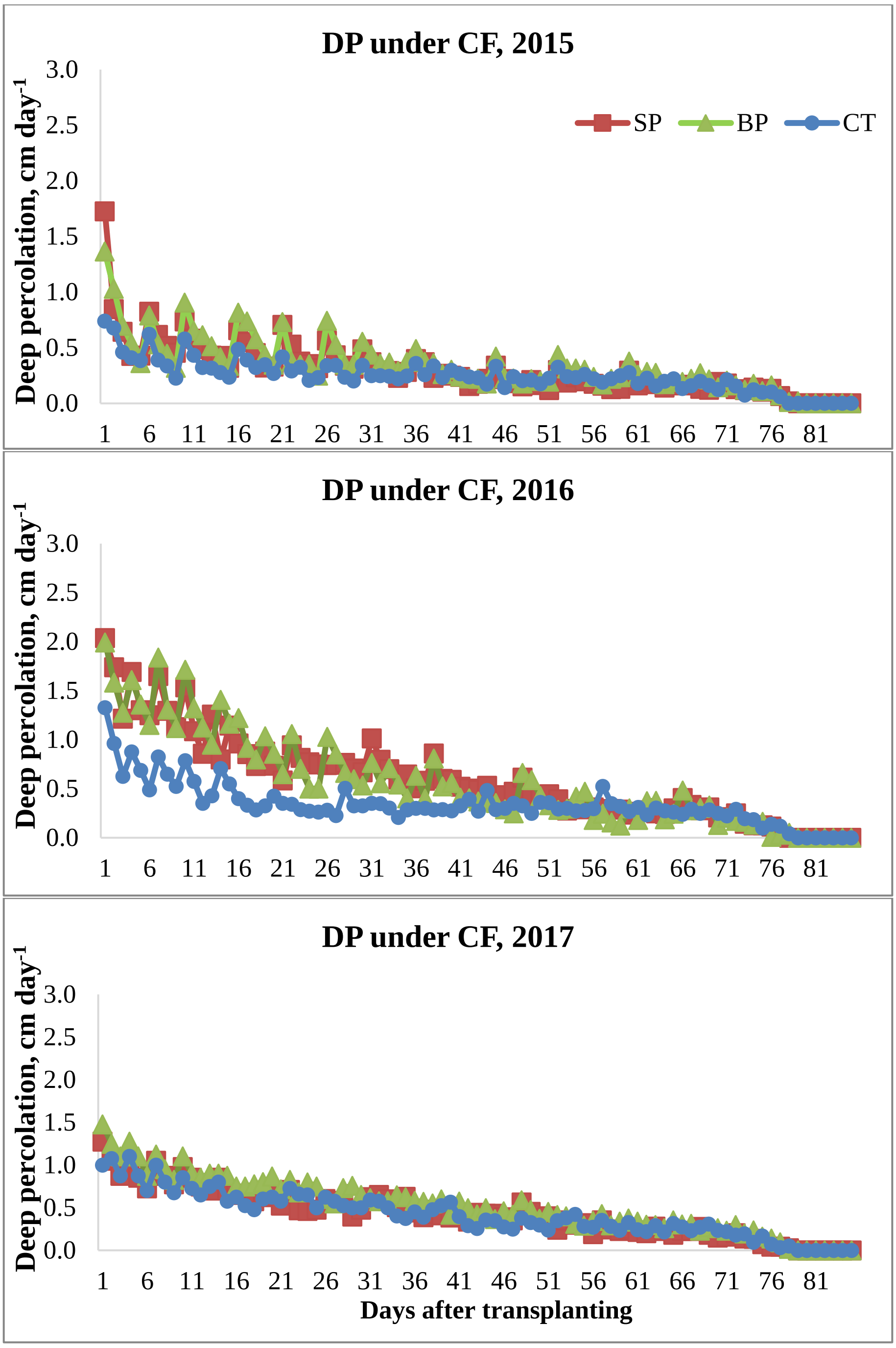


Figure 6.2 Daily deep percolation for three tillage treatment under continuous flooding irrigation in three years. DP= deep percolation, CF= Continuous flooding, SP= Strip planting, BP=Bed planting, CT= Conventional tillage

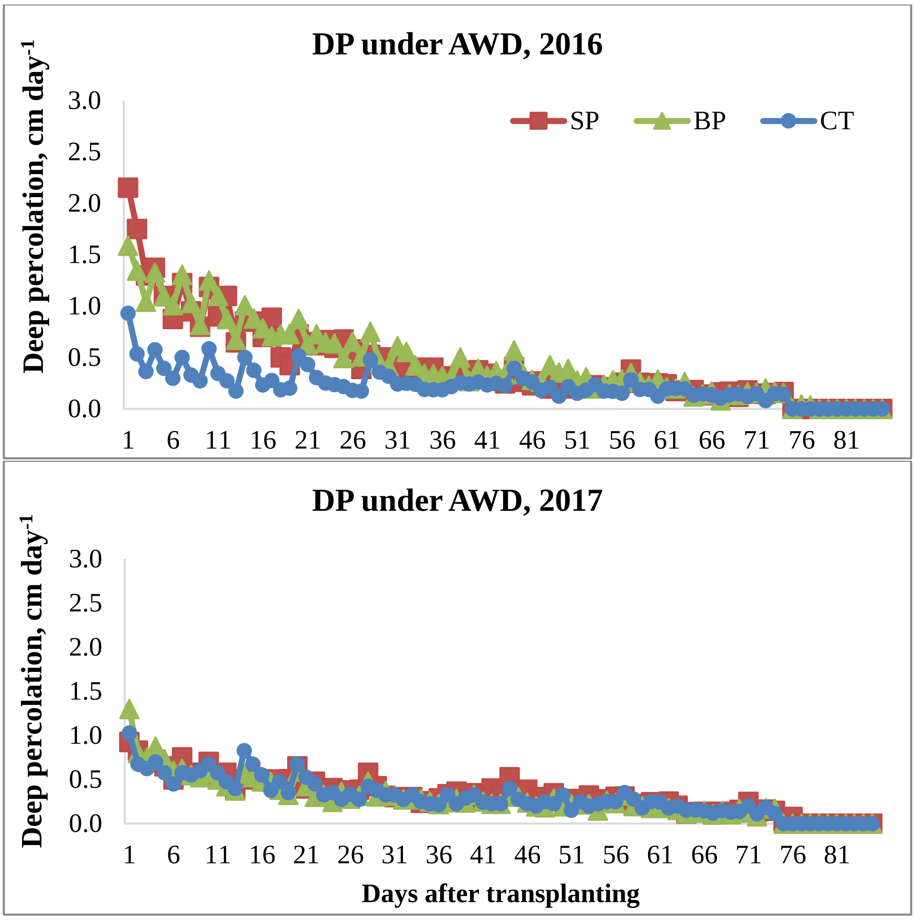


Figure 6.3 Daily deep percolation for three tillage treatment under alternate wetting and drying irrigation in 2016 and 2017. DP= deep percolation, AWD= Alternate wetting and drying, SP= Strip planting, BP=Bed planting, CT= Conventional tillage

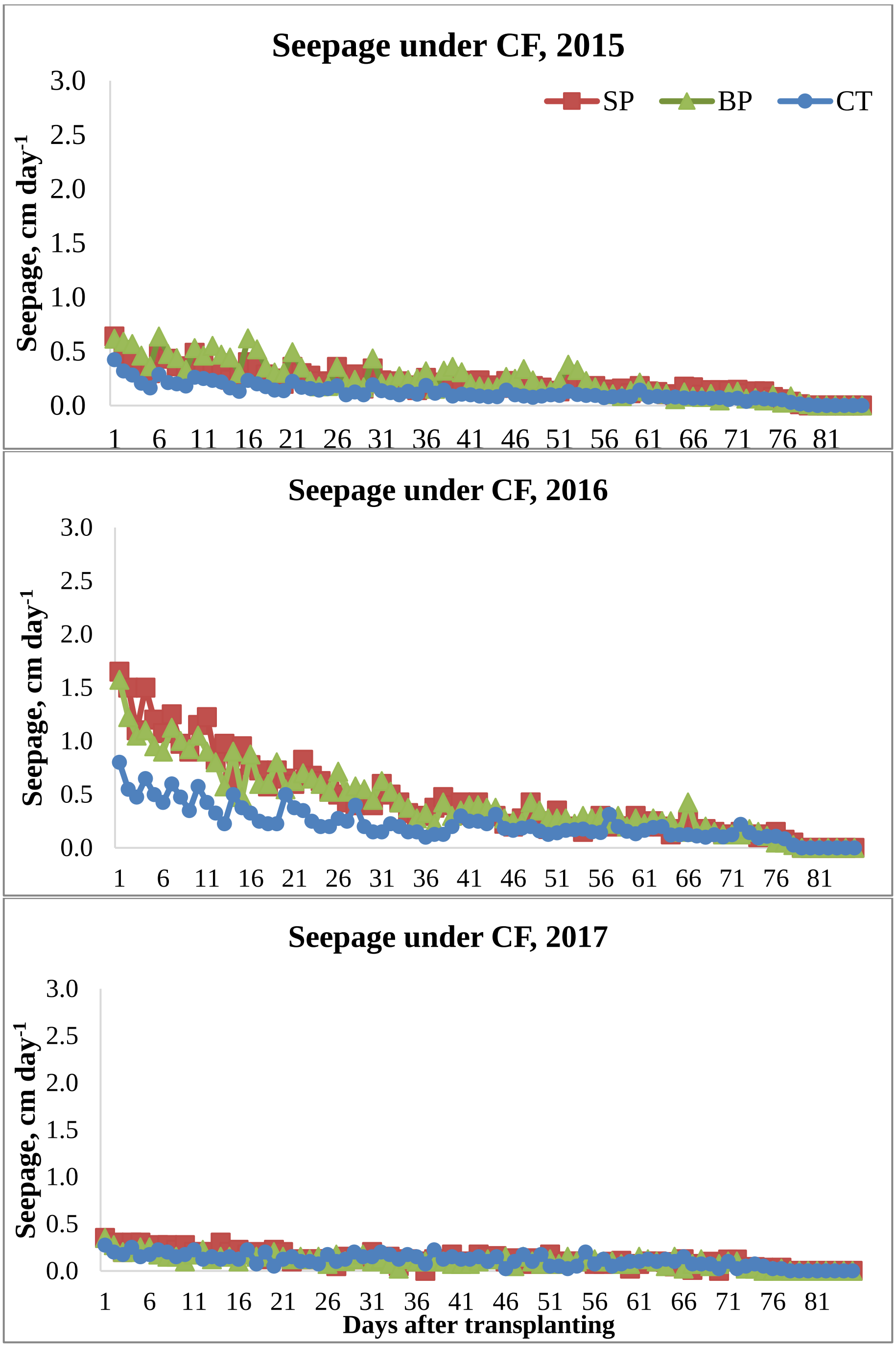


Figure 6.4 Daily seepage for three tillage treatment under continuous flooding irrigation in three years. SP= Seepage, CF= Continuous flooding, SP= Strip planting, BP=Bed planting, CT= Conventional tillage

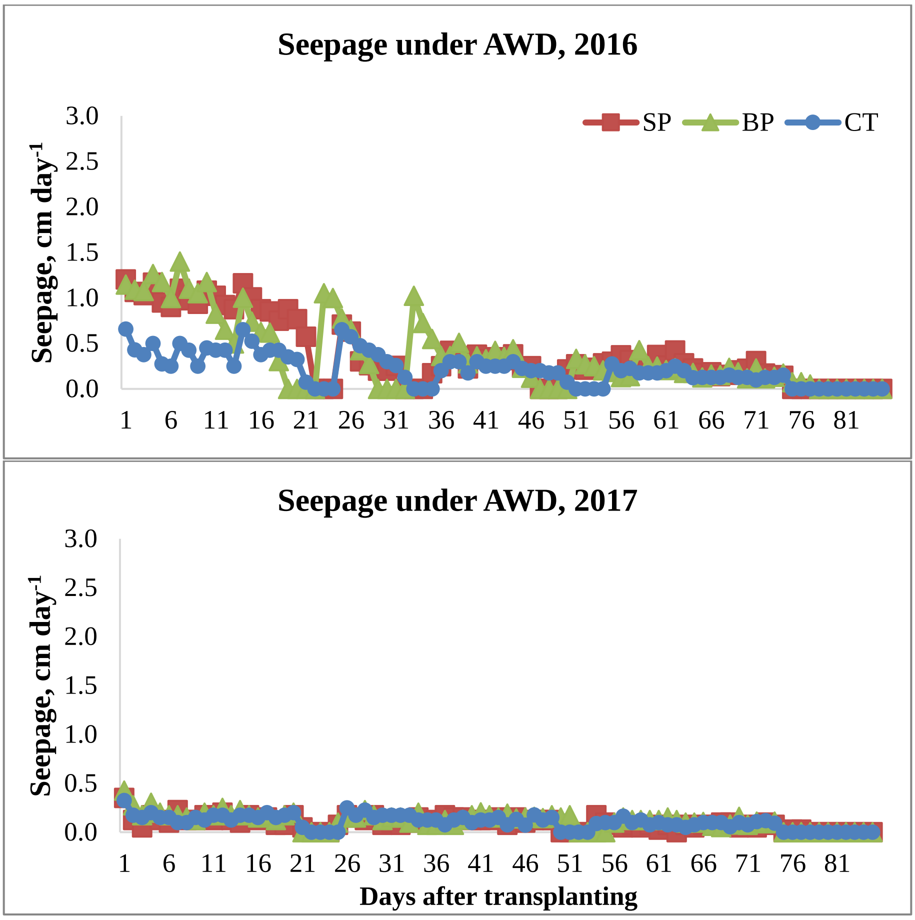


Figure 6.5 Daily seepage for three tillage treatment under alternate wetting and drying irrigation in two years. DP= deep percolation, AWD=Alternate wetting and drying, SP= Strip planting, BP=Bed planting, CT= Conventional tillage

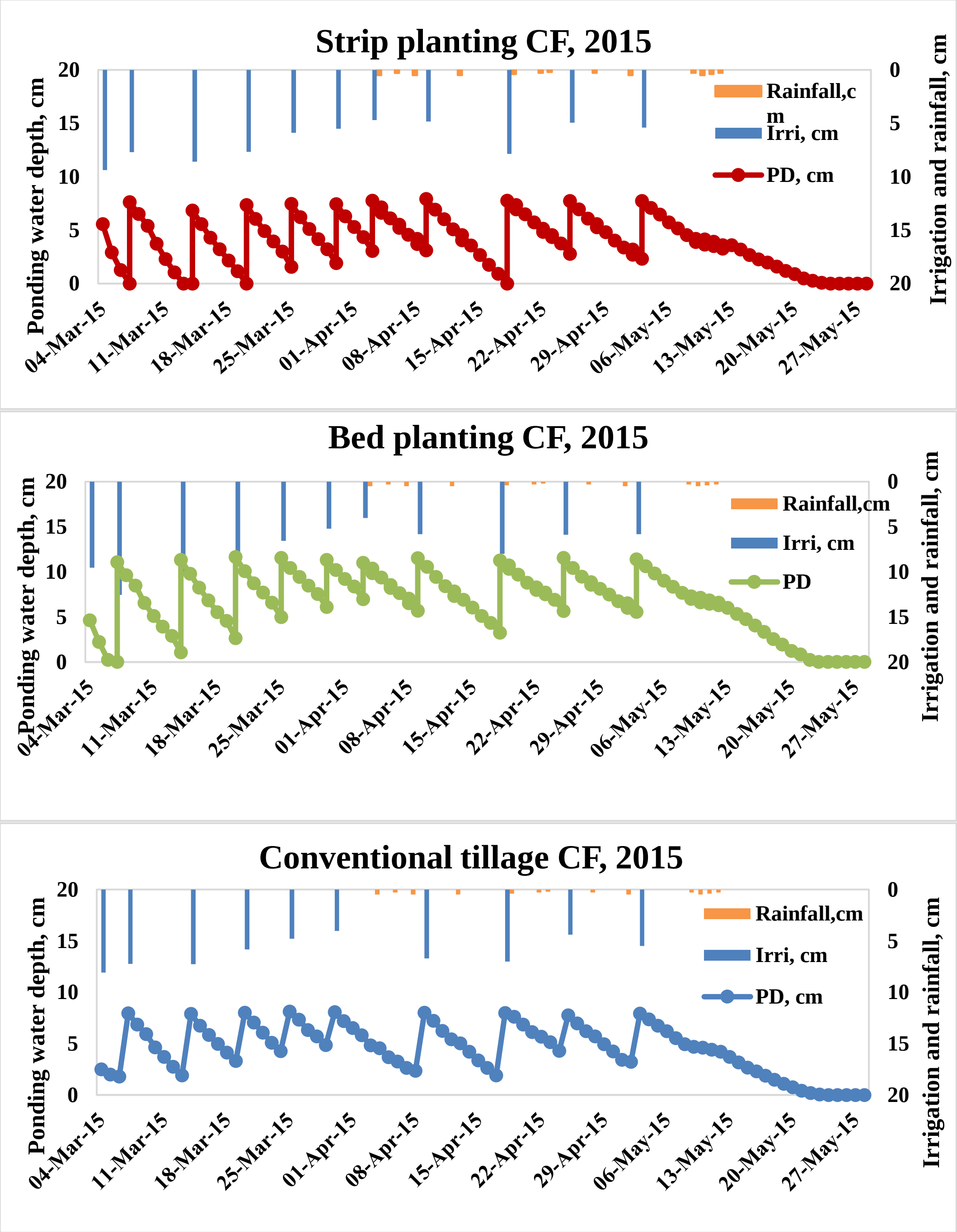


Figure 6.6 Daily ponding water depth (PD, cm) for three tillage treatments under continuous flooding (CF) irrigation in 2015.

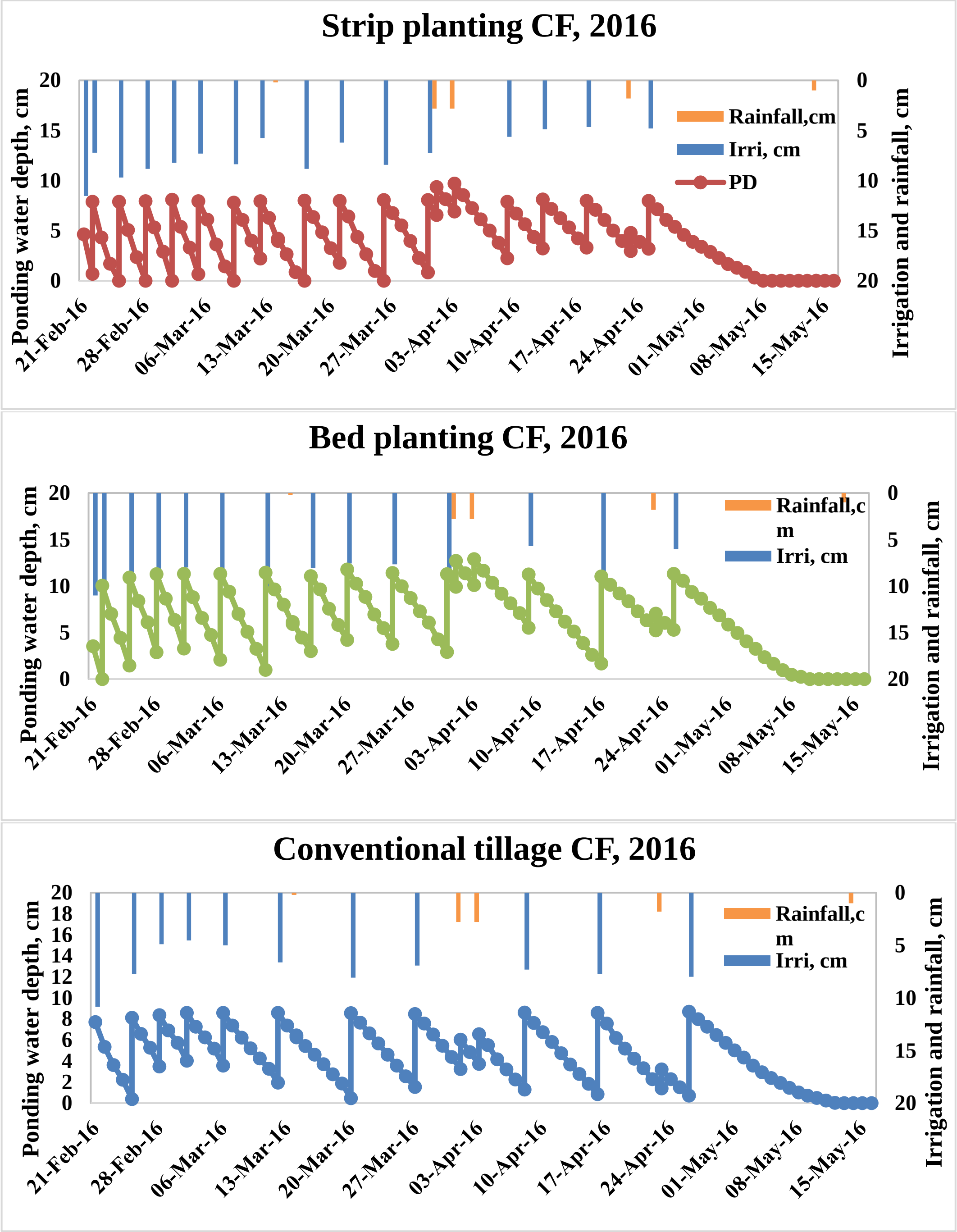


Figure 6.7 Daily ponding water depth (PD, cm) for three tillage treatments under continuous flooding (CF) irrigation in 2016.

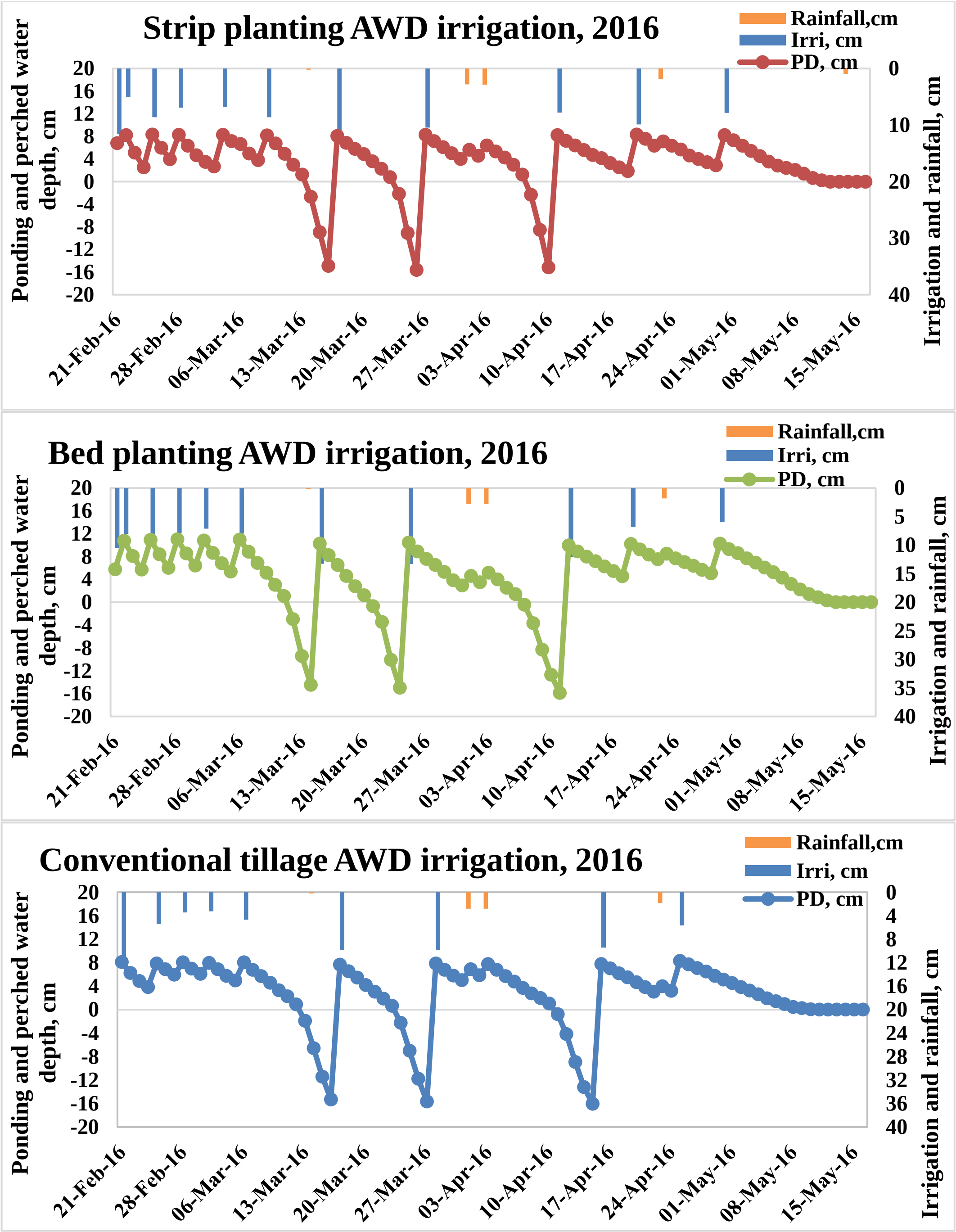


Figure 6.8 Daily ponding water depth for three tillage treatments under alternate wetting and drying irrigation from 2016.

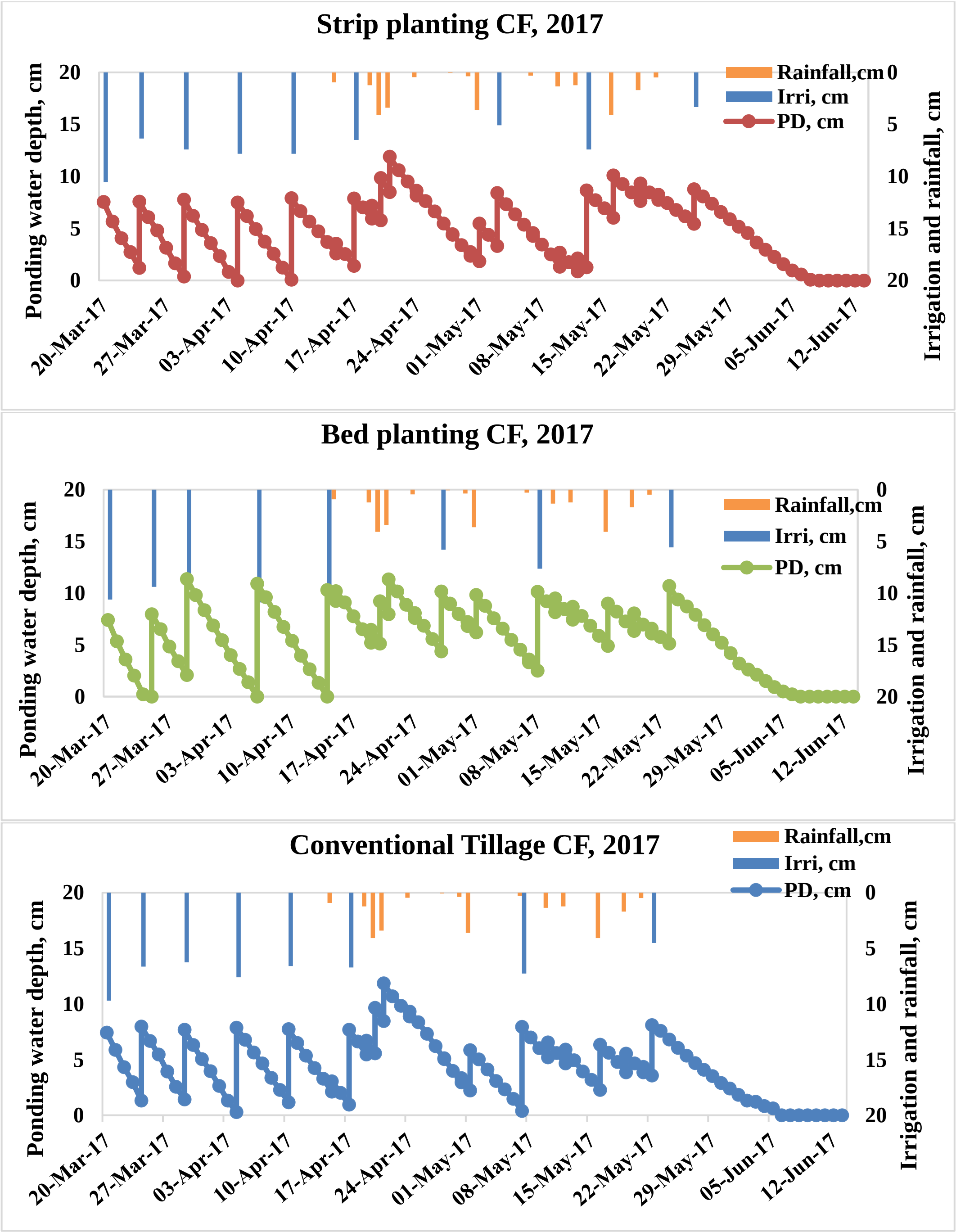


Figure 6.9 Daily ponding water depth for three tillage treatments under continuous flooding (CF) irrigation in 2017.

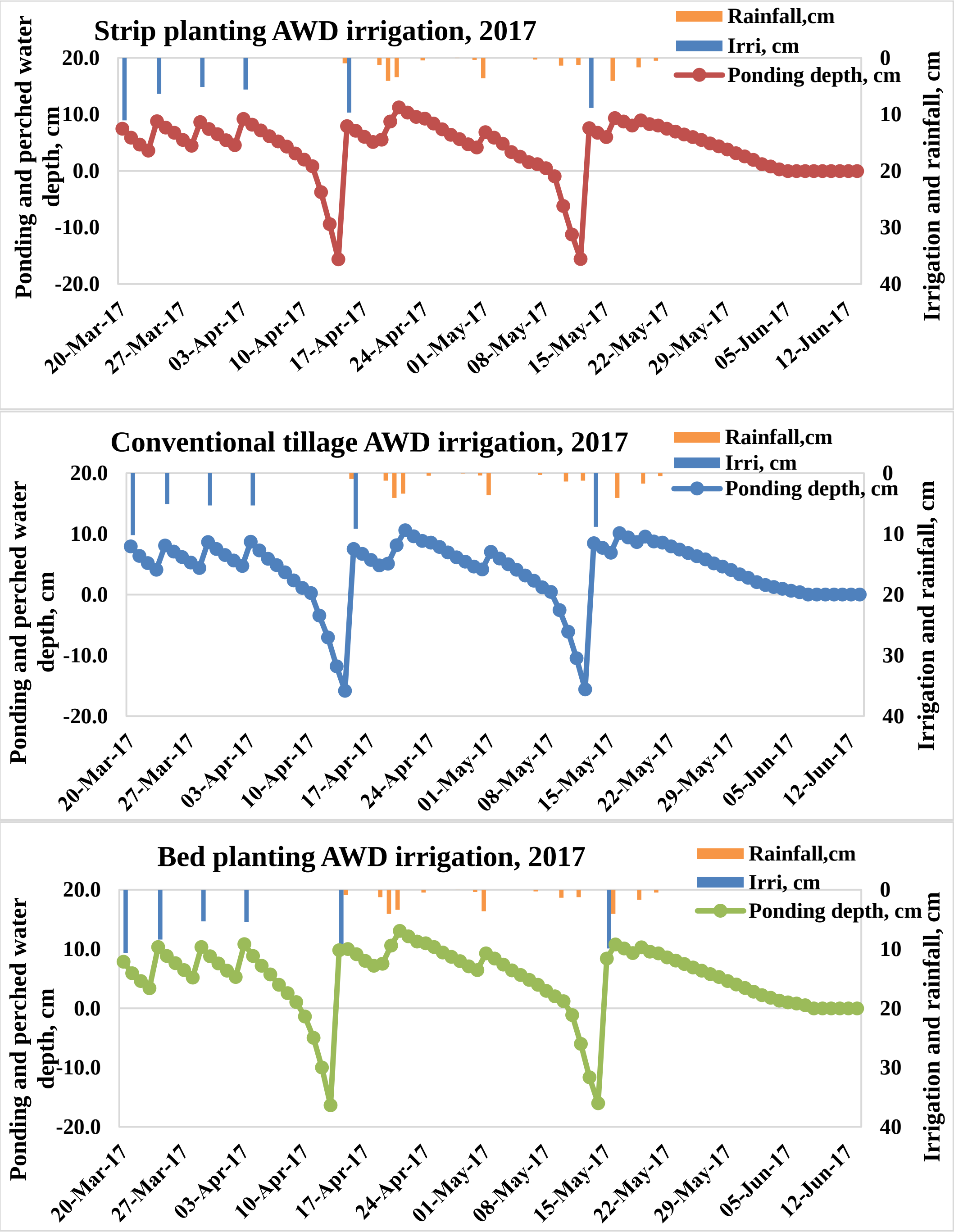


Figure 6.10 Daily ponding water depth (PD, cm) for three tillage treatments under alternate wetting and drying irrigation in 2017.

6.3.9 Effect of tillage on total water use, rice grain yield and water productivity

Seasonal rainfall during different years under the study is shown in Figure 3.2. During the Boro rice season (cool, dry season), the years 2015 and 2016 had relatively low seasonal rainfall, 5.0 and 8.6 cm, respectively. In 2017, rainfall was 23.3 cm and well distributed during vegetative phases, which resulted in less application of irrigation water. Tillage effect on total water use (irrigation and rainfall) was significant only in 2016, both under CF and AWD irrigation (Table 6.5). The amount of water applied to the field and the rainfall were converted to the volume of water (m^3). Under CF irrigation, the amount of total water use in SP and BP was 46 % and 42 % higher than CT. While under AWD irrigation, SP and BP received 46 % and 48 % higher total water compared to CT. Tillage treatment did not significantly affect rice grain yield in any of the years in either of the irrigation management. However, CT gave higher WP compared to BP and SP in 2015 and 2016. The increment in WP by the CT ranged from 17 % to 48 % compared to SP, while the increases were 39 % to 53 % compared to BP. In 2017 there was no significant difference in WP of rice under three tillage treatments and two irrigation management.

Table 6.5 Yield, total water use (irrigation and rainfall), and water productivity for Boro Rice from 2015 to 2017.

2015						
Treatments[a]	**Yield, Total water input, Water productivity**					
Tillage	**Yield, t ha^{-1}**		**Total water, m^3**		**Water productivity, kg m^{-3}**	
	LR	**HR**	**LR**	**HR**	**LR**	**HR**
SP	6.39	7.10	8517	8015	0.75	0.91
BP	5.88	6.33	8916	9156	0.68	0.72
CT	6.46	7.08	7108	6914	0.91	1.03
$LSD_{0.05}$, Residue	0.2*		ns		0.08*	
$LSD_{0.05}$, Tillage	ns		ns		0.19*	

[a]Treatments, SP=Strip planting, BP=Bed planting, CT=Conventional Tillage, CF= Continuous Flood irrigation, LR=Low residue, HR=High residue, LSD= Least Significant Difference. *Significant at 5 % level

2016				
Treatments[a]		**Yield, Total water input, Water productivity**		
Irrigation	**Tillage**	**Yield, t ha^{-1}**	**Total water, m^3**	**Water productivity, kg m^{-3}**
CF	SP	6.93	13020	0.53
	BP	6.62	12721	0.52
	CT	6.78	8932	0.77
LSD$_{0.05}$, Tillage		Ns	1110*	0.05
Treatments[a]		**Yield, Total water input, Water productivity**		
Irrigation	**Tillage**	**Yield, t ha^{-1}**	**Total water, m^3**	**Water productivity, kg m^{-3}**
AWD	SP	6.54	10642	0.61
	BP	6.35	10813	0.59
	CT	6.60	7274	0.90
LSD$_{0.05}$, Tillage		Ns	362*	0.07*

[a]Treatments, SP=Strip planting, BP=Bed planting, CT=Conventional Tillage, CF= Continuous Flood irrigation, AWD= Alternate wetting and drying irrigation. LSD= Least Significant Difference, *Significant at 5 % level

2017				
Treatments[a]		**Yield, Total water input, Water productivity**		
Irrigation	**Tillage**	**Yield, t ha^{-1}**	**Total water, m^3**	**Water productivity, kg m^{-3}**
CF	SP	6.62	8398	0.77
	BP	6.53	9174	0.71
	CT	6.67	8145	0.82
LSD$_{0.05}$, Tillage		Ns	ns	ns
Treatments[a]		**Yield, Total water input, Water productivity**		
Irrigation	**Tillage**	**Yield, t ha^{-1}**	**Total water, m^3**	**Water productivity, kg m^{-3}**
AWD	SP	6.10	7286	0.84
	BP	6.41	7067	0.91
	CT	6.52	6858	0.95
LSD$_{0.05}$, Tillage		Ns	ns	ns

[a]Treatments, SP=Strip planting, BP=Bed planting, CT=Conventional Tillage, CT= Continuous Flood irrigation, AWD= Alternate wetting and drying irrigation. LSD= Least Significant Difference.

6.4 Discussion

The water balance was assessed during the Boro rice season in three consecutive years with contrasting irrigation regimes, rainfall, transplanting dates and varied control of seepage. Different conclusions about water balance can be drawn from each year. The 2016 results were most dissimilar to the other years due to the lack of control on lateral seepage and the transplanting of the irrigated Boro rice ~ 2 weeks before the surrounding farmers began to transplant Boro rice. This exacerbated the lateral seepage and deep percolation and greatly increased irrigation water requirement. By contrast, in the 2017 season, the control of lateral seepage by a plastic sheet under bunds to 60 cm depth and the synchronised transplanting of

Boro rice with the surrounding farmers reduced lateral seepage and deep percolation and hence reduced irrigation water requirement for SP. Hence in the following discussion, most emphasis is on contrasting the effects of the crop establishment method on water balance in 2016 and 2017.

Despite the differences in water balance components among the crop establishment methods, there was no difference among the methods in ET_c or crop yield.

6.4.1 Effect of SP on irrigation water requirement for land preparation

In 2016, SP plots required two consecutive irrigations for land preparation, one about 12.0 cm on the day before transplanting and another about 0.7 cm in the morning of rice transplanting. By contrast, only single irrigation of about 10.9 cm was applied on the day before transplanting for CT, which was enough for puddling and transplanting of seedlings. Furthermore, at the time of 1st field measurements of ponding depth, it was observed that the ponding depth in the SP plots dropped from 11.5 cm to 4.6 cm within about two hours of irrigation water application for land preparation. By contrast, in the CT, the ponding depth declined from 10.9 cm to 7.7 cm within the same period. This observation suggests a quicker infiltration in the SP plots compared to CT plots in a couple of hours after the first irrigation application. Similarly, the percolation rates of the first day after land preparation (about 20 hours, from the 1st irrigation application to the 2nd ponding depth measurement, 2nd ponding depth was measured before the 2nd irrigation application on the 2nd day) was higher in the SP plots (5.0 cm day^{-1}) compared to the CT plots (3.0 cm day^{-1}) (Table 6.3). A similar trend was also observed in terms of seepage rates in the 1st day, where SP plots had seepage rates twice as high as CT plots (Table 6.2). Thus, in 2016, the higher amount of irrigation requirement for land preparation in SP plots was attributed to higher deep percolation and higher seepage loss through the unprotected bunds to the surrounding farmers' plot, which was not cultivated until 20 days after the 1st irrigation in the research plot. In 2015 and 2017, deep percolation in the SP plot between land preparation to transplanting was significantly higher, but seepage was similar compared to the CT (Table 6.2), suggesting that in 2015 and 2017 years, protected bunds and synchronized transplanting with the surrounding farmers' plot reduced seepage loss but not the deep percolation. Thus, the three years results suggest that the higher amount of irrigation water applied to SP for land preparation than the CT plots was mostly due to the higher percolation in the SP plot. The first reason for higher percolation in the SP plot was the high infiltration rates in the SP treatment as discussed in Chapter 3. Rice production in clay soil results in soil cracking upon drying. Irrigation for land preparation in the rice field thus involves water application to cracked soils and results in bypass flow losses (water that flows through cracks to the subsoil). The second reason for higher percolation in SP plots might be the cracks in the plough pan that was not closed after rewatering. By contrast, puddling fills cracks (Yoshida and Adachi, 2001), and breaks down soil aggregates and drastically reduces the permeability of the subsurface layer (Sharma and De Datta, 1986).

In an experiment done in two districts of Bangladesh practising SP for one season, Hossen *et al.* (2018) reported a 23 % reduction of water input for land preparation in SP compared to CT. This contradicts the current results, which might be attributed to the short time span of practising minimum soil disturbance. The short-term practice of SP may not be sufficient to alter the permeability of the plough pan, while the carry-over effect of puddling that persisted in the SP plots might have helped to hinder water infiltration during the period of land preparation (Hossen *et al.*, 2018).

6.4.2 Effect of SP on irrigation water requirement from transplanting to harvest

CF Irrigation

In 2016, the irrigation water requirement from transplanting to harvest was 47 % higher in the SP than CT, mainly due to 63 % higher water requirement in the SP plot from transplanting to panicle initiation (35 DAT). Daily deep percolation and seepage during the 2016 rice season suggest that both percolation and seepage rate in the first 35 days were higher in the SP plot compared to CT. By contrast, the rest of the season showed no significant differences in daily percolation and seepage between SP and CT treatment. The higher percolation rates in the first 35 days could be attributed to the high infiltration through the cracks developed in the undisturbed weak plough pan upon drying. As the season progressed, rewatering of the soil profile allowed the clays to swell and cracks to close, which reduced the free vertical movement of water. The higher seepage rates in the SP plot in the early rice season could also be attributed to the fact that rice in the research plot was transplanted 20 days before the rice transplanting in the adjacent farmers' fields. During these days, water seepage rates were high, probably due to horizontal water movement through the unprotected bunds to the surrounding dry fields leading to higher irrigation requirement in the early rice season. However, in 2015 and 2017, protected bunds and synchronized transplanting with the surrounding farmers' fields reduced the seepage of water over the whole season. Thus, in 2015 and 2017, daily seepage according to different growing stages was not significantly different between SP and CT treatment. Similar seepage in both SP and CT was also reflected in the similar irrigation requirement for 2015 and 2017 under CF irrigation. This suggests that provided seepage is controlled or minimal, irrigation water requirement was similar for SP and CT, despite higher percolation in the SP plot (Table 6.2).

Other studies in the IGP also show higher irrigation water requirement in non-puddled rice compared to puddled transplanted rice (PTR). Sudhir-Yadav *et al.* (2011), in a clay loam soil, observed that twice as much irrigation water was required in direct-seeded rice (DSR) compared to PTR when irrigation was applied daily. They reported that deep drainage was much higher in DSR than PTR after 2 years. In contrast to this result, Sudhir-Yadav *et al.* (2014) with silty clay loam soil in a study for one wet season reported non-puddled transplanted rice (NPTR) compared to PTR received 13 % less irrigation. Water saving was mainly due to water savings in the land preparation under NPTR. Both studies did not report any water saving due to reducing seepage losses despite each plot being bounded by earthen bunds with plastic lining up to a depth of 50 cm. In the current study, SP received 50 % higher irrigation water compared to CT under continuous flooding irrigation in 2016 when there was no plastic lining in the bunds. However, in 2017 when plastic lining was inserted to a depth of 60 cm, SP received similar irrigation water compared to CT under continuous flooding irrigation. Experimenting with strip tillage direct-seeded rice (STDSR) in a clay loam soil in the wet season for four years from 2012 to 2015, Alam *et al.* (2018a) reported STDSR saved 33-66 % irrigation water compared to PTR. The variation in the irrigation input was not due to the tillage methods, rather due to the variation in the amount of rainfall across the four years. Choudhury *et al.* (2007) in a study for one season with sandy loam soil, reported dry direct-seeded rice received 50 % less irrigation water compared to PTR due to 43 % less deep percolation beyond the root zone. Other studies have shown that puddling decreases irrigation input to rice due to reduced infiltration (Tuong *et al.*, 1994; Kukal and Aggarwal, 2002).

AWD Irrigation

In 2016, under SP treatment, AWD irrigation saved five irrigations that resulted in 24 % water savings compared to CF irrigation. Again, under CT treatment, AWD irrigation saved 21 % water over CF irrigation. The water savings was due to zero seepage and reduced percolation during the water disappearing days under AWD irrigation methods (Arora, 2006; Belder *et al.*, 2007; Bouman *et al.*, 2007; Choudhury *et al.*, 2007; Sudhir-Yadav *et al.*, 2011). Irrigation water savings in AWD irrigation treatment in the current study compared to CF was consistent with the findings of many other studies where researchers found 15-40 % saving of irrigation water by CT-AWD treatment (Humphreys *et al.*, 2010).

In 2016, under AWD irrigation treatment, SP received 52 % more water than CT during the whole season. From transplanting to before commencement of AWD at 15 DAT, SP-AWD and

CT-AWD received, respectively, four and three irrigations. Thus, higher irrigation requirement in SP-AWD irrigation was partly due to the increased number of irrigation and higher amount of water requirement (due to higher infiltration) before the commencement of AWD. After the commencement of AWD, SP-AWD received 26 % more water than CT-AWD, even though both treatments received four irrigations. Higher irrigation requirement in SP-AWD treatment than CT-AWD after commencement of AWD was due to 25-33 % higher water requirement in each irrigation event (Figure-6.6). Each AWD irrigation event occurred when the perched water depth dropped to 15 cm below the surface. Then water was applied first to saturate the 15 cm depth of soil and then to pond the field to 8 cm depth for both SP and CT. A higher amount of water applied to the SP plot in an individual irrigation event during the AWD period suggest that the higher amount was required to saturate the 15 cm soil depth (because of the low bulk density) and higher drainage during the irrigation event through cracks that extended down to the plough pan and the lack of puddling to seal the cracks. It is well established that puddling decreases infiltration rate and consequently deep drainage (Mousavi *et al.*, 2009).

There were three AWD events in SP and CT treatments in 2016. Under SP treatment, standing water disappeared quickly, and the perched water level reached 15 cm depth after three days in each AWD events, which resulted in a total of 9 water disappearing days and 70 ponding days from transplanting to flowering stage. For CT treatment, the water disappeared slowly, and the perched water level took one more day to reach 15 cm depth in each AWD event, which resulted in 12 water disappearing days and 65 ponding days in CT treatment. This means that SP treatment had to be ponded 5 more days to avoid increasing matric potential more than -10 kPa in each AWD event. Water required to maintain ponding in SP for 5 more days might have partly increased the total water requirement in SP plots.

The well-distributed rainfall in 2017 resulted in two AWD events and no differences between CT and SP in ponding and AWD days.

While there were many studies in the IGP showing irrigation water savings with AWD versus CF, none showed a comparison between the SP-AWD and CT-AWD treatment. There were few reports on water savings under AWD irrigation in non-puddled direct-seeded rice (DSR) or ZT rice compared to puddled transplanted rice (PTR). Sudhir-Yadav *et al.* (2011) observed DSR-20 kPa (when soil water potential increased to -20 kPa) reduced the irrigation input by 30-53 % in comparison to PTR-20 kPa. Mandal *et al.* (2009) reported 60 % irrigation water saving with DSR compared to PTR on a silty loam soil in Nepal when both treatments were irrigated after soil water potential decreased to -10 kPa in 15 cm soil depth. Bhushan *et al.* (2007) observed irrigation water saving of 25-16 % with ZT-DSR compared with PTR when irrigation for both establishment methods was scheduled on the appearance of hairline cracks.

6.4.3 Effect of SP on seepage and percolation losses

CF irrigation

Higher infiltration rates measured before rice transplanting in the SP plots (as discussed in Chapter 3) are reflected in the percolation losses early in the rice season. Higher percolation rates observed in the SP plots were mainly due to the reduced bulk density, increased total porosity, and the higher steady-state infiltration rates in the topsoil and the plough pan. The undisturbed pore connectedness in the SP plots might have contributed to the faster vertical movement of water to the subsoil. However, saturated hydraulic conductivity (K_{sat}) of both SP and CT were not significantly different, which might be attributed to the fact that K_{sat} measurements in the SP plots were taken from spots without any cracks that were not really representative of the whole SP plot. Indeed, a few random measurements in the SP plots were taken in the spots with clearly noticeable ~2 mm wide cracks. The mean K_{sat} in the cracks was 5.3 cm hr^{-1} (results not shown in Chapter 3), while the average values recorded for SP were 1.39 cm hr^{-1}. The higher percolation rates in the non-puddled SP plots were thus also attributed to the cracks developed upon drying. These cracks probably extended down to plough pan and created an aperture for vertical movement of water (Wopereis *et al.*, 1992; Tuong *et al.*, 1996; Cabangon and Tuong, 2000; Liu *et al.*, 2003). Tuong *et al.* (1996) quantified the flow process when flood irrigation is applied to cracked soil. Irrigation water moves rapidly in the crack networks ahead of the surface waterfront. Part of this water infiltrates into the subsoil, bypassing the topsoil, thus recharging the groundwater.

In 2016, the percolation rate in the SP plots was double that in the CT plots in the first 35 DAT (Table 6.3). However, after 35 DAT, percolation rates in both the SP and CT were not significantly different, suggesting that the cracks in the plough pan of SP plots closed after the profile was soaked and rewetted. Usually, land preparation in CT involves soaking of soil understanding water for 2-10 days followed by puddling (Wopereis *et al.*, 1992). In contrast, SP does not involve puddling, thus soaking and rewetting of the cracked soil took about 35 days.

In 2017, plastic sheet inserted in the bunds to 60 cm below ground surface reduced percolation rates, and therefore percolation rates and total percolation during the whole rice season between SP and CT were statistically equal. However, in 2015, plastic sheets in the bunds to 15 cm below the soil surface reduced seepage but did not reduce percolation from the SP plot. When the seepage from the topsoil is restricted by the protected bunds, but the subsoil is permeable, water infiltrates into the subsoil, and significant under-bund seepage takes place to the surroundings through lateral drainage (Tuong *et al.*, 1994; Cabangon and Tuong, 2000).

In the current study, there were no significant differences in seepage between SP and CT in 2015 and 2017. This finding suggests that plastic lining greatly reduced seepage losses throughout the whole plot (Table 6.2). Experimenting with flat beds and DSR in New Delhi, India, Choudhury *et al.* (2007) reported a reduction of seepage with plastic lining in the bunds 10 cm below the soil surface. In 2016 in the current study, without plastic lining and transplanting rice 20 days earlier than the surrounding farmers' plot caused seepage in the SP plot at twice the rate in the CT plot. Higher seepage in the SP was observed in the first month of the rice season. However, when the lateral flow of water to the surrounding fields became equilibrated, seepage rates in SP resulted in significantly similar to the CT plot.

6.4.3.1 AWD irrigation

The lower total deep drainage losses (seepage and deep percolation) in AWD rice than in CF rice was caused by both reduced rates of seepage and reduced rates of percolation (Arora, 2006; Belder *et al.*, 2007; Bouman *et al.*, 2007; Choudhury *et al.*, 2007; Sudhir-Yadav *et al.*, 2011). Strip planting rice under AWD had 14-22 % less seepage and 22-26 % less percolation than SP-CF. However, CT-AWD reduced seepage by 6-10 % and percolation losses by 27-33 %. This means that the reduction in seepage losses under SP-AWD was larger than the CT-AWD. However, such reduction may be smaller in farmers' fields as seepage from small plots is disproportionately high due to the large perimeter to area ratio (Tuong *et al.*, 1994; Humphreys *et al.*, 2008). For the current study, this ratio is about 0.41 m/m^2. In comparison, the perimeter to area ratio of a typical Rajshahi farmers' rice irrigation block (0.33 acre or 45 × 30 m) is about 0.11 m/m^2.

Several findings of reducing seepage and percolation losses under non-flooded irrigation have been reported. Experimenting with dry direct-seeded rice watered to field capacity on flat land at New Delhi, India, Choudhury *et al.* (2007) reported quite similar results to our findings in reducing seepage and percolation losses. Compared with flooded transplanted rice, with a total water input of 136.0 cm, dry-seeded rice kept at field capacity on flat land had 22-38 % less seepage and percolation losses. They used plastic lining to 10 cm below the ground surface. In another experiment, Sudhir-Yadav *et al.* (2011) reported a 54-64 % reduction in seepage and 66-82 % reduction in percolation losses of dry-seeded rice by switching from daily-irrigated to 20 kPa soil water tension (when soil water potential decreased to -20 kPa, referred to as AWD treatment). Humphreys *et al.* (2008) found a 50 % reduction in total deep drainage (seepage and in-field deep drainage) by switching from CF PTR on the flat to 2 days of water disappearing in puddled transplanted rice.

6.4.4 Effect of SP on Evapotranspiration

For both SP and CT, ET_c was similar over three years under CF irrigation which could be attributed to a similar atmospheric vapour pressure deficit above the canopy for both tillage treatments.

Shifting from CF to AWD irrigation, SP reduced 6-7 ponded days. The reduced evaporation from the water surface under AWD treatment, which was exposed to 6-7 days fewer during the whole season than the water surface under CF, resulted in 6-11 % reduced crop evapotranspiration from the SP-AWD treatment.

6.4.5 Effect of SP on grain yield

Averaged over tillage and irrigation treatments, the rice yields were 6.5 t ha^{-1}, 6.6 t ha^{-1} and 6.5 t ha^{-1} respectively in 2015, 2016 and 2017, with no significant yield differences among years. The values of BRRI dhan28 rice yield are comparable to the potential yield of 6.0 t ha^{-1} for the same variety as suggested by BRRI (2013). In 2015, high residue retention yielded higher rice grain than low residue, while there was no effect of tillage practices on rice grain yield. The higher rice yield might be attributed to the slowing down of the N mineralization in the early stage due to minimum soil disturbance with non-puddling, but increased soil total N and plant N uptake in the later stage in the HR treatment than in the LR treatment (Alam *et al.*, 2020). In 2016 and 2017, there was no significant effect of residue retention on rice grain yield.

Very few researchers have reported the effect of non-puddled transplanted rice on grain yield. For example, Bhushan *et al.* (2007), Saharawat *et al.* (2010), and Nandan *et al.* (2018) reported no significant yield differences between conventional puddled transplanted rice and no-tillage or reduced tillage non-puddled transplanted rice in different research farms of India, while

Saharawat *et al.* (2009) reported reduced tillage non-puddled transplanted rice yielded 0.3 t ha^{-1} more grain over conventional puddled transplanted rice in the farmers' fields. Gathala *et al.* (2011a) reported a 20-23 % rice yield reduction in ZT transplanted rice compared to CT. In the present study, the rice grain yield under SP was similar to that of CT. In the same region of Bangladesh and with the same rice variety (BRRI dhan28), Haque *et al.* (2016) reported similar yields of the conventional puddled (CT) and reduced tillage non-puddled (SP) transplanted rice both in farmer's field trials and in replicated experiments. These results of rice yields in the Northwest region of Bangladesh suggest that, transplanted rice grown in minimum disturbance non-puddled soil performed similar to rice grown in the puddled soil.

In the present study, the rice grain yield of CT-CF was similar to that of CT-AWD, which is also in close conformity with the results done in the research farm of Bangladesh Rice Research Institute, Gazipur Bangladesh, with CT and AWD irrigation (BRRI, 2018). In the present study, averaged across the tillage treatments, grain yields in CF and AWD irrigation treatments were statistically on par, which could be attributed to the maintenance of SWC in the root zone around field capacity during the water disappearing days. The perched water level in the AWD irrigation treatments was not more than 15 cm below the surface of the CT and SP plots. At this perched water level, SWC in the 0-20 cm soil depths of three tillage treatments ranged between 35-37 %, which also indicated water potential was around -10 kPa (field capacity, see water retention curve in Chapter 3 Figure-3.8). The findings of the current study also confirm the results of Mahajan *et al.* (2012), Belder *et al.* (2004) and Lu *et al.* (2002), who reported that CT rice did not suffer from water stress, and grain yield was not affected when the soil water potential did not fall below -10 kPa. Earlier studies have also shown that mid-season AWD in certain cases leads to improvement in rice yields by improving the oxygen status of the root zone and improving the rice root system (Uphoff and Randriamiharisoa, 2002)

6.4.6 Effect of SP on water productivity

Despite similar rice grain yield in SP and CT, WP of SP was significantly lower than that of CT in three years. In an earlier study, Gathala *et al.* (2011a) reported 7 years the average WP under ZT transplanted rice (ZT-TPR) was lower than the WP under puddled transplanted rice (PTR), though ZT-TPR received lower water input compared to PTR. The lower WP in the SP compared to CT in the current study was due to the higher water input to SP.

6.4.7 Effect of BP on irrigation water requirement for land preparation

The irrigation water requirement for land preparation in BP treatment ranged from 10.0 to 21.0 cm over three years. In 2015 and 2017, BP required 10.0 cm water for land preparation which was applied on the day before transplanting. In 2016, BP required two consecutive water applications for land preparation of about 10.0 cm each which was applied one on the day before transplanting and another in the morning of the rice transplanting. In 2016, a higher amount of water required for land preparation in BP could be attributed to the higher percolation and higher seepage through the unprotected bunds to the surrounding farmer's field. The fields surrounding the plots were not irrigated until 20 days after transplanting of the experimental plot, which might have exacerbated seepage water movement under the bunds to these adjacent fields. In 2016, the first water application event on the day before transplanting showed rapid infiltration in the furrows, and water thus disappeared within 4-5 hours, which were associated with higher infiltration capacity in the BP plots (see Chapter 3). Despite the volumetric limitation of the furrows and the more rapid progress of irrigation water across the field (Humphreys *et al.*, 2008), the irrigation amounts on the BP plots were higher in the current study compared to the CT during the first water application for land preparation probably due to macropore development (e.g. cracks and root channels) (Humphreys *et al.*, 2008). During infiltration measurements in 2017, small cracks were observed in the furrows with varying depths, although cracks size and depths were not determined. In 2015 and 2017, water for land preparation was statistically similar in BP and CT, suggesting that lateral seepage loss to the surrounding fields were hindered because of the protected bunds by the plastic sheets and the synchronised irrigation and transplanting rice in the research field with the surrounding farmer's fields.

6.4.8 Effect of BP on irrigation water requirement from transplanting to harvest

6.4.8.1 CF irrigation

As the infiltration capacity in the BP treatment were higher than CT, keeping the furrow always flooded meant that the BP plots were usually irrigated slightly more frequently in the early rice season (up to 35 DAT). In 2016, the total irrigation input in BP plots was 48 % higher than the CT plot due to higher post-transplanting irrigation. In 2016, the number of irrigations from land preparation to PI was 10 for BP and seven for CT treatments. After PI, the number of irrigations up to harvest was four for both BP and CT. These results suggest that variation in the total water use and the total number of irrigations between BP and CT was mainly due to the variation of those from land preparation to PI. In BP plots, the total number of irrigations in 2015 was 11, out of which seven irrigations were applied from land preparation to the PI stage. Likewise, out of eight irrigations in 2017, five irrigations were applied from land preparation to PI in BP plots. The greater cracking and porosity on the permanent beds might have increased bypass flow (Kukal *et al.*, 2010) and hence caused higher irrigation water requirement from post- transplanting up to PI.

Total water input (irrigation) to rice in BP and CT plots were much higher in 2016 than in the other two years. Under CF irrigation, total input was 118.0 cm and 80.0 cm in BP and CT in 2016, respectively, compared with 60-90 cm in 2015 and 2017. This suggests that restricting seepage reduced irrigation amount by 25 % in both BP and CT under CF irrigation. In 2017, in the rice season, 23 cm of rainfall contributed to crop water use. The well-distributed rainfall in the middle of the rice season (26 DAT to 62 DAT) reduced the irrigation water requirement for BP in 2017.

Consistent with the current study, Kukal *et al.* (2010) reported higher irrigation application to rice in BP treatment compared to CT. By contrast, many other studies reported BP saved 9 to 58 % water compared to CT (Sharma *et al.*, 2002; Balasubramanian *et al.*, 2003; Gupta *et al.*, 2003; Singh *et al.*, 2005; Bhushan *et al.*, 2007; Choudhury *et al.*, 2007; Jehangir *et al.*, 2007; Khan, 2016). The timespan of these studies is ranged from one season to two years.

6.4.8.2 AWD irrigation

In 2016, without plastic sheets in the bunds, percolation under BP reduced by 26 % with AWD irrigation relative to CF irrigation, while in 2017, with plastic sheets in the bunds, the reduction in percolation was 77 %. The lower water inputs under BP in AWD irrigation than in CF irrigation was thus caused mainly due to negligible seepage and reduced percolation, and partly by reduced ET_c during the non-ponded days in AWD events. During the whole rice season, the number of ponding days under continuous flooded irrigation was 77, while it was 70 under AWD irrigation, suggesting that reduced percolation from the unsaturated soil during non-ponded days reduced the total percolation under AWD irrigation treatments. These findings are also consistent with the findings of Choudhury *et al.* (2007). Furthermore, in unsaturated condition during AWD events, seepage from the rice plot reduced by 15 % in AWD irrigation compared to CF irrigation. Agrawal *et al.* (2004) and Mandal (1990) also reported no seepage loss from the rice field under the unsaturated rice field.

6.4.9 Effect of BP on seepage and percolation losses

6.4.9.1 CF irrigation

The increased irrigation water used under BP plots than conventional puddled plots was mainly due to the seepage and percolation losses during the first 35 days. The seepage and percolation rates were similar in the rest of the season in 2016. In 2017, the seepage and percolation rates under BP-CF and CT-CF were not significantly different (0.65 cm day^{-1}) up to 35 DAT, mainly due to the control of seepage. However, unlike the current field experiment, farmers can generally not afford to install plastic sheets in the bunds of their rice fields. In 2016, it was observed that the seepage rates in the experimental plots adjacent to the surrounding farmers' field were higher compared to the experimental plots located far from the farmers' plots. Under BP treatment, the deep percolation was higher in the first 35 days under both flooded and AWD irrigation methods. This was mainly because under both irrigation methods, plots were continuously flooded for 15 days after transplanting to overcoming the transplanting shock to seedlings. Under both irrigation methods, the deep percolation occurred mostly in the first 35 DAT, especially in a young crop; most of the water cannot be taken up or stored in the root zone and is lost as deep percolation (Bouman *et al.*, 2002).

6.4.9.2 AWD irrigation

The lower total deep drainage losses (seepage and deep percolation) in AWD than in CF was caused by both reduced rates of seepage and reduced rates of percolation (Arora, 2006; Belder *et al.*, 2007; Bouman *et al.*, 2007; Choudhury *et al.*, 2007; Sudhir-Yadav *et al.*, 2011). In the BP treatment shifting from CF to AWD irrigation reduced seepage by 15 % and percolation by 21-43 %. However, CT-AWD reduced seepage by 6-10 % and percolation losses by 27-33 %. This means AWD irrigation performed better in BP than CT in reducing deep drainage.

6.4.10 Effect of BP on Evapotranspiration

6.4.10.1 CF irrigation

Bed Planting treatment reduced ET_c by 2.3 cm in 2016 under CF irrigation. In the BP system, the furrow holds water and occupies half of the total plot surface area. Thus, exposure of water to the atmosphere in the furrow is comparatively lower than the CT plots. In addition, the exposure of a partially filled furrow is lower than the full furrow. Thus, evaporation from the furrow was less than the evaporation from the ponded CT treatment; as a result, the crop evapotranspiration was lower in BP than CT.

6.4.10.2 AWD irrigation

Alternate wetting and drying irrigation reduced ET_c by only 11 % compared to CF irrigation in BP plots. Due to the trapezoidal shape of the furrow, as the ponding depth in the furrow is reduced, the exposed surface of the water is also reduced. Thus, the rate of evaporation from the water surface is reduced with the decreasing ponded water depth approaching the AWD events. However, during the saturated and unsaturated condition in the non-ponded days, still, there is evaporation from the furrows and the beds. The furrow and the bed collectively present a greater total surface area than flat land. The higher evaporation from this surface could be the cause of the low ET_c reduction by AWD irrigation in BP.

6.4.11 Effect of BP on rice grain yield

Overall results indicate that BP produced a similar grain yield compared to CT in each of the three years. However, other studies have reported inconsistent results of transplanted rice on beds. Kukal *et al.* (2006); Yadvinder-Singh *et al.* (2009) reported yields of transplanted rice on permanent beds were depressed relative to yields of PTR with the same AWD water management regardless of the age of the undisturbed permanent beds from 1st to 8th crop. Kukal *et al.* (2010) reported yield of transplanted rice on fresh beds was 7-15 % lower than the transplanted rice in CT, while the magnitude of the yield decline was increased to 33-44 % on the permanent bed over four years. Gathala *et al.* (2011a) reported transplanted rice on a raised bed prepared by a tractor-drawn bed planter in the first year and without reshaping in the following year had substantial yield loss with a negative time trend. These previous studies have proven that rice grain yield declined under the aged permanent bed where beds were neither tilled nor reshaped after the beds were once formed. The consistently similar yield in the bed compared to CT in three years in the current study might have been attributed to the loose soil in the top of the reshaped bed that facilitated the condition of tilled soil.

In the present study, yields of BP-AWD was similar to that of CT-CF treatment which is inconsistent with the findings in Punjab, India, where yields of BP-AWD were significantly lower than CT-CF treatment (Kukal *et al.*, 2006). Similarly, Yadvinder-Singh *et al.* (2009) reported grain yield under BP-AWD was only 33 % of the CT-AWD treatment. These results of rice yields in the Northwest region of Bangladesh suggest that transplanted rice grown in BP performed similarly to rice grown in CT both under AWD and CF irrigation. The differences in rice yield performance on beds in the present study and those in Punjab, india could be due to the difference in width of the wheels of the machines used for reshaping of the beds, and the location of the transplanted rice seedlings on beds. For example, in the present study, the reshaping was done with a 2-WT. Whereas in Punjab, India the reshaping was done with a 4-wheel tractor. Thus, when the wheels of the 4-wheel tractor passed through the furrows, the side of the wheels might have compacted the wall of the furrows, where the rice seedlings were transplanted in the next year (Kukal *et al.*, 2008). In the present study the rice seedlings were transplanted on the top of the bed where BD was lower (see Chapter 3). Kukal *et al.* (2008) showed significantly higher BD in the edge of the beds resulting in narrower horizontal root spreading.

6.4.12 Effect of BP on water productivity

Similar to SP, BP gave significantly lower WP compared to CT. Consistent with this result, Gathala *et al.* (2011a) reported lower WP in transplanted rice on bed compared to PTR. The difference in WP between BP and CT in the current study was the higher water requirement in BP compared to CT despite the fact that the rice grain yield in both tillage treatments was the same.

6.5 Conclusion

Rice yield was unaffected by the tillage and irrigation method over the three years, indicating that the water balance factors altered by tillage and irrigation method did not impact the suitability of growing condition for Boro rice growth. Crop ET_c was also similar among tillage methods and only decreased by 2.3 cm under CF on BP. This suggests that variation in soil hydrology was less influential than the aboveground conditions for Boro rice ET_c. By contrast, water balance was greatly altered by whether seepage under bunds was controlled or not. When seepage under the bunds was unrestricted, and transplanting preceded that in surrounding farmer's fields by 2 weeks, as in 2016, there was a 10 cm higher irrigation requirement at land preparation and 24 cm in the early stages of the rice season collectively for SP and BP compared to CT. In contrast, when seepage under bunds was controlled, this water balance component was decreased by 62 %, as was the irrigation water requirement for land preparation by 43 % (8 cm) for both SP and BP. In 2017, protected bunds also reduced percolation by 15 cm (compared to unprotected bund in 2016) for SP during the whole growing season and resulted in similar irrigation requirement compared to CT. However, the irrigation requirement from transplanting to PI was still 4 cm higher under BP than CT, which caused a 10 cm higher total water requirement for BP. In 2016, with the unprotected bund, irrigation requirement from transplanting to PI under SP was 27 cm higher than CT due to the 16 cm higher percolation and 13 cm higher seepage during this growing stage. Therefore, it can be concluded that where lateral seepage is unrestricted, SP required higher total irrigation water compared to CT but not when lateral seepage was negligible or prevented. Furthermore, regardless of lateral seepage control, BP required more irrigation water than CT due to the higher requirement during the period from land preparation up to the PI stage of the Boro rice-growing season.

Seepage in SP and BP plots was the maximum under CF irrigation in 2016 when the greatest water volumes were added among the three years. Moreover, the volume of seepage was 19 cm higher in SP and BP than CT ($p<0.05$) under CF water management. Seepage in SP and BP was on average 30 % of the total water use, and that in CT was 23 % under CF. The AWD water management reduced seepage by 11 % compared to the seepage under CF water management regardless of year and tillage treatments.

In 2016, 21 cm higher deep percolation observed in the SP and BP plots was mainly due to the reduced bulk density, increased total porosity, and the higher steady-state infiltration rates in the topsoil and the plough pan of the SP and BP plots. The higher deep percolation in the non-puddled SP and BP plots could also be attributed to the cracks developed upon drying before initiation of the land preparation. However, the percolation differences were only observed in the first 35 DAT from land preparation to panicle initiation stage during when deep percolation in the SP and BP plots was twice as high as in the CT plots. No significant differences in deep percolation between tillage treatments were observed after panicle initiation when cracks in the plough pan of SP and BP plots closed upon rewetting.

7 General discussion

This thesis presents findings from 2015-2017 on the effects of minimum soil disturbance and increased crop residue retention on soil physical properties and on components of the water balance and WP at two long-term experimental sites that were established in 2010 at Alipur and Digram of Rajshahi Division (in two contrasting agro-ecological zones in the Barind area), Bangladesh in the Eastern Gangetic Plain (EGP comprises Eastern India, Nepaland Bangladesh). Of the two sites, one represents a rice-dominated system (mustard-irrigated rice-monsoon rice) and the other a rice-based system (wheat-jute/mungbean-monsoon rice) during the study period of this thesis. Since the establishment of the experimental sites, three tillage treatments, namely SP, BP, and CT, have been used for both dryland crops and wetland rice. For wheat, seeds were row-sown during the mechanised SP or BP operations but broadcast after CT. For rice in SP and BP, rice seedlings were hand transplanted in non-puddled soil following the overnight inundation of the field under the water, while rice under CT was hand transplanted in the puddled soil. Since the establishment in 2010 of the research site described in this thesis, Islam (2016) and Alam *et al.* (2018b) have successively conducted research with the effect of minimum soil disturbance and increased residue retention on crop production, soil properties and greenhouse gas emissions. But there was a research gap in terms of soil physical properties and water balance. In this thesis, the water balance for two different component crops in two cropping systems was studied, namely, irrigated wheat in the wheat-jute/mungbean-monsoon rice system at Digram and irrigated rice in the mustard-irrigated rice-monsoon system rice at Alipur.

Two-wheel tractors are widely used in smallholder farms in South Asia and other parts of the world and have become very popular in Bangladesh as the main means of land preparation for crop establishment. But the effect of repeated rotary tillage and wheel trafficking by the 2-WT on soil compaction and the least limiting water range of soils have not been examined before.

The effect of multiple-pass wheeling and increased weight of a 2-WT on the compaction in the soil profile were studied for two seasons in two non-CA plots near the long-term CA plots at Alipur and Digram.

This chapter links the results reported in four experimental chapters and draws conclusions from the studies about the medium-long term effects of CA on soil physical properties and water balance in rice-based cropping systems in the EGP. A framework for future research has also been outlined at the end of this chapter.

7.1 Tillage and residue management effects on soil physical properties

Seven years' practice of minimum soil disturbance with the retention of increased crop residue altered the soil physical properties in both silty loam soil at Alipur and silty clay loam soil at Digram, respectively. The physical changes were reflected in the reduction of BD, enhancement of TP and reduction of PR in the 0-20 cm soil depth (Chapter-3).

In the 0-10 cm soil depth, BD decreased from 1.37 to 1.33 g cm^{-3} at Alipur and 1.27 to 1.24 g cm^{-3} at Digram soil due to HR treatment compared to LR. The HR treatment also increased macroporosity by an average of 55 % over LR treatment. The reduction in BD can be attributed to the increase in macroporosity and hence the enhancement of TP in the surface soil. In accordance with these results, Bhattacharyya *et al.* (2015) reported lower BD in 0-10 under increased residue retention due to loose soil and more pore space created. Improved soil aggregation under HR treatment probably also helped in reducing BD (Govaerts *et al.*, 2009; Gathala *et al.*, 2011b). Although soil organic carbon (SOC) has not been examined under the current study, the remarkable improvement in SOC in seven years, as reported by Alam *et al.* (2018b) for the same fields, caused by the decomposition of retained crop residues over the years (Lal *et al.*, 1980; Khurshid *et al.*, 2006) and less oxidation of *in situ* organic matter (roots, etc.) due to absence of tillage and absence of soil redistribution (Edwards *et al.*, 1992; Reicosky *et al.*, 1995) directly influenced the reduction in BD. Reduction in BD due to increasing SOC in the first few centimetres of the clay loam and loam soil profile after seven years and eleven years of CA has also been observed, respectively, by Jemai *et al.* (2013) and Chen *et al.* (2009). Retaining 100 % of the rice and wheat residue on clay loam soil surface for 3 crop cycles (2012-2015), Choudhary *et al.* (2018b) reported 0.12 gm cm^{-3} less BD in ZT than CT in the 0-10 cm depth. The findings of the current study corroborate other results observed in soils of very similar natures and climatic conditions where minimum soil disturbance with increased crop residue retention resulted in positive effects on soil BD in the surface 10 cm soil profile (Bhattacharyya *et al.*, 2008; Govaerts *et al.*, 2009; Islam, 2016).

The current research has found that tillage treatments had a significant influence on soil BD in the 0-20 cm soil depth irrespective of residue management. In comparison with CT, the average (two soils) decrease in BD was 4.5 % and 2.6 % in 0-10 cm depth for SP and BP tillage, respectively. Reduction in BD in the 0-10 cm depth in NT system has also been reported by other researchers (Hill and Cruse, 1985; Dao, 1996; Shaver *et al.*, 2002; Shirani *et al.*, 2002; McVay *et al.*, 2006; Jemai *et al.*, 2013; Kahlon *et al.*, 2013; Salem *et al.*, 2015; Parihar *et al.*, 2016; Choudhary *et al.*, 2018b). On the contrary, other studies have reported higher BD under NT in the surface soil layer compared to that under CT (Kumar *et al.*, 2002; Bhattacharyya *et al.*, 2009; Gathala *et al.*, 2011b; Huang *et al.*, 2012; Jemai *et al.*, 2012; Jat *et al.*, 2013; Dikgwatlhe *et al.*, 2014). Soil BD in the current study gradually increased with the increase in soil depth, and the highest BD values were measured in the 10-20 cm depth for all tillage treatments. The data clearly indicates a plough pan at this depth. A similar observation was also reported by Kahlon *et al.* (2013) and Unger (1995). In 10-20 cm depth, in comparison with CT, the average decrease in BD was 3.8 % and 4.6 % for SP and BP, respectively. Very few researchers have reported the reduction in BD at the subsurface (10-20 cm) soil due to the NT system compared to CT (Gathala *et al.*, 2011b; Kahlon *et al.*, 2013). Singh *et al.* (2016) for

IGP India soil reported shifting from puddled transplanted rice/conventional tillage maize to zero tillage direct-seeded rice/zero tillage maize has reduced BD by 3.2 % at 15-30 cm depth. Under similar tillage treatment combinations in the same fields as this study, Islam (2016) observed no significant differences in BD values between SP and CT at 10-15 cm soil depth. The lack of change in BD under SP compared to CT at 10-15 cm depth could have been due to the shorter duration of the experiment (3.5 years, 7 crop cycles) (Jat *et al.*, 2018). Remarkably, after seven years (this study) the BD decreased at 10-20 cm soil depth in SP compared to CT, which indicates that reversal of subsoil compaction by natural amelioration due to prolonged absence of puddling is a relatively slow process. The pore size distribution data of this study indicated that after seven years in 10-20 cm depth of silty clay loam soil at Digram, SP increased macroporosity by 87 % and mesoporosity by 27 %, while reducing microporosity by 13 % compared to CT. These results indicated that the decrease in BD in the subsoil under SP was largely associated with the development of macropores, thereby helping to reduce soil compaction and increase TP. Very few researchers have reported the enhancement in macroporosity in the subsurface (10-20 cm) soil due to the NT system compared to CT (Bai *et al.*, 2008; He *et al.*, 2009a; He *et al.*, 2009b). The development of soil macropores in the subsoil after seven years may originate from soil biological activity, including roots and earthworms (Jemai *et al.*, 2013). Indeed, unquantified observations during field measurements of soil parameters suggested that earthworms were more frequent in SP than CT plots. The trend of decreasing BD in the subsoil infers that long-term SP is effective in dissipating the plough pan in this region which has important implication for root distribution with depth and for water balance (Chapter 4, 5, and 6).

In accord with BD, PR was also significantly affected by tillage, residue and depth. Irrespective of residue treatment, PR at 10-20 cm depth decreased from 2.15 MPa (CT) to 1.93 MPa (SP) at Alipur and 2.55 MPa (CT) to 2.32 MPa (SP) at Digram. The results of reduction of PR in the subsurface layer agreed with earlier reports (Gathala *et al.*, 2011b; Parihar *et al.*, 2016; Singh *et al.*, 2016). By contrast, Jat *et al.* (2018) reported, after 4 years, there were no significant differences between CT and CA in terms of PR at the subsurface layer (10-30 cm). Penetration resistance in a given soil is directly related to BD and inversely related to soil water content (Sharma and De Datta, 1986). In the current study, PR closely followed the same trend as BD. However, the soil water content at the time of PR measurement at 10-20 cm depth was significantly higher in SP (28.1 %) compared to CT (21.2 %). This result suggests that the reduction in PR values in SP compared to CT in the 10-20 cm depth could be partly due to the higher SWC in SP treatment at the subsurface. Similar to the PR data of this study, under a 7-year-old experiment, Mondal *et al.* (2019) observed that despite similar BD values between CA and CT, a significant reduction in PR in the subsurface layer under CA compared to CT could be due to the higher subsurface soil water content in CA compared to CT. Very few studies have reported the positive impact of SP on reducing both BD and PR in the subsurface, and hence the finding of this study is novel. The reduced BD enhanced TP and reduced soil strength in the 10-20 cm suggest from this study that plough pan tended to weaken under long term SP tillage.

As hypothesized, continuous use of long-term (7 years) minimum soil disturbance with residue retention changed the soil physical properties such that they also altered the soil hydraulic properties in the 0-20 cm depth. Lower BD and hence higher total porosity (TP) in the SP and in beds positively increased saturated hydraulic conductivity (K_{sat}), infiltration capacity and water storage capacity both in the surface soil and plough pan. Soil K_{sat} (cm hr^{-1}) was significantly increased by SP and BP from 1.00 for CT to 1.39 for SP and to 1.52 for BP in the 0-10 cm silty loam soil at Alipur. Soil K_{sat} increased from 0.32 for CT to 0.66 for SP and to 0.81 for BP in the 0-10 cm silty clay loam soil at Digram. The K_{sat} results are in accord with those of Naresh *et al.* (2011) and Bhattacharyya *et al.* (2006b), who reported an increase in K_{sat}

under permanent beds with residue retained compared to CT without residue. Bhattacharyya *et al.* (2008), in an RW cropping system, reported values of K_{sat} in the 0-15 cm soil depth were higher with ZT than with CT after four years of treatment implementation. Similar findings have also been reported (Ehlers, 1975; Osunbitan *et al.*, 2005; Bhattacharyya *et al.*, 2006a; Rasool *et al.*, 2007; LI *et al.*, 2011; Parihar *et al.*, 2016). On the contrary, Carter and Kunelius (1986) and Heard *et al.* (1988) found reduced K_{sat} values for NT. Saturated hydraulic conductivity is a combined measure of the size and continuity of pores. The effect of SP was to increase the SOC (measured by Alam *et al.* (2018b)) and aggregation (not measured), and thereby increase the volume fraction of larger pores in the surface soil. The higher K_{sat} in the surface soil under SP than CT is consistent with the generally accepted idea that more rapid movement of soil water occurs via macropores despite the fact that they occupy a small fraction of total soil porosity (Cameira *et al.*, 2003). However, the difference in volume of macroporosity between SP and CT was small (0.9 to 2.5 cm^{-3}/100 cm^{-3}), suggesting that the greater K_{sat} in SP than CT was due to better connected macropores in SP than in CT in the surface soil. Similar findings have also been reported by Bhattacharyya *et al.* (2008) and Bhattacharyya *et al.* (2006a). The decrease in K_{sat} in CT could be attributed to the destruction of continuity of macropores in the intensively tilled ploughed layer (Singh *et al.*, 2002b). In 10-20 cm soil depth, K_{sat} increased from 0.22 for CT to 0.48 for SP and to 0.43 cm hr^{-1} for BP in the silty clay loam soil at Digram. In a sandy clay loam soil of the Indian Himalaya, Bhattacharyya *et al.* (2006a) also reported ZT significantly increased K_{sat} in the 15-22.5 cm depth compared to CT. By contrast, Parihar *et al.* (2016) found no difference in K_{sat} between ZT and CT in the densest soil layer at 30-45 cm depth. The increase in K_{sat} in the 10-20 cm depth under SP was mainly due to the decrease in BD and increased TP due to the increase in macroporosity. However, the proportion of macropores relative to total porosity was comparatively low, so that greater pore continuity as a result of minimum soil disturbance in the SP may explain the increase in K_{sat} in the 10-20 cm depth. Greater pore continuity for NT systems has been mentioned by Ehlers (1977) as the cause of greater K_{sat} under NT compared to CT. Although K_{sat} can be extremely variable, the higher K_{sat} values under SP might have been partially due to the macro-channels produced after decay of roots and/or due to earthworm activities under undisturbed SP soil unlike CT (Joschko *et al.*, 1992; Strudley *et al.*, 2008; Saha *et al.*, 2010).

Despite having lower BD and higher TP in SP at Alipur there was no measurable difference in K_{sat} values for SP and CT in the plough pan. Possibly this is due to the avoidance of measurements on cracks in the plough pan. Subsequent measurement of K_{sat} on cracks in the plough pan produced a mean value of 5.3 cm h^{-1} which was fourteen times higher than the mean values of K_{sat} in the plough pan of three tillage treatments for Alipur (0.38 cm h^{-1}). Indeed, steady-state infiltration in SP was higher than in CT at Alipur, indicating water permeability has improved by 10-20 cm since the steady-state infiltration rates are governed by the porosity of the subsoil (Bissett and Oleary, 1996; Saha *et al.*, 2010).

Strip planting resulted in twice the rate of steady-state infiltration (I_s) as CT, while BP showed three times higher I_s compared to CT in the silty loam soil at Alipur. While in the silty clay loam soil at Digram, SP and BP had about three times higher I_s over the CT treatments. After a seven-year permanent plot study, Gathala *et al.* (2011b) reported steady-state infiltration in ZT transplanted rice followed by ZT direct-seeded wheat was higher (0.34 cm hr^{-1}) than CT puddled transplanted rice followed by CT direct-seeded wheat (0.13 cm hr^{-1}). Savabi *et al.* (2008) also reported that ZT in silty loam and silty clay loam soil enhanced infiltration rates with time. Many other researchers have also reported higher infiltration rate (initial as well as steady-state) under ZT compared to CT (Li *et al.*, 2007; Bhattacharyya *et al.*, 2008; Singh *et al.*, 2014; Singh *et al.*, 2016). On the contrary, Sharma *et al.* (2005) found no significant difference in the infiltration rate of silty clay loam soil under the two tillage treatments during three years of experimentation and reported higher infiltration under CT than under ZT. Mondal *et al.* (2019) found no variation between CA and CT in terms of initial and steady-state infiltration rates. Similar to the finding of the current study, Gathala *et al.* (2011b), Jat *et al.* (2009) and Jat *et al.* (2013) have also reported higher infiltration rate under BP compared to CT.

Minimum soil disturbance and HR retention improved the water storage capacity of the soil both at the surface and in the plough pan. Decomposed organic materials over the years serve as a porous material and possess greater specific surface area, and eventually adsorb more water. At Digram, SP stored about 1-3 % more water than CT at matric potential 0 kPa to -1500 kPa in the 0-20 cm soil depth. This means that SP stored 0.2-0.6 cm more plant-available water in the 20 cm soil depth, which though small in volume, beneficially reduced irrigation requirement for wheat from germination to later in the growing season. The water retention curve for Alipur showed SP stored a similar increase in plant available water relative to CT at field capacity, which is important for post-monsoon rice dry land crop during seed germination. However, real-time measurement of SWC in the field either at the time of PR measurement or before irrigation for different growing stages of wheat crop revealed larger variation in soil water storage capacity between tillage treatments. For example, at sowing of wheat, SP stored 1.2—1.7 cm more plant available water than CT in the top 30 cm depth. This increase was even larger at the beginning of the grain filling stage when SP stored 1.5—1.9 cm of more soil water than CT in the 0-30 cm depth. At Alipur, SP stored 0.8 cm more water in the 0-30 cm depth compared to CT at the PR measurement four weeks after the monsoon rice harvest.

7.2 Effect of infiltration variability on the irrigation requirement

The increased infiltration capacity in SP reduced the irrigation requirement for wheat but increased it for rice. For wheat, irrigation was applied to the extent that the SWC in the soil profile up to 180 cm attained field capacity, and no excess water was applied that could be drained out beyond that depth. Increased infiltration capacity under SP had further advantages over CT due to the levelled surface in SP, caused by the minimum soil disturbance, which facilitated the faster spread of water across the field while allowing the water to infiltrate deep into the soil to the extent that the SWC could reach the field capacity. Furthermore, the increased SOC in the topsoil helped to store more SWC and reduce evaporation. Also, the water that infiltrated deep in the soil was protected from rapid evaporation. This was how under SP, increased infiltration and applying water to reach the FC saved up to 33 %. irrigation water for wheat

In contrast, higher deep drainage was recorded in rice due to the hydraulic pressure head created by the ponded water above the soil surface. Increased infiltration capacity in the SP, in this case, also induced additional deep drainage and caused 34 % more irrigation requirement for rice. Thus, the third hypothesis for the current study that minimum soil disturbance over time may destroy or weaken the plough pan and, in turn, alter water balance, which may be detrimental for rice irrigation requirements, appears to be supported for soils in Northwest Bangladesh.

Irrigation water management, such as midseason AWD irrigation and the control of seepage under bunds, greatly influenced *in situ* infiltration. Under AWD irrigation, *in situ* infiltration was reduced by reducing seepage and deep percolation losses. Alternate wetting and drying irrigation compared to CF irrigation reduced deep percolation by 25 % in SP, while shifting from CF to AWD irrigation for CT reduced by 33 % the water volume lost through deep percolation. Relatively AWD irrigation performed better in CT plot in reducing deep percolation compared to SP. There were three AWD events in both SP and CT treatments in 2016. In the SP treatment, ponded water disappeared quickly, and the perched water level reached 15 cm depth within three days in each AWD event, which resulted in total of 9 water-disappearing days and 70 ponding days from the transplanting to flowering stage of rice. While in CT treatment, the water disappeared slowly, and the perched water level took one more day to reach 15 cm depth in each AWD event, which resulted in 12 water-disappearing days and 65 ponding days in CT treatment. This means that SP treatment had to be ponded 5 more days to avoid increasing matric potential more than -10 kPa in each AWD event. Water required to maintain ponding in SP for 5 more days than CT under AWD irrigation partly increased the total water requirement in SP plots.

In 2015 and 2017, when seepage was controlled between plots and towards the surrounding fields, values were similar in SP and CT, but percolation was higher in SP than CT. Hence, three years results suggest that, whether or not seepage was controlled, there was a greater volume of water was lost through deep percolation in the SP plot as a result of high infiltration.

The main differences in irrigation requirement between SP and CT treatments in rice occurred from land preparation to 35 DAT. Faster infiltration in the SP plots compared to CT in two hours of the first irrigation for land preparation resulted in mean *in situ* infiltration of 5.0 cm day^{-1} in SP compared to 3.0 cm day^{-1} in CT, before transplanting of rice. The significantly higher infiltration in SP compared to CT was extended to 35 DAT with a mean infiltration of 0.95 cm day^{-1} in SP than 0.44 cm day^{-1} in CT, while rest of the season, the infiltration in SP and CT was similar (mean 0.27 cm day^{-1}). The higher infiltration rates in the early rice season were attributed to the high infiltration through the cracks developed in the SP plot due to lack of puddling, while later in the season, the decline in infiltration rates suggest that cracks closed due to swelling of clays due to rewatering.

7.3 Effect of wheel compaction by a 2-WT

At both sites, both increased loading weight and increased number of wheel passes increased BD and PR in the 0-5 cm depth, but the greater differences in BD and PR were achieved by increasing the number of wheel passes. Increased number of passes also increased BD and PR at the 5-10 cm soil depth in Digram soil since there was no shallow plough pan at this depth. Cumulative compaction effect due to increased wheel passes in the surface soil in this case transmitted to the 5-10 cm depth. In addition, conventional tillage, even without any extra loading, when run at 5-10 cm depth with the increased number of wheel passes produced increased BD and PR at the 5-10 cm depth. Compaction by CT-4Pass at 5-10 cm depth indicated that a 2-WT when frequently trafficked at this depth for many years, created a dense soil layer which is reasonably related to the formation of the plough pan in fields (Chapter 3). With CT-4Pass, there was no significant effect of extra loading on the compaction in the 5-10 or 10-15 cm depth.

Increased BD and PR caused by compaction both in 0-5 cm and 5-10 cm were reflected in the lower value of LLWR. In most cases, SWC at 10 % air-filled porosity (θ_{AFP}) was lower than the SWC at field capacity (θ_{FC}), and the SWC at PR equivalent to 2.5 MPa (θ_{PR}) was higher than the SWC at permanent wilting point (θ_{PWP}). The lower value of θ_{AFP} and higher value of θ_{PR} collectively caused the lower value of LLWR since both were respectively the upper limit and the lower limit of the LLWR following soil compaction. Reduction in LLWR values due to θ_{AFP} and θ_{PR} being the upper limit and lower limit of the LLWR was also observed by (Chen *et al.*, 2014). In the current study, despite having higher plant available water content (PAW= $\theta_{FC} – \theta_{PWP}$), lower value of LLWR opens only a small window of SWC within which roots can penetrate in the soil, and beyond that limit, plant roots have restricted penetration in the soil (Da Silva *et al.*, 1994). The value of LLWR in the 0-5 cm ranged between 6-23 %, with the lowest value in the ST200-4Pass and with the highest value in the CT-4Pass treatments. The BD values under CT was lower than the loading weight treatments. Thus, the LLWR under CT, either in the single wheel pass or four wheel passes, was defined by the θ_{FC} and θ_{PWP} and was equal to PAW. A similar observation of low BD values and wider LLWR under CT was also reported (Calonego and Rosolem, 2011; Kahlon and Chawla, 2017). The value of LLWR declined rapidly in the plough pan and ranged between 0-5 %. Similar results with sandy clay loam soil in IGP were also reported by Mishra *et al.* (2015). Percent reduction in PAW in the 0-5 cm depth ranged from 0-60 % considering all treatments. Under CT, the percentage reduction in PAW was 0 % since the PAW was equal to LLWR. Percentage reduction in PAW was worst in the plough pan with a reduction of >100 %. This means that in the plough pan the root penetration could be severely restricted due to the lack of water available for uptake by the plant roots (Da Silva *et al.*, 1994).

Compaction by a 2-WT had a substantial effect on the chickpea emergence. Percent chickpea emergence was higher in the tilled soil in the CT plot, while compacted soil under ST200-4Pass gave the lowest value of percent chickpea emergence. Percentage emergence in the No traffic plot was intermediate. Several weeks after the seed sowing, it was observed in the ST200-4Pass plots that the main and lateral roots of some of the emerged chickpeas were coiled inwards and upwards inside a hole made for the seed placement. These are symptoms consistent with soil strength values that limit chickpea root elongation (Vance *et al.*, 2015).

The ground pressure of a 2-WT used in Bangladesh lies at the bottom of the range of the ground pressure for all tractors used in the world (Chamen, 2011). However, the consequences of compaction in the surface soil and even in the subsoil could be more severe if the ground pressure of a 2-WT is increased or a 4-WT with higher ground pressure is used. Keeping the weight and the ground pressure as low as possible should be the aim of manufacturing agricultural machinery for Bangladesh. Recently research on combine harvester and mechanized rice transplanter has begun in Bangladesh (Hossain *et al.*, 2015; Hossen *et al.*, 2019). Given the present results, the weight of these machines and their wheel ground pressures need further consideration. Rubber tracks could create less compaction than the wheels of a machine.

Infiltration results showed higher infiltration after a single pass than after four passes. Strip planting is a minimum soil disturbance technique where tillage operation, seed and fertiliser placement are done with single pass wheel traffic. Thus, reduced compaction by SP served the opportunity to increase infiltration and hydraulic conductivity, which also altered the water balance both in the silty loam and silty clay loam soil.

Compaction experiments have been done in two non-CA plots near the long term experimental sites. However, the LLWR value for SP-HR treatment can be inferred by putting the corresponding BD value in the equation of LLWR vs BD line for the 0-5 cm depth presented in Chapter 4 (Figure 4.15 for Alipur soil and Figure 4.24 for Digram). The relationship of LLWR vs BD line for the 0-5 cm depth suggests that the LLWR for BD value of 1.31 g cm^{-3} under SP-HR at the surface soil is 19 % at Alipur. The PAWC for SP-HR, as reported in Chapter 3 of this thesis, was 22 % or 2.2 cm. This means that percent reduction in PAW in Alipur was 14 %.

In the current study, wheel compaction was studied in a non-CA field. However, the compaction scenario may be different for a long-term CA field. It was reported that the surface soil of the CA field is higher in SOC (Alam *et al.*, 2018b). A soil with high organic matter is less likely to be compacted (Soane, 1990; Thomas *et al.*, 1996). Conservation agriculture practice facilitates fertilizer and seeding operation in a single pass. Thus, single pass traffic by a low weight 2-WT is unlikely to create compaction in the surface soil and the subsurface soil. Furthermore, in the SP practice, wheel traffic position will vary from season to season. Thus, compacted soil by single wheel pass in the first season will likely to be loosened in the next season's strip tillage operation. Thus, the cumulative strip planting effect over three planting seasons in a year and over several years may not lead to significant compaction in the surface and subsurface soil especially in the soils with swell-shrink clays (Pillai and McGarry, 1999; Radford *et al.*, 2007).

7.4 Controlled traffic farming system

Controlled traffic is based on the principle of not driving randomly over the soil but concentrating traffic onto specific tracks and confining the compaction to a relatively small proportion of the cropped area (Tullberg *et al.*, 2007). Controlled traffic farming, combined with conservation tillage, provides a way to enhance the soil properties and improve infiltration, increase plant-available water, and reduce soil erosion caused by runoff (Hamza and Anderson, 2005). The benefits of minimum soil disturbance establishment are that vehicular wheeling is confined to the inter-row space for SP. If the traffic is controlled and the wheeling follows the same line year after year, the inter-row space, which is not wheeled, may be restored by natural amelioration. However, SP does not necessarily follow the same track in every operation. Still, the displacement of the track during SP could be as small as only 10 cm from the track of the previous season.

Bed planting is another example of controlled traffic where wheel traffic is limited to the furrows only and allows the soil of the furrows to be compacted. However, the width of the wheel needs consideration while designing the dimension of the furrow. If the bottom of the furrow is narrower than the width of the wheel, the wall of the bed is likely to be compacted by the side of the wheel during trafficking. Compaction by the wheel at the bottom of the furrow is favourable for less irrigation water infiltration, but compaction in the bed restricts root growth.

7.5 Real water saving vs groundwater recharge

For farmers, water saving equates with less irrigation and hence lower water pumping cost, especially if associated with increasing yield. Real water saving occurs when losses that cannot be recaptured are reduced or eliminated (Seckler, 1996; Loeve *et al.*, 2002). Saving water in the cropping system is actually about reducing non-beneficial losses that cannot be economically recaptured elsewhere in the system. These non-beneficial losses are evaporation from the soil and the deep drainage that becomes contaminated and is not suitable for reuse. Under the current study, SP increased steady-state infiltration by three times and total infiltration by 60 % compared to CT. The deep percolation losses in irrigated rice season in 2016 under SP and CT were 53 cm and 30 cm, respectively (Table 6.1). Hence, CA practices appear to increase deep percolation. However, deep drainage and under bund seepage are not real water losses in the landscape since that water is not contaminated and will return to the groundwater where it is potentially available for reuse (Humphreys *et al.*, 2008). In the current study, groundwater monitoring during the 2016 irrigated rice season is presented in Figure 7.2. The groundwater table depth did not reflect any groundwater recharge at the observation well; rather, the groundwater depth was increased at the end of the season. The observation well was located 20 m away from the long-term experimental field, but there was a deep tube well located 200 m from the observation well. The amount of water that was withdrawn from the deep tube could have exceeded the amount of water recharged from the CA plot.

Taking a CA plot outside the radius of influence of a deep tube well could have facilitated the estimation of actual groundwater recharge from the deep drainage component of irrigation water. Furthermore, groundwater recharge estimation techniques, such as water table fluctuation methods (Healy and Cook, 2002; Lutz *et al.*, 2015) and/or application of tracer materials (Scanlon *et al.*, 2002; Ali *et al.*, 2019) could be used to estimate the groundwater recharge from the CA plot.

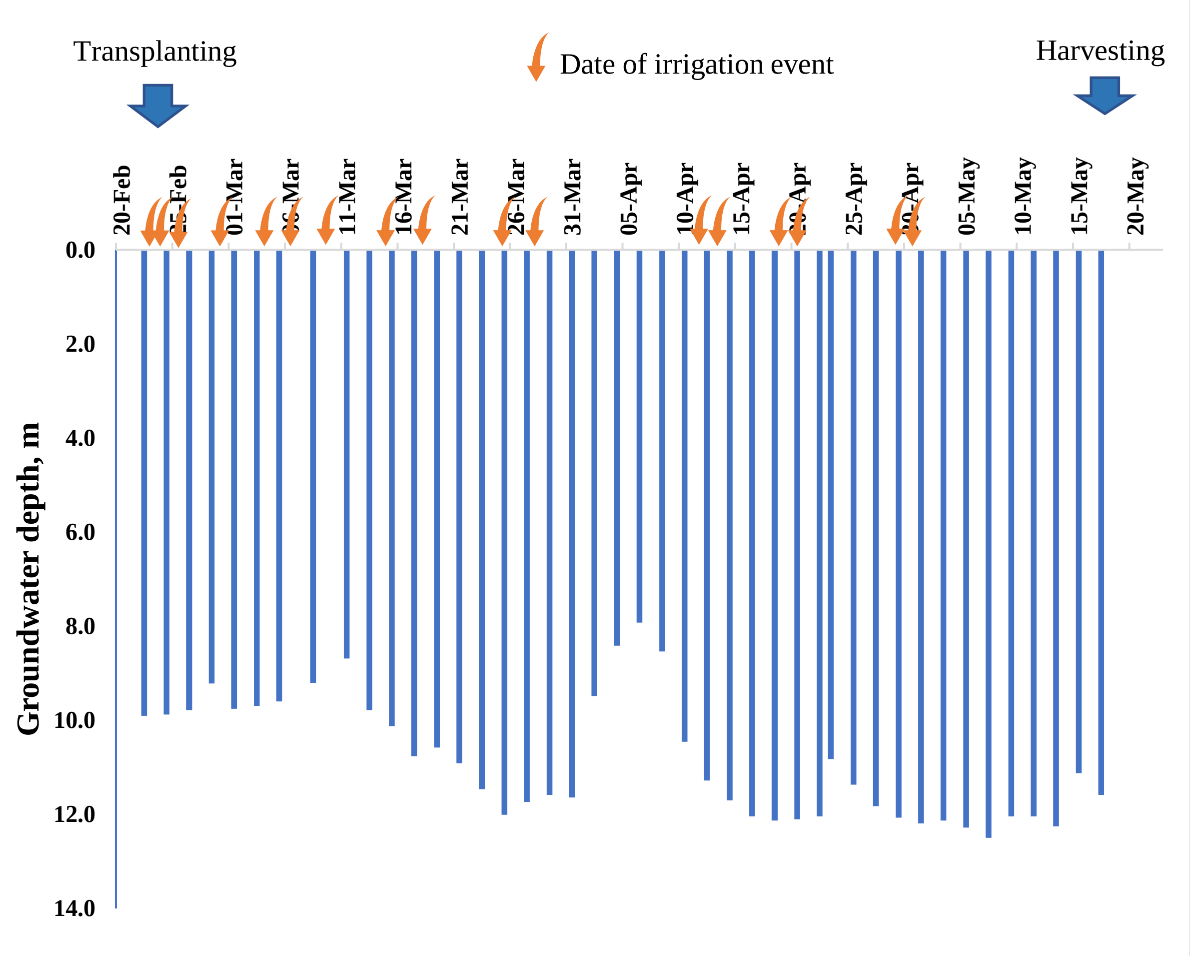


Figure 7.1 Groundwater level fluctuation at Alipur long term experimental field as observed from a borehole located 20 m away from the field. Red arrows indicate the date of irrigation events in the CA plots.

7.6 Effect of tillage and residue management on the crop performance

In the three seasons, the wheat yield was always higher in SP than in CT. Strip planting with high residue retention increased SOC (Alam *et al.*, 2018b) and reduced BD and PR (Chapter 3), which likely improved wheat root growth. It is hypothesized that roots extended down through the plough pan and extracted water for plant growth during the critical growth stages, which enhances crop yield.

Tillage and residue did not affect the yield of rice in the three years. These results are in accordance with other researchers who also found no yield differences of rice in the zero tillage or no-tillage treatments (Bhushan *et al.*, 2007; Saharawat *et al.*, 2010; Nandan *et al.*, 2018). In the rice field, the soil is always saturated or in the field capacity, which allows similar water and nutrient availability for all three tillage treatments. Rice performed well in both continuous irrigation and AWD irrigation treatments. Under AWD irrigation at 15 cm perched water depth, the soil was always at the field capacity, which avoids water stress to the rice plant at any time of the season. Thus, with a favourable water environment, rice yielded the same for all irrigation and tillage treatments. These results are consistent with many other findings in the IGP, which found no yield penalty in the AWD irrigation treatments compared to the continuous flood irrigation treatments (Lu *et al.*, 2002; Belder *et al.*, 2004; Mahajan *et al.*, 2012).

7.7 Recommendations for Further Research

- The proportion and size distribution of water-stable aggregates is an important soil physical parameter that determines the soil BD, pore connectedness, and hence hydraulic conductivity. The plant root penetration is also influenced by the soil aggregates. Soil aggregates are highly associated with SOC content. Soil organic carbon was increased by practising CA for 5 years, as reported elsewhere (Alam *et al.*, 2018b).. Thus, soil aggregate stability is also likely to be increased substantially by practising CA, but the extent of the increase and the relative effects of minimum soil disturbance and increased crop residue retention on water-stable aggregates needs to be investigated.
- Biological activities such as the population of earthworms are highly linked with increasing soil organic matter in CA. Thus, the increasing earthworm population and their activities in repairing the compactness of the soil need to be investigated in the northwest Bangladesh.

- As discussed before, irrigation water is only really saved when the non-beneficial water loss is reduced or eliminated. Deep drainage from the CA field was higher, but that component of the water balance is not a loss if the water contributes to the groundwater since it can be reusable. New research to directly quantify the rate of recharge would strengthen the water balance estimates. One way to make real water savings in the rice is to reduce soil evaporation that escapes to the atmosphere and is never useable. Another possible option for real water savings is if higher water infiltration rates in the monsoon decrease run-off losses. Thus, research is needed to find ways to reduce soil evaporation and to quantify deep drainage throughout the year, including the early wet season.
- Small scale CA practice did not result in measurable groundwater recharge even though the water balance experiments have demonstrated its potentiality. Groundwater recharge investigation under CA is needed at a large scale that can escape the influence from water withdrawal by deep tube wells. Groundwater recharge investigation is needed for both irrigation rice and rainfed monsoon rice and for the fallow period between Boro rice and Aman rice periods.
- Soil compaction research by a 2-WT under different SWC and soil types are needed. Knowing the changes in soil compaction with changes in water content helps to schedule farm trafficking and cultivation operations at the appropriate water content for each soil type.

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9 Appendix

Appendix 5.1 Parameters used in the simulation of Evapotranspiration using DSSAT-CSM-CERES-Wheat model at Digram, Rajshahi in Year 2015 to 2017.

Crop Management Data		
General Information of the plot		
Gross plot area per replication	m^2	40.5
Rows per plot		70
Plot Length	m^2	14
Plot spacing	cm	200
Harvest area	m^2	10
Harvest row number		12
Harvest row length	m^2	4
Environmental information		
Soil	Silty clay loam soil	
Depth	cm	180
Drainage type	No artificial drainage	
Initial condition		
Previous crop		Rice
Root weight	t ha^{-1}	1
Water table depth	cm	180
Crop residue	t ha^{-1}	2
Residue	N %	9.5
Incorporation		100%
Depth	cm	15
Organic carbon		
Treatments	Depth, cm	%
SP-LR	10	0.82
	20	0.4
SP-HR	10	0.9
	20	0.39
BP-LR	10	0.79
	20	0.47
BP-HR	10	0.8
	20	0.49
CT-LR	10	0.75
	20	0.37
CT-HR	10	0.81
	20	0.37
Fertilizer management	Broadcast	
Nitrogen	kg ha^{-1}	120
Caltivar	BARI GOM26	

	Year 1	Year 2	Year 3
Date of sowing	28-Nov-14	28-Nov-15	22-Nov-16
Date of Harvest	24-Mar-15	18-Mar-16	13-Mar-17
For weather parameter and soil bulk density please see Chapter 3			

Appendix 5.2 Amount of irrigation applied at irrigation event for three tillage treatments used in the simulation of Evapotranspiration using DSSAT-CSM-CERES-Wheat model at Digram, Rajshahi in Year 2015 to 2017.

Method of irrigation				Flood		
Treatments	**Irrigation amount and date of application**					
	cm	Date	cm	Date	cm	Date
SP-LR	6.3	13-Dec-14	4.6	13-Dec-15	5.4	07-Dec-16
	6.3	03-Jan-15	4.9	02-Jan-16	5.7	28-Dec-16
	6.5	26-Jan-15	5.1	24-Jan-16	5.6	20-Jan-17
	6.9	17-Feb-15	5.2	15-Feb-16	5.9	11-Feb-17
SP-HR	6.0	13-Dec-14	3.9	13-Dec-15	4.8	07-Dec-16
	6.2	03-Jan-15	4.3	02-Jan-16	5.2	28-Dec-16
	6.6	26-Jan-15	4.5	24-Jan-16	5.6	20-Jan-17
	6.7	17-Feb-15	4.5	15-Feb-16	5.9	11-Feb-17
BP-LR	6.9	13-Dec-14	4.7	13-Dec-15	5.6	07-Dec-16
	7.4	03-Jan-15	5.0	02-Jan-16	5.9	28-Dec-16
	7.3	26-Jan-15	5.2	24-Jan-16	6.1	20-Jan-17
	7.6	17-Feb-15	5.5	15-Feb-16	6.3	11-Feb-17
BP-HR	6.2	13-Dec-14	4.9	13-Dec-15	5.2	07-Dec-16
	6.6	03-Jan-15	5.1	02-Jan-16	5.9	28-Dec-16
	7.0	26-Jan-15	5.6	24-Jan-16	6.0	20-Jan-17
	6.8	17-Feb-15	5.8	15-Feb-16	6.1	11-Feb-17
CT-LR	8.8	13-Dec-14	6.7	13-Dec-15	5.8	07-Dec-16
	8.9	03-Jan-15	6.8	02-Jan-16	6.6	28-Dec-16
	9.1	26-Jan-15	7.3	24-Jan-16	6.9	20-Jan-17
	9.5	17-Feb-15	7.5	15-Feb-16	7.2	11-Feb-17
CT-HR	8.2	13-Dec-14	6.4	13-Dec-15	5.8	07-Dec-16
	8.7	03-Jan-15	6.5	02-Jan-16	6.3	28-Dec-16
	8.7	26-Jan-15	6.8	24-Jan-16	6.7	20-Jan-17
	8.8	17-Feb-15	7.3	15-Feb-16	7.4	11-Feb-17

10 Publications from this study

Journal article

Bell, R.W., Haque, M.E., Jahiruddin, M., Rahman, M.M., Begum, M., Miah, M.A.M., Islam, M.A., Hossen, M.A., Salahin, N., Zahan, T., Hossain, M.M., Alam, M.K., 2019. Conservation Agriculture for rice-based intensive cropping by smallholders in the eastern gangetic plain. Agriculture 9, 1-17.

Conference paper

Haque, M.E., Bell, R.W., Islam, M.A., Alam, M.K., Mahmud, M.N.H., M., J., 2018. Long-term impact of smallholders' Conservation Agriculture in rainfed and irrigated systems. 2nd African Congress of Conservation Agriculture. African Tillage Network.

Mahmud, M.N.H., Bell, R.W., Vance, W.H., 2017. Strip planting increases yield and water productivity of wheat (Triticum aestivum) in Northwest Bangladesh. International conference on Agri Biotech and Environmental Engineering, 11-12 September, San Antonio, USA.

Mahmud, M.N.H., Bell, R.W., Vance, W., 2017. Chickpea emergence responses to compaction by 2-wheel tractor in two soils of Northwest Bangladesh. In: Haque, M.E., Bell, R.W., Vance, W.H. (Eds.), 2nd Conference on Conservation Agriculture for Smallholders (CASH-II), 14-16 February, Mymensing, Bangladesh.

Mahmud, M.N.H., Bell, R.W., Vance, W., Haque, M.E., 2017. Effect of minimum tillage systems on water balance for rice-based rotations in Northwest Bangladesh. In: Haque, M., Bell, R.W., Vance, W. (Eds.), 2nd Conference on Conservation Agriculture for Smallholders (CASH-II), 14-16 February, Mymensingh, Bangladesh, pp. 62-64.